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Tropical Deltas and Coastal Zones

Food Production, Communities and Environment at the Land–Water Interface

Edited by

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Preface

Tropical megadeltas contain some of the most significant areas of urban, agricultural and industrial development in the world. These regions also possess ecosystems that are both critically important and highly endangered, and hold a rich collection of historical and cultural resources. The increasing pace of human development activities in tropical megadeltas has altered the functionality of these ecosystems drastically and produced escalating economic and sociocultural impacts that threaten critical food-producing areas. Tropical megadeltas have long been under stress from overexploitation and mismanagement, and now the looming spectre of sea-level rise associated with global warming presents a new and potentially far more dangerous threat to these regions.

Delta 2007 held in Bang Sean, Thailand, in November 2007 brought together a diverse range of research scientists to examine the state of tropical megadeltas, with a particular focus on agriculture, fisheries, aquaculture and the environment. This book is a compendium of selected papers from the conference that can be broadly categorized as land and water management, fisheries and aquaculture and rice-based agriculture systems. Intensification of aquaculture and rice-based agriculture frequently produces negative effects that range from environmental degradation to social conflict; managing these impacts in a sustainable manner is imperative if we hope to protect the social and ecological foundations of tropical deltaic systems. New approaches to the intensification and diversification of rice-based production systems are presented in this book, which could impact positively on the livelihoods of millions who inhabit the deltaic areas of South, South-east and East Asia if implemented on a large scale. More importantly, these innovations could begin to reverse our current exploitive behaviour and ensure the preservation of critical ecosystems. A significant section of the compendium is devoted to the intensification of marine shrimp aquaculture production. Negative impacts associated with shrimp production are well recognized, and several innovative approaches to waste management are presented. Further critical questions are raised over the introduction of exotic shrimp species and the long-term impact this could have on native species, which suggests a cautionary approach to future development.

A clear consensus emerged from the conference that highlighted the importance of social mobilization and the role of communities in decision making. This could take the form of the direct involvement of stakeholders in decision-making processes or conflict resolution through to economic-based incentives that promote sustainable development. Clearly integrated coastal zone management forms a basic platform on which negotiation and consensus can be achieved. Another clear message of the conference was the need for policy makers to acknowledge the diversity of socio-economic and environmental processes that exist at the local, regional and national scales. This diversity can only be reflected into future policy discussions through a bottom-up paradigm, as opposed to a command and control strategy. Centralized and distant governance often fails to account for diverse social needs and environmental conditions at the regional and local levels.

We gratefully acknowledge the support of conference sponsors such as the Food and Agriculture Organization of the United Nations – Regional Office for Asia and the Pacific, the CGIAR Challenge Program on Water and Food, the International Water Management Institute, the International Rice Research Institute, and the WorldFish Center and Burapha University in Bangsaen, Thailand. We also wish to thank the many anonymous reviewers who provided invaluable assistance throughout the process of selecting and reviewing the papers, and Iljas Baker, Mark Flaherty and Bill Hardy for their great contribution in editing the papers that appear in this compendium.

The Editors

Series Foreword:

Comprehensive Assessment of Water Management in Agriculture

There is broad consensus on the need to improve water management and to invest in water for food, as these are critical to meeting the Millennium Development Goals (MDGs). The role of water in food and livelihood security is a major issue of concern in the context of persistent poverty and continued environmental degradation. Although there is considerable knowledge on the issue of water management, an overarching picture on the water–food–livelihoods–environment nexus is missing, leaving uncertainties about management and investment decisions that will meet both food and environmental security objectives.

The Comprehensive Assessment (CA) of Water Management in Agriculture is an innovative multi-institute process aimed at identifying existing knowledge and stimulating thought on ways to manage water resources to continue meeting the needs of both humans and ecosystems. The CA critically evaluates the benefits, costs and impacts of the past 50 years of water development and challenges to water management currently facing communities. It assesses innovative solutions and explores the consequences of potential investment and management decisions. The CA is designed as a learning process, engaging networks of stakeholders to produce knowledge synthesis and methodologies. The main output of the CA is an assessment report that aims to guide investment and management decisions in the near future, considering their impact over the next 50 years in order to enhance food and environmental security to support the achievement of the MDGs. This assessment report is backed by CA research and knowledge-sharing activities.

The primary assessment research findings are presented in a series of books that will form the scientific basis of the Comprehensive Assessment of Water Management in Agriculture. The books will cover a range of vital topics in the areas of water, agriculture, food security and ecosystems – the entire spectrum of developing and managing water in agriculture, from fully irrigated to fully rainfed lands. They are about people and society, why they decide to adopt certain practices and not others and, in particular, how water management can help poor people. They are about ecosystems – how agriculture affects ecosystems, the goods and services ecosystems provide for food security and how water can be managed to meet both food and environmental security objectives. This is the ninth book in the series.

Managing water effectively to meet food and environmental objectives will require the concerted action of individuals from across several professions and disciplines – farmers, fishers, water managers, economists, hydrologists, irrigation specialists, agronomists and social scientists. The material presented in this book represents an effort to bring a diverse group of people together to present a truly cross-disciplinary perspective on water, food and environmental issues in the coastal zone. The complete set of books should be invaluable for resource managers, researchers and field implementers. These books will provide source material from which policy statements, practical manuals and educational and training material can be prepared.

The CA is carried out by a coalition of partners that includes 11 Future Harvest agricultural research centres supported by the Consultative Group on International Agricultural Research (CGIAR), the Food and Agriculture Organization of the United Nations (FAO) and partners from some 80 research and development institutes globally. Co-sponsors of the assessment, institutes that are interested in the results and help frame the assessment, are the Ramsar Convention, the Convention on Biological Diversity, the FAO and the CGIAR.

For production of this book, financial support from the governments of the Netherlands and Switzerland for the CA is appreciated.

David Molden
Series Editor
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1 Policy, Planning and Management at the Land–Water Interface

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Introduction

Tropical coastal deltas present one of the most challenging planning and management settings given their diverse character and location at the land–water interface. These areas are home to large populated centres such as Dhaka, Bangkok and Hanoi, and are significant centres of both agricultural production and industrial development. Coastal deltas also contain critical and sensitive ecosystems such as mangroves and a rich collection of historical and cultural resources. Human communities in coastal deltas are equally diverse, with the economic circumstances of many urban centres contrasting sharply with the impoverished conditions that exist in many rural communities. The increasing pace of human development activities in coastal deltas over the past 50 years has also strained environmental resources and produced escalating economic and sociocultural impacts (Mimura, 2006).

One of the most prominent issues in the recent evolution of tropical delta systems has been the widespread expansion of shrimp aquaculture, first in Thailand and then throughout coastal parts of East Asia, South-east Asia and South Asia (Chuenpagdee and Pauly, 2004). The rapid growth of shrimp farming has led to the dramatic transformation of coastal land use and subsequent environmental impacts that include: loss of mangrove habitats, water pollution, land salinization and declining fisheries (Primavera, 1997; Talaue-McManus, 2006). Recent developments have also seen marine shrimp aquaculture spread upstream into freshwater areas of tropical deltas (Flaherty *et al*., 2000) and the emergence of new hardy strains of domesticated shrimp has allowed coastal areas previously decimated by virulent disease pathogens to resume production.

Rice-based agriculture in coastal deltas received far less attention until increasing demand recently led to concerns over the price and availability of rice throughout Asia and other parts of the tropical developing world. Rice is a staple food for millions of people in both coastal and inland areas and current research on production in coastal deltas is examining varying intensities of fresh and saltwater usage to maximize production. Other research is focusing on designing resilient rice varieties for coastal deltas using modern breeding tools and improving rice productivity through integrated nutrient management (Dobermann *et al*., 2002). The role of women in rice agriculture is also being investigated in the changing social landscape of important coastal production areas such as Bangladesh and Vietnam. Even less attention has been paid to inland fisheries, despite its important role in maintaining food security for impoverished delta communities. Fisheries have almost been forgotten in the recent rush to develop new forms of aquaculture, and the impacts of aquaculture, along with expanding urban and industrial activities, have affected water quality and aquatic habitats negatively in coastal deltas throughout the tropical developing world (Naylor *et al.*, 1998; Tal *et al.*, 2009).

Managing the increasing demand for coastal resources and the inevitable conflicts between competing user groups represents a major future challenge for tropical resource managers. Land and water management in coastal deltas historically has focused on the exclusion of salt waters that flow inland from the coast during the dry season. Management strategies have included the construction of embankments and sluice gates to ensure freshwater availability for agricultural production (typically rice) throughout the year. This approach fails to recognize the diversity of rural livelihoods and ecosystems in coastal deltaic areas, the environmental consequences of altering natural saltwater flows and the emergence of new activities such as shrimp farming that require brackish water. The development of market-driven activities such as shrimp aquaculture has, therefore, challenged our assumptions regarding land and water management objectives at the brackishwater interface and has forced us to consider new directions. Questions have emerged in recent years over the fate of coastal delta regions as a finite resource base that is facing increased levels of environmental stress and inexorable rates of population growth.

Coastal planning and management initiatives across the region are tasked with meeting this challenge and providing for human health, viable livelihood opportunities and environmental integrity. However, progress in achieving these objectives has been slow, given the diversity and complexity of issues facing managers in coastal deltas. Further complicating future planning efforts is the emergence of global climate change as a critically important issue. The most recent reports of the Intergovernmental Panel on Climate Change (IPCC, 2007) suggest that sea levels could rise significantly in the near future and evidence of this is already being seen in Vietnam. The implications of sea-level rise and the magnitude of change in many tropical deltas could have profound consequences. Many areas will be subject to increased flooding and saline intrusion into groundwater systems in the absence of mitigation measures. This could conceivably prompt inland migration of both people and agriculture operations that rely on fresh water for maximum productivity. The IPCC models also predict more variable and intense periods of rainfall and drought, placing greater stresses on water management systems to provide for the growing needs of a concentrated population in many coastal deltas (Meehl *et al.*, 2007). It remains to be seen just how dramatic the potential impact of global warming will be on coastal deltas, but it is clear that change is occurring and that resource managers and decision makers must explore and choose carefully the most appropriate form of mitigation, given the potential environmental, social and economic costs.

Land and water management

One of the most prevalent concerns voiced at the Delta 2007 Conference was the inherent difficulty of developing, implementing and maintaining appropriate land and water management policies in coastal deltas. Being heterogeneous, highly complex and dynamically changing, coastal zones are often not administered in ways that support the judicious management of natural resources. In this volume, Chuenpagdee *et al.* (Chapter 29) describe a user-friendly, computerized tool for profiling and visualizing coastal transects, which could be used in data-sparse situations commonly encountered in developing countries. They suggest that a simple and highly graphical manner of depicting and comparing coastal transects can help provide better insight and understanding of the multiplicity of uses, interactions and impacts. The differing needs of agriculture and coastal aquaculture for water supplies is widely recognized and conflict over the timing and availability of brackish water and fresh water has been noted in many areas. Alternative land use strategies such as seasonal changes in cropping patterns have the potential to enhance both crop productivity and ecological diversity, but existing management regimes continue to focus on engineering solutions that simply regulate brackishwater and freshwater flows using sluices or dams. More effective land and water management strategies are required in coastal deltas to resolve the existing conflict between agriculture and aquaculture, to improve environmental conditions and to support local populations that depend on coastal deltas for their livelihoods. Increased stakeholder involvement and innovative governance structures are also needed to address the intrinsic complexities of land and water management at the coastal land–water interface.

As outlined above, the conflicting demands of rice-based agriculture and shrimp aquaculture for water are often at the heart of water management concerns in coastal deltas. Short-term rental of traditional rice land in south-western Bangladesh by brackishwater shrimp producers resulted in soil degradation, loss of biodiversity and diminished agricultural productivity after several shrimp production cycles were completed. Productivity of rice lands adjacent to intensive shrimp farms has also diminished as a result of saline seepage. Many rice farmers have been impacted negatively by these land and water management conflicts and small-scale fishers have been excluded from their traditional fishing grounds. In response, the Bangladeshi government has promoted a community-based, integrated planning system that encourages local participation. In his presentation at the Delta 2007 Conference, Ghani highlighted initial efforts at implementing the co-management concept based on the national Guidelines for Participatory Water Management (GPWM) in the Rupsha section of polder 36/1, one of several polders constructed by the Bangladesh Water Development Board (BWDB) and the Local Government and Engineering Department (LGED) to prevent salinity intrusion. Broad-based consultations resulted in a consensus on co-management arrangements where local beneficiaries took leadership of polder management and planning agricultural activities, with technical support from relevant government agencies and rural development NGOs. Priorities identified included rehabilitation of degraded flood control, drainage and irrigation (FCDI) infrastructure and water bodies to enable year-round use of the land and water resources for diversified food production activities. However, it was noted by the local communities that implementation of these plans was contingent on removal of the negative impacts of upstream brackishwater shrimp culture on their water resources. This emphasizes the need for broader area planning and management of land use and water supply to enable improvements to be made to livelihood activities at the local scale.

More evidence of benefits from local participation in land and water management is presented by Islam *et al*. (Chapter 25), in one of several subprojects initiated by the LGED at two villages in Khulna District. This case study suggests that agriculture and fisheries production can be stabilized through participatory water management programmes implemented by a community-constituted water management association with support from NGO and local government institutions. Local stakeholders have invested in water management efforts by owning the water management infrastructure, accepting responsibility for future maintenance and ensuring adherence to water-use regulations, since water is considered common property in Bangladesh. More significantly, the empowerment afforded through the subproject has helped small landowners to re-establish their rights to their lands formerly leased on unfair terms by external shrimp cultivators and has allowed them the opportunity to intensify use and improve productivity through the adoption of modern rice varieties and diversifying aquaculture production, both in conjunction and in rotation with rice.

These attempts to improve food and water productivity in the tidally-inundated coastal zone of south-western Bangladesh potentially can benefit from scientific investigations on rice and rice integrated with aquaculture farming practices. Mondal *et al*. (Chapter 20) outlines farmer–field experiments conducted in polder 30 in the Batiaghata Subdistrict which show that proper timing and adjustment of the rice cropping calendar in the *boro* (dry) season can maximize utilization of river water before it becomes too saline. This reduces dependence on reservoir water, and the limited supplies of reservoir-stored fresh water can be used to irrigate rather larger areas of *boro* rice and thus benefit more farmers. From on-farm experiments carried out in polder 16/1, Alam *et al.* (Chapter 7) demonstrate the feasibility of cultivating certain high-yielding rice varieties along with short-duration fish and/or prawn during the low-salinity period (August–December), followed by brackishwater shrimp during the high-salinity period (February–August) as a strategy to increase total farm productivity and net income. This farming system depends on a dual fresh- and brackishwater regime to increase water productivity, but requires good water management and physical infrastructure design and operation to accommodate the differing water depth needs of shrimp and rice.

Conflicts resulting from sectoral competition extend to India as well. In a case study presented by Narayanan (Chapter 22), environmental degradation, social unrest and issues of governance have emerged in two of India's largest wetland lagoons. In the Vembanad Lake region, sectoral interests compete for control of a sluice that regulates freshwater and brackishwater flows. Opening the sluice flushes the lagoon and replenishes fish stocks to the benefit of fishers, whereas closing the sluice prevents saline flows into agricultural fields, which benefits farmers. State agencies with conflicting political interests have attempted to influence the operation of the sluice and this prevents the development of a broader management scheme that treats the region as an integrated ecosystem. In response to lessons learned from the events at Vembanad, a local development authority was created at Chilika Lagoon to balance competing resource activities and support ecological integrity. The most prominent achievement of this local development authority involved the opening of a new lagoon mouth, but the subsequent emergence of positive and negative impacts on lagoon ecology highlighted the complexity of managing coastal land and water resources, even with significant stakeholder involvement.

The Vietnamese province of Bac Lieu, located in the Mekong Delta, presents a further case study of land and water management in coastal deltas. The Vietnamese government constructed a series of embankments and sluices in the mid-1990s to limit tidal intrusion and enhance rice production in the Mekong Delta. These construction projects followed a westward pattern and salinity levels in these areas dropped accordingly. By the end of the decade, however, the growth of shrimp farming led local aquaculturalists to demand access to brackish water excluded by the network of control structures. Conflict between rice farmers who needed freshwater supplies and shrimp farmers who required brackishwater flows eventually led to the destruction of a major control structure. The Vietnamese government responded to this situation with efforts to study salinity control measures and promote land use diversification, and the paper by Can *et al.* (Chapter 23) assesses the success of these land and water management strategies at the village level. The Thai government has also recently taken steps to move from a command and control strategy to incentive-based and self-management approaches, as explained by Pongthanapanich (Chapter 21) in her analysis of environmental policy strategies for coastal land conservation in Thailand. In this case, the author applies a multi-objective optimization model to compare environmental management policies and economic-based incentives in a coastal scenario. Increasing interest in the use of market-based incentives to achieve environmental management objectives is noted but, to date, none of these alternative approaches has been implemented in Thailand's coastal areas.

Aquaculture and fisheries

A large number of papers presented at the Delta 2007 Conference discussed the evolution and management of shrimp aquaculture systems. Although the aquaculture industry has been a boon to certain economic interests, it has also produced a suite of ecological concerns including: loss of mangroves, land salinization, water pollution and ecosystem impacts. The authors of these papers focused on responses to these issues and presented alternative management strategies that held the potential to reduce both environmental impacts and sectoral conflicts. Refining seasonal rice–aquaculture systems, improving aquaculture technologies and tightening regulation and policy controls were identified as steps that could improve economic profitability and food security, while also limiting negative and costly environmental impacts. Shrimp aquaculture has produced massive changes in many of Asia's coastal deltas and potential management responses to these changes are outlined in the case studies discussed below.

The shrimp farming industry in Thailand originally focused on producing the native black tiger shrimp (*Penaeus monodon*), but viral disease problems associated with raising this species in captivity proved difficult to overcome. By 2000, disease and associated organic pollution issues threatened the long-term sustainability of many grow-out areas, but instead of reorganizing farm practices to deal with these sustainability issues directly, the Thai aquaculture industry focused on technological adaptations such as the introduction of Pacific white shrimp (*Litopenaeus vannamei*). This exotic species was less susceptible to native disease pathogens and quickly replaced black tiger shrimp as the principal species under cultivation throughout most of Thailand. Panutrakul *et al*. (Chapter 6) outline the potential ecological implications of exotic species introductions by assessing the ability of Pacific white shrimp to survive and compete with native shrimp species in Thailand's Bangpakong River. Results indicate that the Pacific white shrimp is present in the wild as a result of escapes or intentional releases and is able to tolerate a wider range of salinity levels than the native black tiger shrimp. The Pacific white shrimp is also able to outcompete a range of native shrimp species for food as a result of its aggressive nature. The research supports the need for risk analysis of planned introductions in the aquaculture industry. Senanan *et al*. (Chapter 5) also discuss difficulties associated with risk assessment and risk management, as these relate to the introduction of the Pacific white shrimp in Thailand. A variety of geographic and social science investigation methods have been used to estimate risks such as the spread of alien pathogens, the ability of the species to establish new populations in the wild and the ability of the exotic species to reproduce. This study raises numerous critical questions on the use of exotic species for commercial aquaculture production and describes a framework for assessing risks to native species and protecting habitats in other parts of Asia that support shrimp farming.

Saint-Paul and Barletta (Chapter 33) stress the urgency of scientifically establishing the ecological link between mangrove ecosystem services and the fisheries resources off the Brazilian coast to provide a sound basis for fisheries management. They argue for the use of fish otoliths as biochemical tracers to provide unequivocal evidence of habitat dependence and connectivity between juvenile and adult fish populations for formulating strategies to sustain the fish stocks that are so important to the fishing industry in the vicinity of the Amazon Delta.

In Vietnam, the concept of ecological and social trade-offs in water management inherent to a Bayesian modelling approach is presented by Baran *et al*. (Chapter 10). In the latter half of the 1990s, the Vietnamese government constructed a series of sluice gates in Bac Lieu Province to limit saline tidal flows into lands devoted to rice production. Market conditions shifted over this period, which encouraged the production of shrimp and created a conflict between agricultural and aquacultural interests requiring either freshwater or saline inputs. To investigate this issue, the authors used stakeholder consultations at the provincial and community levels to construct a Bayesian model that compared different sluice management schemes and their impacts on household income, food production and environmental considerations. Four sluice operation examples were modelled and compared to current baseline operations. The analysis indicates that trade-offs between food production, household income and environmental considerations can be identified in each scenario. Closing the sluice gates decreases open access freshwater fish catches, increases water pollution and creates the least environmental damage as a result of low production intensities. However, this 'closed gate' scenario does not improve food security as rice production increases only modestly as a result of the higher acidity levels created by the limited water exchanges. Keeping the sluice gates open allows salt water into the area, which increases household income by favouring shrimp production, but at the cost of reduced food security, as rice cultivation is reduced. Two intermediate scenarios present more balanced trade-offs between food production, household income and environmental considerations, and a combined shrimp–rice production system is recommended by the authors as the most suitable option. Complementing this chapter is a study by Baran *et al*. (Chapter 2), which analyses the aquatic resources of Bac Lieu that are subject to saltwater flows. This study is one of the few to examine specifically inland fisheries in a coastal delta context. In this 2-year study, the researchers established 14 sampling stations across four different zones to capture the variability of fish and shrimp catches, in addition to eight environmental parameters.

Resource allocation in the coastal zone is always a formidable task. Andalecio and Cruz (Chapter 3) analyse the situation in Dagupan, Philippines, by assessing resource-use conflicts and examining strategies for better integrating aquaculture into existing coastal management schemes. Regulations controlling fisheries are currently integrated into Filipino coastal management policies, but this is not the case with respect to aquaculture activities such as milkfish farming, which have grown dramatically in recent years. Uncontrolled aquaculture development can affect regional water quality negatively, obstruct water circulation and produce excessive siltation in deltaic areas downstream. The development of milkfish aquaculture has created economic benefits, but this rapid growth has been at the expense of adequate management practices. The authors outline a management framework that includes stakeholder interviews, aerial photograph interpretation and field assignments, and propose a priority use zoning policy to accommodate a multiple use strategy in the Dagupan River Basin.

In Bangladesh, shrimp aquaculture has grown threefold since 2000 and now represents the third most important export crop in that country. As in neighbouring Asian countries, this growth has also been accompanied by reduced indigenous fish populations, losses of mangrove fauna and flora and the release of untreated wastewater into coastal environments. Continued future expansion of shrimp farming in Bangladesh highlights the need for a precautionary management approach to deal with organic waste production. Bioremediation that could be achieved through the implementation of polyculture farming systems to convert organic waste into usable resources rather than focusing on treatment and disposal technologies were proposed by Mohammad Abdul Latif Siddique at the Delta 2007 Conference. Polyculture utilizes multiple species with differing biological needs and nutrient uptake levels to act as biofilters, enhance detritus removal and combine probiotics with antibiotic applications. However, suitability of this practice is still to be considered.

Joffre *et al*. (Chapter 4) also present an interesting comparison of the evolution of shrimp aquaculture in the Ganges and Mekong deltas, analysing the factors that have driven the adoption of farming methods and how farmers have managed constraints imposed by differing environmental conditions. Shrimp farming emerged in Bangladesh in the early 1980s and in the Mekong Delta in the latter half of the same decade. Development of the industry in each country has, however, taken notably different paths. Hatcheries are located far from other production infrastructures in Bangladesh, while in contrast, the shrimp production chain is spatially compact in the Mekong Delta, which creates significantly lower costs for Vietnamese farmers. Access to water also affects the efficiency of shrimp farmers in the two study sites. A robust canal network developed in the Mekong Delta during the 19th century provided Vietnamese shrimp farmers with private access to water. No similar supply system exists in Bangladesh and water must be obtained from communal ponds, which increases the risks of viral disease outbreaks. Vietnamese farmers also own their land and are legally able to modify pond infrastructure as needed, whereas Bangladeshi farmers typically lease land and have less freedom to modify their operations. Lastly, farmers in Vietnam have greater access to information and newer technologies via a more extensive information network than farmers in Bangladesh.

Finally, Bush *et al*. (Chapter 9) present a broad analysis of shrimp farming in Asia by investigating the relative merits of integrated and closed production systems. The former integrates shrimp farms into the intertidal landscape to protect coastal ecological functions and limit the spread of disease, whereas the latter approach moves production entirely beyond the intertidal zone into areas isolated from the surrounding environment. Integrated systems require a significant initial investment, however, and do not explicitly prevent the proliferation of shrimp farms in intertidal areas such as mangrove forests. The intention of this study is not to determine the optimal form of aquaculture, but instead to analyse how decisions are made and how these decisions relate to resiliency and the linkages between social and ecological systems. Resiliency is defined as being dynamic and adaptive. This allows the authors to analyse the impacts of external disturbances on both the evolution of the shrimp aquaculture industry and on decision-making processes. The disparate influences of market forces and state legislative powers on shrimp production are also analysed in the context of market-based tools such as certification schemes. Market access for producers using both integrated and closed system forms of production is considered, which leads to a discussion of system tolerance to negative impacts on biodiversity and production, the appropriate scale of integration into the coastal ecosystem and trade-offs between ecological integrity and social welfare.

Rice-based agriculture

Farmers in coastal areas face considerable uncertainties because of ecosystem complexities and limited access to new technologies. Development and deployment of salt-tolerant varieties is an effective and affordable entry point for improving the rice productivity in these areas and can contribute significantly to system productivity when combined with appropriate resource management practices. Papers presented on this topic at the Delta 2007 Conference summarized some of the research conducted under the CGIAR Challenge Program on Water and Food Project (Project No 7). These studies examined technologies and strategies for improving agricultural productivity and food security in salt-affected coastal areas. The papers provided benchmark information on the social, economic and biophysical aspects of selected sites; evaluated rice varietal development and participatory testing strategies; studied integrated crop and resource management options; and investigated prospects for crop intensification and diversification to enhance and sustain system productivity, farmers' incomes and livelihoods.

Paris *et al*. (Chapter 24) present a case study from coastal Orissa, India, where the socio-economic characteristics of the farming households, indigenous knowledge and farming practices, gender roles, share of rice and other sources of income in livelihood systems and profitability of current rice cultivation practices and inputs have been assessed through baseline surveys. Through focus group discussions, farmers identified their problems, prioritized their needs and matched them with opportunities to improve their livelihoods. Follow-up surveys demonstrated considerable progress, with the improved varieties attaining at least double the yields of traditional ones. Few new crops were accepted as rotation crops after rice and farmers were able to maintain sufficient food for the whole year, instead of for 4–9 months before. The chapter also outlines the lessons learned and needs and constraints, and identifies new livelihood opportunities. A key message from these studies is that adoption of new technologies by farmers in coastal areas is poor, even though some of these technologies have been available for a significant time.

Ismail *et al*. (Chapter 12) highlight the major abiotic factors facing rice production in coastal areas as increased salinity and other soil problems, short-term complete submergence, longer-term partial floods and natural disasters. They also discuss the opportunities available through germplasm enhancement to develop varieties that combine tolerance of these conditions and provide protection for farmers against persistent abiotic stresses and their occasional surges through natural hazards. Opportunities include the development of more resilient varieties combining tolerance to most stresses through modern breeding tools, as well as the development and use of management strategies more suited to these varieties.

Developing rice varieties with wider adaptation and broader tolerance of prevailing stresses is more viable for these areas, where abiotic stresses are particularly variable and complex, and growing conditions are too risky to persuade farmers to invest in inputs. Mostly, superior performance of genotypes under experimental conditions does not guarantee their acceptance by farmers and occasionally farmers reject genotypes that yield well if they do not satisfy their quality preferences. Singh *et al*. (Chapter 13) discuss participatory varietal selection (PVS) approaches, in which farmers participate in varietal screening and adaptation testing, which are followed to accelerate the adoption of salt-tolerant varieties. Through this approach, numerous varieties are released or nominated for release after demonstrating a yield advantage of at least 1.5 t/ha over that of local varieties.

The occurrence of high salinity during the dry season and excessive wetness in the wet season prevents the growing of other upland crops in most tropical deltas, limiting opportunities to rice only. This is despite the excellent potential for crop and income diversification with the current availability of short-maturing, salt-tolerant rice varieties. Two case studies are presented from Mahanadi Delta, coastal Orissa, India. In the first case, Mahata *et al*. (Chapter 18) demonstrated the benefits of using integrated nutrient management combining chemical and biofertilizers with improved salt-tolerant rice varieties. Green manures are more effective in areas where waterlogging occurs for a longer duration and where chemical fertilizers cannot be used. Organic fertilizers also have the benefits of being cheap and more effective in mitigating soil salinity beside their nutritional value. Despite certain limitations, *Sesbania* as green manure and *Azolla* as a biofertilizer offer considerable opportunities to improve soil quality and enhance rice productivity in these saline soils. In the second study, Singh *et al*. (Chapter 19) discuss the prospects for crop intensification by introducing non-rice crops during the dry season, and few crops have been selected by farmers that have shown substantial improvement in system productivity and farmers' incomes. Apparently, opportunities exist for the introduction of new non-rice crops through water harvesting via the construction of ponds and sluice gates and the use of rainwater stored in sand dunes. Sunflower, *Basella*, watermelon, chilli, pumpkin, groundnut, tomato, bitter gourd and okra have all been evaluated under high and low-to-medium salinity levels. Based on both overall performance and farmers' crop preferences, sunflower, chilli, watermelon and okra have been selected for out-scaling.

Bardhan Roy (Chapter 15) discusses the impact of *boro* rice on improving household food security in coastal West Bengal (WB), India. The availability of short-maturing, salt-tolerant varieties and early planting allows the spread of dry season (*boro*) rice and this contributes significantly to food security, increasing household incomes by about 48%. Still, about 37% loss in *boro* rice production is attributed to salt stress. This system is being adopted mainly by small and marginal farmers. Multivariate analysis of the two main farming systems, rice–*boro* rice and rice–aquaculture in coastal West Bengal indicates that biophysical and technical factors are more important for the adoption of either system than socio-economic factors. It is the less educated farmers with smaller landholdings who are more inclined to adopt intensive systems, and the availability of finance is not a major constraint to the adoption of *boro* rice. Experiments were conducted in agricultural fields using different sowing/planting times of high-yielding rice varieties to maximize the use of river water during high tides and dependency on reservoir water in the *boro* season; and to develop technique(s) for the conjunctive use of rainfall and groundwater. From these trials, it is evident that the cropping intensity of the traditional single cropped area could be increased by advancing rice cultivation in the *boro* season and by conjunctive use of available rainfall and groundwater resources in the pre-monsoon (*aus*) season.

The delta of the Ganges–Brahmaputra river system in Bangladesh is a flat, tide-dominated plain. Soils in these areas constitute some of the most productive lands, yet their characterization has received little attention, despite its importance in determining their potential use for farming and current constraints. Saleque *et al*. (Chapter 11) present an example of soil characterization in selected sites and identify the major constraints as high salinity and Zn deficiency. As in other deltas, the study highlights a great opportunity to increase system productivity in these areas if high-yielding, short-maturing and input-responsive varieties are introduced, together with validated best practices for their management. Farmers in these regions still use local rice varieties with little or no fertilizer use. With the availability of these new varieties, chemical fertilizer use becomes essential and new soil-test-based and site-specific recommendations need to be developed and adjusted.

Participatory strategies have given farmers the opportunity to be part of the decision-making process and to develop a sense of ownership of new interventions. This is particularly important in coastal deltas where challenges are numerous and site specific. The importance of including farmers in targeted breeding and participatory variety selection (PVS) is demonstrated in the presentation made by Salam *et al.* (Chapter 14), where considerable progress has been made in developing suitable high-yielding varieties for south Bangladesh. The PVS approach was used to select suitable varieties for the three major seasons, T-*aman* (wet), *boro* (dry/winter) and *aus* (dry direct seeded) seasons. Activities included the collection and preservation of local material for breeding and other future uses and PVS testing of material developed at IRRI and locally. Monitoring of salinity in nearby rivers also demonstrated the potential for use of surface water for dry-season rice. Nutrient management trials show that the soil is relatively rich in K and the fertilizer recommendations currently being used are still valid for these saline soils. Preliminary studies established tremendous opportunities for increasing annual productivity through conservation and the proper use of available surface freshwater resources.

Germplasm improvement activities in Bangladesh include analysing tolerance to abiotic stresses caused by salinity, submergence, stagnant flooding, drought and problem soils; understanding causal mechanisms; and transfer of tolerance into popular varieties and elite breeding lines. A marker-assisted backcrossing (MABC) system has been used to speed the pyramiding of major quantitative trait loci (QTLs) underlying these stresses. Selection of the proper rice strain used in appropriate locations was achieved through a systematic exchange and farmer-centred evaluation of rice germplasm for salt-affected areas, including PVS trials under the platform of the International Network for Genetic Evaluation of Rice (INGER).

The Mekong Delta has not benefited sufficiently from the recent growth in agriculture productivity in Vietnam as a result of the low productivity of most areas. This is caused by several factors, including rapid population growth, industrial expansion at the expense of agricultural lands, land degradation and persisting abiotic stresses. Salt-affected soils in the delta are by far the most degraded, a consequence of an array of coexisting abiotic stresses including high salt, acid sulfate soils, toxic amounts of aluminium and iron and deficiency in nutrients such as P and K. Three main approaches are being followed to increase and sustain agriculture productivity in the Mekong Delta: (i) increase the area under cultivation by exploring less productive marginal lands; (ii) increasing yields through development of high-yielding varieties tolerant of prevailing stresses, together with their proper management practices; and (iii) increasing the value of agricultural products through the introduction of better-adapted high-value crops. Lang *et al.* (Chapter 16) summarize the recent efforts being undertaken at the field level to enhance the productivity of these lands, including the development and participatory evaluation of suitable varieties, more intensive and profitable cropping patterns and better nutrient management options. Germplasm enhancement efforts involve the development of high-yielding, short-maturing varieties for less saline areas with ample fresh water, non-rice high-value crops such as soybean and groundnut, for areas where freshwater resources are relatively scarce during the dry season, and rice–aquaculture systems when salinity is high during the dry season. To meet farmers' needs and market demands, considerable progress has been made in deploying high-yielding, salt-tolerant varieties via novel breeding methods, together with management practices relevant to these new varieties and coupled with the introduction of effective cropping patterns.

Key Findings and the Impending Challenge of Global Climate Change

Improved policies for coastal deltas

A clear message of the Delta 2007 Conference was the need for policy makers to acknowledge the diversity of the socio-economic and environmental processes that exist at the local, regional and national scales. This diversity can only be incorporated into future policy discussions through a bottom-up paradigm, as opposed to a command and control strategy. Centralized and distant governance often fails to account for diverse social needs and environmental conditions at the regional and local level. Policies arising from such frameworks can, therefore, be ineffective or even harmful to the well-being of local communities and environments. Engaging local communities and stakeholders in the policy development process is clearly the most appropriate strategy to improve resource allocation, protect the socioeconomic welfare of delta communities and enhance the integrity of environmental systems that increasingly are being eroded. Multidisciplinary and scaled research approaches that consider the interests of local stakeholders are required to address the disparate interests of coastal communities and minimize social conflict. Policies that strengthen education networks between both small-scale and large-scale farmers and between farmers and external sources are also needed to improve the spread and adoption of new technologies. Education policies such as these could improve production efficiencies and minimize the technological and economic disadvantages faced by small-scale farmers and geographically isolated communities. Lastly, policies that promote equitable access to resources could allow disadvantaged or marginal communities to share both the responsibility and economic benefits associated with improved land and water management in coastal deltas.

Encouraging community-based land and water management

A second key message of the Delta 2007 Conference is that participatory land and water resource management schemes are needed to support the long-term stability of delta communities and environments. Examples include the creation of multi-scale water management associations, co-management structures and local governance approaches where government personnel act as advisors or partners. Water management associations are designed to regulate water usage among different stakeholders, provide a forum for conflict resolution and create a role for local empowerment. Amendments to existing laws are often required to facilitate these processes, but the conference presented clear evidence that farmers were willing to adopt participatory approaches in both crop and water management. Another critical issue involves the need to 'scale up' the results of community-level research to improve results throughout the entire planning and management system. Guidelines for community–government partnerships and the election of local management committees should be developed to avoid social unrest throughout the project life cycle, and the valuable role that non-governmental organizations can play in sustaining innovative forms of local management should also be recognized.

The need for resilient agriculture and aquaculture

Coastal deltas are a challenging environment with significant variability (both spatial and temporal) that is relatively neglected with regard to opportunities for research and development. The location and extent of problem areas have not been well defined or quantified. Significant potential does exist, however, to fill these knowledge gaps and increase the productivity and resilience of coastal resources. In particular, further research on the baseline biophysical parameters that characterize tropical deltas is needed. More resilient farming systems will also depend on developing optimization models that incorporate a combination of rice, aquaculture and finished products. These seasonally alternating or simultaneously diversified schemes hold the potential to generate higher income with fewer risks than monoculture systems. Additional research is also needed to identify rice varieties exhibiting greater resistance to insects, salinity and temperature extremes. Underutilized salt-tolerant crops such as okra and sunflower may become more attractive as environmental conditions change, and biofertilization holds promise for enhancing the yield of salt-tolerant rice varieties. The implementation of aquaculture zoning systems to regulate resource use is also highlighted to address the needs of local communities better and prevent environmental degradation. Planning areas should be delineated on the basis of environmental, social, economic and institutional considerations before reclassification into priority use zones. Innovative approaches such as polyculture should be adopted to minimize wastewater and maximize production. Alternating rice–shrimp systems hold significant potential to enhance environmental resilience in seasonally saline areas, and these systems also display more stable economic returns in comparison to either intensive shrimp or intensive rice monocultures. Specific attention should be given to the key concept of resilience and how this contributes to our understanding of environmental management and conservation in tropical coastal deltas.

The impending challenge of climate change and sea-level rise

It is becoming increasingly evident that the impacts of global warming and sea-level rise could affect tropical coastal deltas dramatically. Increasingly powerful storms could directly threaten lives or indirectly harm impoverished communities by damaging the agricultural infrastructure. Extended or more severe periods of drought could appear and demand more stringent efforts at rationing finite freshwater supplies. Both of these events represent serious challenges to regional food security in areas that are primarily dependent on rice production. Stronger storm systems could also exacerbate coastal erosion further and lead to the loss of agricultural lands and mangroves that represent a critical fisheries habitat. Rising sea levels associated with global warming will also complicate the already difficult challenge of managing water resources in coastal deltas as salt water intrudes further inland. This could potentially force rice farmers to construct additional defensive barriers, consider alternative production schemes or relocate operations unless further advances in the development of salt-tolerant crop varieties emerge. Given the uncertain extent and severity of potential climate change impacts, the development of management responses which can cope with a wide range of future scenarios is imperative. Finally, lost in the attention given to the physical impacts of climate change is the likelihood that a greater part of many social and economic costs will be borne unequally by already marginalized social groups such as women and the poor. These and other vulnerable groups that depend on specific coastal resources may find themselves adrift should their existing livelihood strategies become unfeasible or impractical. Developing strategies to manage these risks will become increasingly important as coastal populations continue to rise and could play an important role in averting further marginalization and social upheaval.

References

Chuenpagdee, R. and Pauly, D. (2004) Improving the state of coastal areas in the Asia-Pacific region. *Coastal Management* 32, 3–15.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C. and Adviento, M.A.A. (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* 74, 37–66.

Flaherty, M., Szuster, B. and Miller, P. (2000) Low salinity inland shrimp farming in Thailand. *Ambio* 29(3), 174–179.

IPCC (2007) *Climate Change 2007: Synthesis Report. Summary for Policymakers*. Intergovernmental Panel on Climate Change (IPCC).

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J. and Zhao, Z.C. (2007) Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds) *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York.

Mimura, N. (2006) State of the environment in the Asia and Pacific coastal zones and effects of global change. In: Harvey, N. (ed.) *Global Change and Integrated Coastal Management: The Asia-Pacific Region*. Springer, Dordrecht, the Netherlands, pp. 17–38.

Naylor, R.L., Goldburg, R.J., Mooney, H., Beveridge, M., Clay, J., Folke, C., Kautsky, N., Lubchenco, J., Primavera, J. and Williams, M. (1998) Nature's subsidies to shrimp and salmon farming. *Science* 282, 883–884.

Primavera, J.H. (1997) Socio-economic impacts of shrimp culture. *Aquaculture Research* 28, 815–827.

Tal, Y., Schreier, H., Sowers, K., Stubblefield, J., Place, A. and Zohar, Y. (2009) Environmentally sustainable land-based marine aquaculture. *Aquaculture* 286, 28–35.

Talaue-McManus, L. (2006) Pressures on rural coasts in the Asia-Pacific region. In: Harvey, N. (ed.) *Global Change and Integrated Coastal Management: The Asia-Pacific Region*. Springer, Dordrecht, the Netherlands, pp. 197–229.

2 Aquatic Resources and Environmental Variability in Bac Lieu Province (Southern Vietnam)

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Abstract

The dynamics of aquatic resources in the canals of Bac Lieu Province, in southern Vietnam, are detailed and synthesized in this study. Nekton and eight environmental parameters were monitored in this province between 2004 and 2006, at 14 sites sampled three times a year. The study area, located along the coastal zone, is characterized by a variable environment subject to saline, freshwater and acidic pulses. The spatio-temporal dynamics of aquatic resources and their relationships with environmental parameters are detailed. The dominance of either freshwater or estuarine fauna, the dynamics of assemblages and the catches of fishers appear to be largely influenced by the management of sluice gates built along the coastal zone.

Introduction

In this study, we summarize the results of aquatic resources monitoring in Bac Lieu Province, southern Vietnam (Fig. 2.1) during the period from 2004 to 2006. The study area, located along the coastal zone, is characterized by a dense canal network and a variable environment subject to saline, freshwater and acidic pulses. The environmental characteristics of this area have been described in Hoanh (1996) and its socio-economic and agricultural conditions in Hoanh *et al*. (2006a). An important feature of the study area is a series of sluice gates built along the coastline between 1994 and 2000 to control the intrusion of seawater during the dry season, thus protecting rice agriculture. This water control system dramatically influences the inland coastal hydrology and water quality in the province (Kam *et al*., 2001; Hoanh *et al*., 2006b). It therefore has implications for the environmental and biodiversity features of the canals (Hoanh *et al*., 2003; Gowing *et al*., 2006a), and ultimately for farming practices and land use in the province (Hoanh *et al*., 2001; Tuong *et al*., 2003; Kam *et al*., 2006).

In this context, the goals of this study were: (i) to characterize the environmental and aquatic diversity and variability of the study area subject to saltwater management; and (ii) to develop a comprehensive model of aquatic resources in the province (Baran *et al*., 2006). The latter undertaking aimed to improve the operation of the sluice gates by adding ecological considerations to the water management objectives, which were formerly focused on agronomic criteria only.

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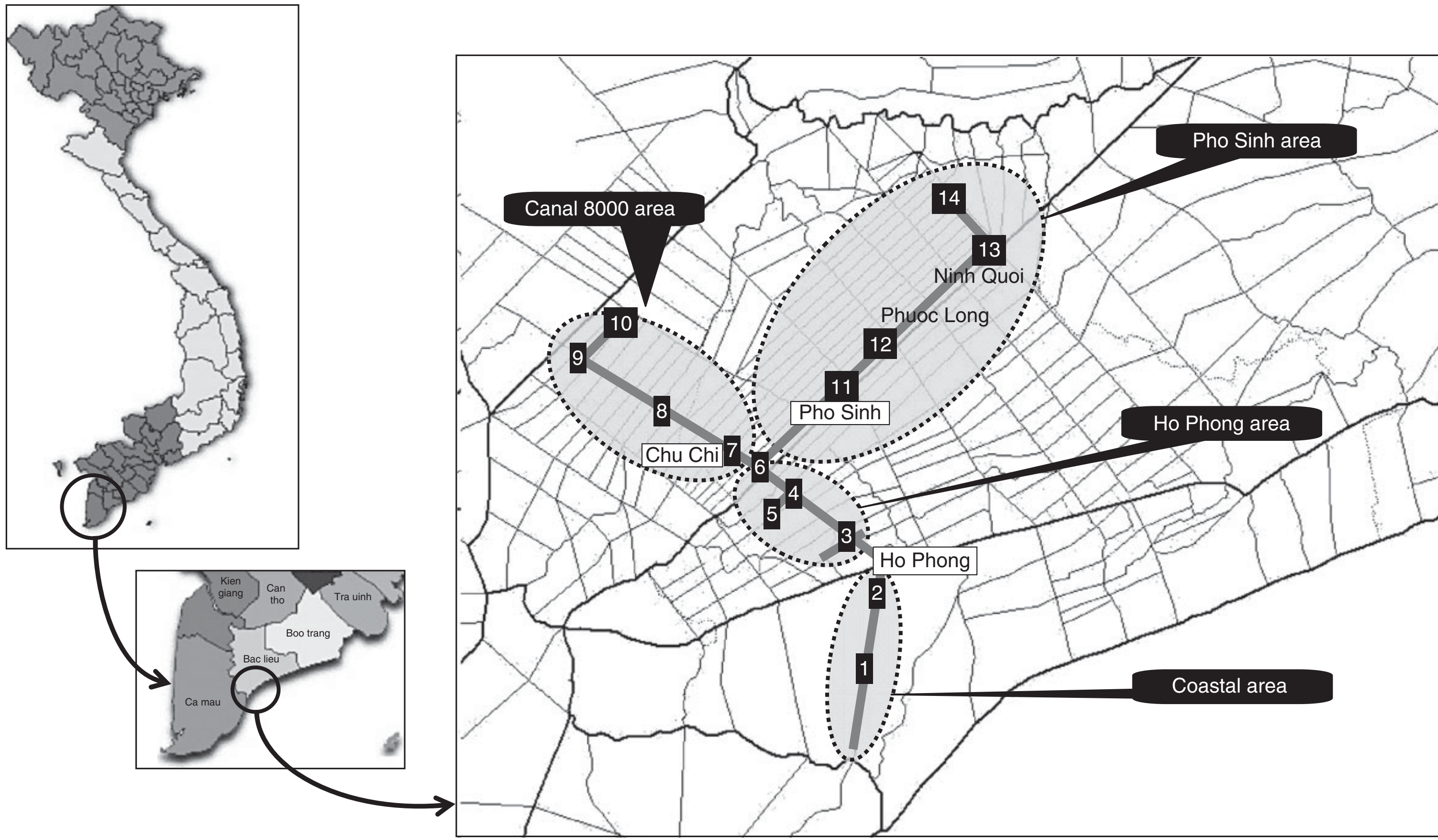

Fig. 2.1. Map showing location of the study area.

The fish fauna of Bac Lieu Province has been described in Yen and Trong (1988) and Khoa and Huong (1993) and the environmental variability has been subject to extensive studies (e.g. Hoanh, 1996; Tran *et al*., 2005), but the seasonal variability of the fish fauna has only been addressed superficially (Dung *et al*., 2002) and, to our knowledge, no study has covered the relationships between faunal and environmental parameters.

The spatio-temporal dynamics of water quality and of aquatic resources in the inland coastal area of Bac Lieu presented here are a synthesis of the seasonal analyses detailed in several project reports (Baran and Chheng, 2004; Chheng, 2004a, b; Chheng and Toan, 2005a, b; Toan and Chheng, 2005). The relationships between faunal and environmental patterns are detailed in this chapter, and the potential influence of sluice gates on the abundance and diversity of aquatic resources is highlighted.

Material and Methods

Sampling protocol

Sampling of aquatic resources took place in the primary and secondary canals inside and outside the area protected by sluice gates in four zones located around Ho Phong town in Bac Lieu Province: the coastal zone area outside of Ho Phong sluice gate; Ho Phong (inside Ho Phong sluice gate); around Canal 8000; and around Pho Sinh (Fig. 2.1). In total, 14 sites in the study area were sampled to capture the spatial variability of environmental parameters in each season.

Sampling was undertaken from June 2004 to March 2006. It covered three distinct seasons in each of the two year-long periods: (i) the dry/saline season, with seawater intrusion inland peaking in March; (ii) the acidic season (acidity released by acid sulfate soils following the first monsoon rains, with a peak in June); and (iii) the rainy/freshwater season, with a flood peak in October corresponding to a pulse of fresh water from the Mekong system during the monsoon. In each season, sampling at all sites took place within a period of 5 days. Since the first sampling was carried out in June 2004, the first year of sampling comprised June 2004, October 2004 and March 2005, and the second year covered June 2005, October 2005 and March 2006.

Sampling information was supplemented by interviews with local fishers. Questions in these interviews pertained to details of fishing activities, variability in water quality, variability in aquatic resources, the influence of sluice gates (before/after construction, open/closed periods) and relationships between water quality and aquatic resources.

Description of the environment

Eight variables describing water quality were measured: water temperature (°C, thermometer); pH (probe); salinity (g/l, field probe); total dissolved solids (TDS, mg/l, weighing); dissolved oxygen concentration (DO, mg/l, Winkler method); hydrogen sulfide concentration (H_2S, mg/l, standard iodine method); ammonium concentration (NH_4^+, mg/l, indo-phenol blue method); and phosphate concentration (PO_4^{3-}, mg/l, molybdate-ascorbic acid method).

Description of aquatic resources

Aquatic resources were sampled using two complementary methods: trawling and gillnet fishing.

Trawling is the dominant fishing method in the study area and has been recommended as the best sampling approach by most fishers during interviews (Baran and Chheng, 2004). Sampling was done with a local traditional bottom trawl on skates (1 × 4 m mouth and 25 mm mesh size), dragged for approximately 120 min along the canal. GPS was used to determine the geographic position of the boat, as well as ground speed and trawling distance. These trawl parameters were used to estimate the volume of sampled water required for calculating catch per unit effort (CPUE).

Gillnet fishing is commonly applied in estuarine zones (e.g. Fagade and Olaniyan, 1973; Dorr *et al*., 1985) and is standard in ichthyological studies (Lévêque *et al.*, 1988). Sampling was undertaken three times in each season in the Ho Phong zone and two times in the other sampling zones, using two sets of nets made of three monofilament panels of different mesh sizes (10 mm, 20 mm and 40 mm). Each of these nets was 20 m long and 1 m high. At each site, these two sets were used simultaneously across canals, between 4.00 a.m. and 10.00 a.m.

Fish were preserved in formalin and then numbered, identified at the species level and measured and weighed individually. All data gathered were analysed at the laboratory of the College of Aquaculture and Fisheries of Can Tho University, Vietnam.

Description of statistical methods used

The analysis of environmental patterns (eight continuous variables) and corresponding faunal patterns (species richness and CPUE) was done using principal components analysis (PCA). This multivariate method has proven very efficient for extracting and synthesizing information from chemical or environmental data (e.g. Wold *et al.*, 1987) and to analyse animal/habitat relationships (e.g. Rottenberry and Wiens, 1981). The result of the analysis is a 'factorial map' that consists of the projection of the multi-dimensional space of variables on to an optimal plane, where correlations can be interpreted visually (Carrel *et al.*, 1986). The nature of data analysed here (variables of different nature, multiple units) prompted us to use the centred and normalized option of the PCA.

The analysis focusing on species–environment dynamics was based on eight environmental variables and on trawling CPUE data; it was done with a correspondence analysis that emphasized species distribution (Thioulouse and Chessel, 1992). This analytical method enables a separation of phenomena in time and space and an identification of environmental gradients (Esteve, 1978; Prodon and Lebreton, 1981).

The software ADE-4 (Analyse de Données de l'Environnement; Thioulouse *et al.*, 1997), freely available at http://pbil.univ-lyon1.fr, was used for this analysis.

Beyond standard factorial maps, the results have been presented in the form of choremes, i.e. conceptual maps displaying information or processes in a spatial context (Brunet, 1980, 1993). Choremes have been recommended to facilitate the communication of notions in a complex spatio-temporal context (Klippel, 2003; Klippel *et al.*, 2005) and have been employed in this chapter to summarize processes and patterns influencing water quality and nekton parameters among sites, seasons and years.

Results

Environment

The study area is characterized by high variability between years, between seasons and between sampling zones (Table 2.1).

Dry season (March). In March 2005 and 2006, water temperatures were relatively uniform over the study area (28.4–31.5 °C). The time of day when samples were taken may account for much of the variability. Water pH was relatively uniform among sites and campaigns (6.9–7.8), the water being slightly more basic near the river mouth because of the influence of seawater. Although water was brackish throughout the entire area, salinity was variable because of the operation of the sluice gates: in Ho Phong zone, salinity was low because it was measured while the gates were closed. At other sites, salinity was higher because sampling was done on the following day when the gates were opened; this highlighted the rapid effect of sluice gate operation on salinity. TDS closely followed salinity patterns. DO concentrations were not high (average 4.9 mg/l) but sufficient for most freshwater fishes of the region (Baran *et al.*, 2007a). In March 2005, H_2S concentration was variable but generally high, averaging 0.18 mg/l; this reflected a pollution level unsuitable for the development of eggs and larvae of many fish species. NH_4^+ levels were variable, but never critical to fish health (0.01–0.4 mg/l). PO_4^{3-} was high (0.01–1.2 mg/l), particularly in March 2005, but was generally below the threshold triggering

Table 2.1. Environmental parameters in the study area (individual values in the 14 sampling sites have been averaged per zone).

Campaign	Year	Month	Season	Zone	Temp	pH	Salinity	TDS	DO	H_2S	NH_4^+	PO_4^{3-}
2004–2005	2004	June	Acidic	Canal 8000	30.0	6.5	12.7	12.19	7.12	0.14	0.31	0.02
				Pho Sinh	30.3	5.1	8.5	8.17	6.43	0.07	0.32	0.09
				Coast	29.4	7.3	17.1	15.69	5.40	0.10	0.15	0.03
				Ho Phong	29.5	6.7	16.2	16.56	6.16	0.16	0.62	0.01
		October	Flood	Canal 8000	29.8	7.1	4.7	4.60	4.05	0.52	0.29	0.03
				Pho Sinh	29.9	6.9	1.1	1.11	2.45	0.21	0.18	0.07
				Coast	29.8	7.2	7.0	6.75	6.48	0.45	0.34	0.03
				Ho Phong	30.1	7.2	5.1	4.90	4.67	0.49	0.33	0.03
	2005	March	Dry	Canal 8000	29.3	7.1	29.2	28.10	4.60	0.13	0.05	0.22
				Pho Sinh	30.0	7.2	20.5	19.70	4.21	0.25	0.04	0.58
				Coast	29.5	7.5	29.8	28.65	4.72	0.17	0.07	0.29
				Ho Phong	29.7	7.3	29.7	30.10	3.57	0.16	0.03	0.26
2005–2006	2005	June	Acidic	Canal 8000	30.6	7.2	27.7	26.57	2.22	0.03	0.47	0.19
				Pho Sinh	30.2	6.5	17.6	16.87	2.95	0.08	0.73	0.14
				Coast	30.3	7.6	22.9	22.00	4.56	0.30	0.18	0.06
				Ho Phong	30.3	7.4	25.6	24.70	4.74	0.06	0.31	0.05
		October	Flood	Canal 8000	29.3	7.5	3.0	2.91	4.80	0.06	0.18	0.01
				Pho Sinh	29.2	7.5	0.3	0.31	3.03	0.06	0.24	0.08
				Coast	30.4	7.7	4.0	3.91	5.44	0.07	0.33	0.01
				Ho Phong	29.6	7.6	3.8	3.82	5.76	0.06	0.22	0.02
	2006	March	Dry	Canal 8000	29.3	7.0	30.4	29.30	5.65	0.01	0.04	0.06
				Pho Sinh	29.7	7.6	18.7	18.27	3.79	0.02	0.12	0.05
				Coast	30.8	7.7	30.2	28.80	6.52	0.01	0.02	0.05
				Ho Phong	31.0	7.7	2.8	2.76	5.36	0.01	0.08	0.05

algal blooms. PO_4^{3-} was more concentrated around Phuoc Long in the rice cultivation area (particularly in March 2005); in this zone, enrichment of canal waters with agricultural fertilizers is probable.

Acidic season (June). In June 2004 and 2005, temperature was uniform throughout the study area, averaging 30 °C. Although the range of pH values was similar between years (4.2–7.8), in June 2004 the water was acidic at 13 of the 14 sites, whereas in June 2005 it was acidic at only two sites. Water pH was, in general, lower near the sea and higher further inland, as a result of acidity leached out from the sulfate soils during the first rains of the monsoon season. Salinity decreased with increased distance from the sea, but only reached freshwater levels in the north-east corner of the study area. TDS closely followed salinity patterns, with the lowest concentrations in the north-east area. DO was unsuitable for fish at numerous sites. The H_2S level was variable but higher in June 2004 than in June 2005 and generally unbearable for the early stages of fish species. NH_4^+ concentrations were quite variable (0.1–1.1 mg/l) and increased with increasing distance from the sea. PO_4^{3-} levels were also highly variable among sites and between years, with the highest concentrations in secondary canals.

Rainy season (October). In October 2004 and 2005, water temperature was uniform throughout the study area (28.9–30.7 °C). Similarly, water pH was relatively uniform among sites and between campaigns (6.8–7.9). Two distinct salinity zones were evident each year: from the coast to the end of Canal 8000, where salinities were notably higher, and from Chu Chi to Ninh Quoi. Low salinity (0.1–8.5 g/l) in this latter zone reflected the influx of Mekong fresh water during this period. However, the maximum salinity in October 2005 was less than half that of October 2004, which reflected interannual differences in flood timing and/or intensity. TDS showed spatial and interannual variability similar to salinity. DO (1.52–7.52 mg/l) decreased with distance from the sea. H_2S levels were highly variable in space, with higher concentrations at sites characterized by a higher population density. H_2S concentrations were also notably higher in October 2004 than in October 2005, reaching a pollution level (0.84 mg/l) unsuitable for fish eggs and larvae. NH_4^+ levels were reasonably variable among sites but consistent between years (range: 0.15–0.52 mg/l). As in March, PO_4^{3-} concentration was highest in the rice cultivation area around Ninh Quoi.

Synthesis of water environmental parameters. Temperature was relatively constant among all sites, seasons and years. Although salinity and pH were influenced by sluice gate operation, in general salinity and pH variations did follow the seasonal variation of rainfall and these differences were most pronounced at the north-east sites. Salinity peaked in March, which corresponded to the dry season and the period of greatest saline intrusion under natural conditions. Acidity peaked in June, particularly in the north-east sites, when the first rains of the year released acidity from the acid sulfate soils and washed it into canals. In October, during the monsoon, the canal water approached freshwater conditions, particularly in the north-east sites.

Although water quality parameters did vary seasonally as expected, March 2006 data showed that they were also clearly affected by the fact that the sluice gates were opened or closed at the time of sampling. Therefore, without details of gate operation, it was difficult to determine whether seasonal differences in observed concentrations described above were a result of changes in natural conditions or were the product of the water management regime. Rapid influxes of salt water when sluice gates were opened might also have influenced other parameters by diluting concentrations of pollutants. Environmental indicators also showed that the water was considerably more polluted in the first campaign than in the second, particularly in June and October. These trends were not identified in seasonal analyses, highlighting the value of long-term investigation.

Future studies should acknowledge that environmental data need to be considered in relation to sluice gate operation at the time of sampling. They should also consider interannual variability in order to understand fully the ecological context and to improve predictive

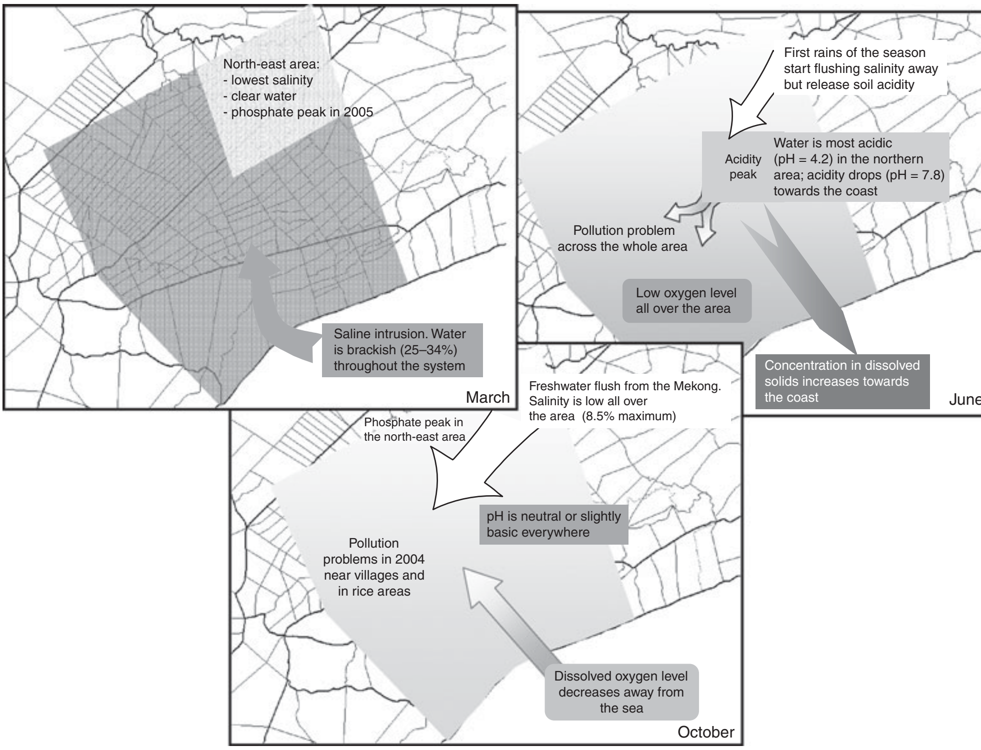

Fig. 2.2. Seasonal variation of water quality factors in the study area.

capabilities. An overview of the seasonal patterns is proposed in Fig. 2.2.

Nekton

Nekton species richness

The sampling of aquatic resources in the study area resulted in the catch and identification of 78 species, including 53 fish species (belonging to 36 families), 16 shrimp species (mainly Penaeids), six crab species and three miscellaneous species, as detailed in Table 2.2. It should be noted that one fish species, *Chimaera phantasma* (No 10), is a marine species known to live on continental shelf edges between 90 and 540 m deep; this probable misidentification is excluded from the analyses.

Of the 53 fish species, 11% are known in FishBase (see www.fishbase.org) as freshwater species, 15% as marine species and 74% as species found in brackish water (this latter category itself is comprised of 26% of species also caught in the marine realm, 12% of purely brackish origin and 36% of species also found in freshwater environments). Among the fish species on the list, six are considered in FishBase as reef-associated; it is surprising to find them inland in this brackish and turbid environment. Overall, 70 species were caught by trawler and 33 by gillnets. Forty-five species were caught by trawler only, eight by gillnets only and 25 species were caught using both gears. The use of gillnets in addition to trawlers increased the species richness of samples by 11%.

The analysis of species diversity in space and time (Table 2.3) shows that March, the period of high salinity, has higher species richness than June and October. This pattern is common in tropical estuarine zones and is explained by the richness of the marine realm, whose species make incursions into coastal zones during the dry/saline season (Baran *et al.*, 1999; Baran, 2000).

In space, biodiversity seemed to be slightly higher at the two extreme sites of the study

Table 2.2. Nekton species sampled during the study.

Family	Species name (Latin)	Species name (Vietnamese)	Water type	Habitat
Fish				
Ambassidae	*Ambassis gymnocephalus*	*Cá són đầu trần*	F/B/M	Demersal
Ambassidae	*Ambassis nalua*	*Cá són*	F/B/M	Demersal
Anabantidae	*Anabas testudineus*	*Cá rô đồng*	F/B	Demersal
Ariidae	*Arius leptonotacanthus*	*Cá úc*	B/M	Demersal
Bagridae	*Mystus gulio*	*Cá chốt*	F/B	Demersal
Bagridae	*Mystus wolffii*	*Cá chốt*	F/B	Demersal
Carangidae	*Selar boops*	*Cá ngân*	M	Reef-associated
Carangidae	*Selaroides leptolepis*	*Cá chi vàng*	B/M	Reef-associated
Channidae	*Channa striata*	*Cá lóc*	F/B	Benthopelagic
Chimaeridae	*Chimaera phantasma*	*Cá chim*	M	Bathydemersal
Cichlidae	*Oreochromis niloticus*	*Cá rô phi*	F/B	Benthopelagic
Cichlidae	*Oreochromis* sp.	*Cá phi*	F/B	Benthopelagic
Clariidae	*Clarias batrachus*	*Cá trê trắng*	F/B	Demersal
Clariidae	*Clarias macrocephalus*	*Cá trê vàng*	F	Benthopelagic
Clupeidae	*Clupanodon thrissa*	*Cá mòi*	F/B	Pelagic
Cobitidae	*Botia modesta*	*Cá heo*	F	Demersal
Cynoglossidae	*Cynoglossus lingua*	*Cá lúõi trâu*	F/B/M	Demersal
Cyprinidae	*Barbonymus gonionotus*	*Cá mè vinh*	F	Benthopelagic
Cyprinidae	*Rasbora lateristriata*	*Cá lòng tong*	F	Benthopelagic
Dasyatidae	*Himantura imbricata*	*Cá đuối*	F/B/M	Demersal
Eleotridae	*Butis butis*	*Cá bống trân*	F/B/M	Demersal
Eleotridae	*Eleotris balia*	*Cá bống trúng*	F/B/M	Demersal
Eleotridae	*Ophiocara porocephala*	*Cá bống sộp*	F/B/M	Demersal
Eleotridae	*Oxyeleotris urophthalmus*	*Cá bống dúa*	F/B	Demersal
Engraulidae	*Coilia rebentischii*	*Cá mào gà*	B/M	Pelagic
Engraulidae	*Setipinna taty*	*Cá lep trắng*	B/M	Pelagic
Engraulidae	*Stolephorus commersonii*	*Cá cóm*	B/M	Pelagic
Gobiidae	*Cryptocentrus russus*	*Cá bống sao*	M	Demersal
Gobiidae	*Glossogobius giuris*	*Cá bống cát*	F/B/M	Benthopelagic
Gobiidae	*Pseudapocryptes elongatus*	*Cá kèo*	F/B	Demersal
Gobiidae	*Trypauchen vagina*	*Cá bống kèo đỏ*	B/M	Demersal
Harpadontinae	*Harpadon nehereus*	*Cá khoai*	B/M	Benthopelagic

Continued

Table 2.2. Continued.

Family	Species name (Latin)	Species name (Vietnamese)	Water type	Habitat
Hemiramphidae	*Zenarchopterus pappenheimi*	*Cá lìm kìm gai*	B/M	Pelagic
Latidae	*Lates calcarifer*	*Cá chẽm*	F/B/M	Demersal
Mastacembelidae	*Macrognathus aculeatus*	*Cá chạch sông*	F/B	Benthopelagic
Mugilidae	*Mugil cephalus*	*Cá đối*	F/B/M	Benthopelagic
Muraenesocidae	*Congresox talabon*	*Cá lạc*	B/M	Demersal
Ophichthiidae	*Ophichthus rutidoderma*	*Cá lác dây*	F/B	Demersal
Osphronemidae	*Trichogaster microlepis*	*Cá sâc điệp*	F	Demersal
Osphronemidae	*Trichogaster trichopterus*	*Cá sặc bướm*	F	Benthopelagic
Platycephalidae	*Sorsogona tuberculata*	*Cá chai*	M	Demersal
Plotosidae	*Plotosus canius*	*Cá ngát*	F/B/M	Demersal
Polynemidae	*Eleutheronema tetradactylum*	*Cá chét*	F/B/M	Pelagic
Polynemidae	*Polynemus paradiseus*	*Cá phèn trắng*	F/B/M	Demersal
Scatophagidae	*Scatophagus argus*	*Cá nâu*	F/B/M	Reef-associated
Sciaenidae	*Pennahia pawak*	*Cá đâú*	M	Benthopelagic
Scombridae	*Scomberomorus commerson*	*Cá thu*	M	Reef-associated
Siganidae	*Siganus javus*	*Cá dìa*	B/M	Reef-associated
Sillaginidae	*Sillago aeolus*	*Cá nhống*	M	Demersal
Siluridae	*Wallago* sp.	*Cá gúng*	F/B	Demersal
Synbranchidae	*Ophisternon bengalense*	*Lịch*	F/B/M	Demersal
Synbranchidae	*Synbranchus bengalensis*	*Lịch*	F/B	Demersal
Synodontidae	*Saurida tumbil*	*Cá mối*	M	Reef-associated
Shrimps/prawns				
Alpheidae	*Alpheus euphrosyne*	*Tôm tích sông*		
Palaemonidae	*Exopalaemon styliferus*	*Tôm vát giáo*		
Palaemonidae	*Macrobrachium equidens*	*Tôm trúng*		
Palaemonidae	*Macrobrachium lar*	*Tép bầu*		
Palaemonidae	*Macrobrachium rosenbergii*	*Tôm càng xanh*		
Penaeidae	*Metapenaeopsis barbata*	*Tôm gậy*		
Penaeidae	*Metapenaeus affinis*	*Tôm chì*		
Penaeidae	*Metapenaeus ensis*	*Tôm dất*		

Continued

Table 2.2. Continued.

Family	Species name (Latin)	Species name (Vietnamese)	Water type	Habitat
Penaeidae	*Metapenaeus lysianassa*	*Tép bạc*		
Penaeidae	*Metapenaeus tenuipes*	*Tôm bạc*		
Penaeidae	*Parapenaeopsis cultrirostris*	*Tôm sắt*		
Penaeidae	*Parapenaeopsis gracillima*	*Tôm giang mỡ*		
Penaeidae	*Penaeus merguiensis*	*Tôm thé*		
Penaeidae	*Penaeus monodon*	*Tôm sú*		
Penaeidae	*Penaeus semisulcatus*	*Tôm vằn*		
Sergestidae	*Acetes vulgaris*	*Ruốc*		
Crabs				
Portunidae	*Charybdis affinis*	*Ghẹđá*		
Portunidae	*Portunus pelagicus*	*Ghexanh*		
Portunidae	*Scylla olivacea*	*Cua đá*		
Portunidae	*Scylla serrata*	*Cua biển*		
Parathelfusidae	*Somanniathelpusa* sp.	*Cua đồng*		
Grapsidae	*Varuna litterata*	*Ghẹm*		
Miscellaneous				
Octopodidae	*Octopus marginatus*	*Bạch tuột*	Octopus	
Sepiidae	*Sepiella inermis*	*Mự*	Squid	
Squillidae	*Harpiosquilla harpax*	*Tôm tích*	Squilla	

F, fresh water; B, brackish water; M, marine.

Table 2.3. Aquatic species diversity in time and space in the study area.

Campaign	Number of species	Season	Number of species	Zone	Number of species
2004–2005	52	March	58	Pho Sinh	54
2005–2006	43	June	47	Canal 8000	47
		October	46	Ho Phong	49
				Coast	56

area: (i) around Pho Sinh, the site most influenced by the Mekong River, reportedly the third most biodiversity-rich river system in the world (Dudgeon, 2000); and (ii) in the coastal zone (coastal zones being characterized globally by a very high biodiversity; Ricklefs, 1990).

Nekton abundance patterns

Overall, the catch was very poor in the study area (Table 2.4), with very small fish caught and very small catches in gears (on average 55 g in gillnets and 373 g in trawl per fishing operation). The average individual weight of fish was 46 g, whereas that of shrimp amounted to 39 g; this indicated that the shrimps caught were mainly large individuals that had escaped from aquaculture ponds (as confirmed by farmers' interviews) and that the fish were just small individuals, possibly juveniles that are dominant in all tropical estuarine zones.

Table 2.4. Catch per gear during the study period.

Gear	Campaign	Month	Abundance (number of individuals)	Biomass (g)	Average biomass (g) per individual	Average biomass (g) per fishing operation
Gillnet	2004–2005	March	7	190	27.2	27
		June	52	451	8.6	64
		October	59	1088	18.4	155
	2005–2006	March	34	719	21.2	60
		June	2	26	13.0	4
		October	8	153	19.1	22
Trawl	2004–2005	March	4097	5352	1.3	446
		June	410	2416	5.9	201
		October	962	4149	4.3	346
	2005–2006	March	2844	6952	2.4	579
		June	1797	3825	2.1	319
		October	1690	4134	2.4	345

The overall temporal variability and spatial variability of the aquatic resources are shown in Table 2.5. Results are based on trawling, whose catch per fishing session is 6.7 times higher than that of gillnets and almost double in terms of species richness.

Interannual variability. Interannual variations of aquatic resources were highly significant, with the trawling CPUE being 59% higher in the second campaign than in the first. The total number of species, however, was comparable between years. A detailed analysis of species caught showed that *Penaeus merguiensis* dominated samples in 2005, accounting for more than 50% of the total catch, but was barely present in 2006.

Seasonal variability. Variations of aquatic resources between seasons were also high, with 67% variation between the months of least abundance (June and October) and the month of highest abundance (March). Thus, for aquatic resources, the season of highest abundance is the dry season, which is also the season of highest biodiversity.

Geographic variability. The zone with the highest abundance of aquatic resources was Ho Phong, but the variability was not very high between Ho Phong, Pho Sinh and the coastal zone; Canal 8000, in contrast, clearly had the least abundant aquatic resources and the lowest biodiversity, possibly because this zone was characterized by acid sulfate soils. A detailed analysis showed that in the first sampling campaign, CPUE (biomass) was highest in the coastal zone and decreased further inland, suggesting the dominance of marine and estuarine species. However, in the second campaign, there was ambiguity about March 2006, as the sluice gates were opened during the sampling

Table 2.5. Average catch per unit effort in time and space (g/m^3 trawled).

Campaign	Average catch per unit effort	Season	Average catch per unit effort	Area	Average catch per unit effort
2004–2005	0.039	March	0.069	Pho Sinh	0.059
2005–2006	0.062	June	0.041	Canal 8000	0.031
Variation (%)	59	October	0.042	Ho Phong	0.062
		Variation (%)	67	Coast	0.050
				Variation (%)	104

period, which might have modified the fish distribution pattern significantly.

Complementary gillnet sampling (also possible in secondary canals, unlike trawling), showed that the catch was much lower in secondary canals than in primary canals. This result was consistent with other studies that concluded that fish diversity and abundance were proportional to the size of the estuarine water body sampled (Baran, 1995, 2000).

Relationships between aquatic resources and the environment

The relationship between aquatic resources and environmental parameters is analysed below in terms of: (i) environmental variability and biodiversity descriptors; and (ii) environmental variability and dominant species. Again, analyses were based on trawling CPUE data, since trawling caught 6.7 times more biomass per operation and, overall, two times more species than gillnets.

Environmental variability and biodiversity descriptors

The analysis of environmental and biodiversity variability is based on the eight environmental variables referred to in Table 2.1, on trawling CPUEs and on species richness as global descriptors of the biodiversity. The method used is a correlation matrix PCA (e.g. centred and normalized PCA, justified by the presence of multiple variables all continuous but of different units; see Nichols, 1977, and Wold *et al*., 1987). In the figures below, the factorial maps of sites and variables were superimposed for interpretation (Carrel *et al*., 1986).

The PCA eigenvalues indicate that 49.8% of the total information in the data (e.g. total inertia) is summarized in the first two axes and that the first four axes represent 75.6% of the total information of the data set. Emphasis is thus put below on the first two axes and complemented by the following two axes (Fig. 2.3).

The factorial map clearly highlights the correlation between species richness and salinity or concentration of dissolved solids (e.g. marine influence; left-hand part of the factorial map). Actually, all the sites are associated with high values of salinity and TDS; this reflects the homogenization of the whole area that is species rich and under strong marine influence in March and, to some extent, in June. As opposed to this pattern, the distribution in October (upper right corner of the factorial map) is also relatively homogeneous (dots of all areas are close) but characterized by low turbidity and fresh water (anticorrelation with salinity and dissolved solids). Therefore, a first cluster defines a marine–freshwater gradient and its associated sites over time.

On the second axis (vertical), high CPUE is illustrated by a particular zone: Ho Phong, in March 2006, whose CPUE is four times higher than the average CPUE in all other samples. The high CPUE is mainly a result of *Parapenaeopsis cultrirostris*, *Metapenaeus tenuipes* and *M. affinis*. It is also clear that high CPUE and species richness (upper left corner of the map) are anticorrelated to high levels of ammonium and hydrogen sulfide (lower right corner of the map): this illustrates clearly the negative impact of pollution on the abundance and diversity of aquatic resources in the study area. Therefore, a second cluster defines an aquatic resources–pollution gradient.

Interestingly, all stations characterized by high pollution pertain to the first campaign (year 2004–2005) and to the months of June and October exclusively, which indicates that the Mekong flood does not suffice to dissolve or eliminate the pollution, and that allowing marine influence through the opening of the sluice gates is beneficial to both pollution level and abundance of aquatic resources.

On the second map, the third axis of the PCA is dedicated to the anticorrelation between pH and temperature, which clarifies the first map where temperature and pH are projected in the same area and results in the impression that they are correlated. The fourth axis highlights the negative correlation between dissolved oxygen and temperature, another anticorrelation well known in environmental data.

Figure 2.3 is distilled further to become a choreme, i.e. a two-dimensional figure expressing spatio-temporal processes (but usually based on geographic maps, not on factorial maps); it synthesizes the evolution over time of the study sites in terms of faunal and environmental factors (Fig. 2.4).

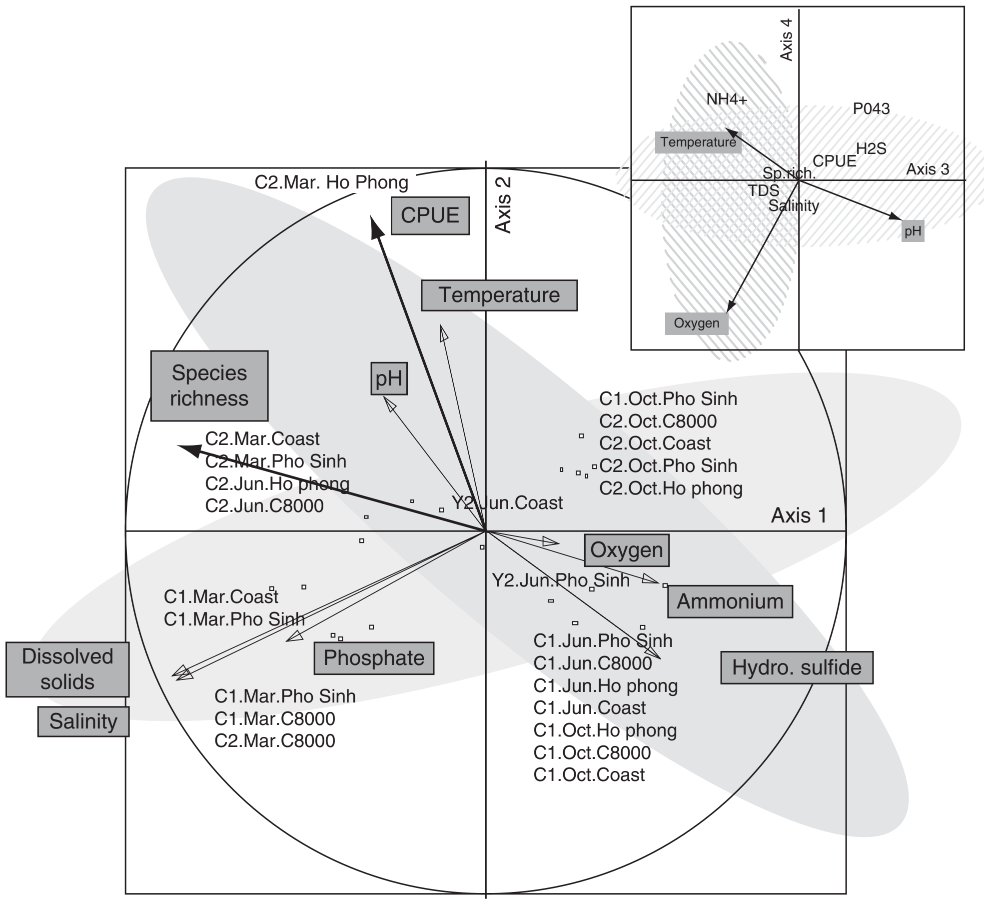

Fig. 2.3. Factorial maps of the PCA on environmental and biodiversity variables. Sites are identified by campaign, then month, then zone (e.g. C2.Oct.C8000 = 2005–2006, October, Canal 8000).

Figure 2.4 shows the evolution of the area over time between four main poles: marine, freshwater, pollution and aquatic resources. June 2004 was the campaign characterized by most pollution and the lowest level of aquatic resources; then the situation evolved, with a seasonal fluctuation between marine and freshwater patterns, towards a better ecological situation characterized in March 2006 by the lowest pollution level and the highest abundance and diversity. This improvement in terms of aquatic resources and pollution can be related to opening of the sluice gates (longer in 2006 than in 2004 and 2005), also reflected by a higher salinity in 2006.

Figure 2.4 also clearly indicates that biomass and diversity of aquatic resources are opposed to pollution (the latter being related to the rice-growing eastern part of the study area) and are correlated conversely to both marine and freshwater influences. Thus, both saline intrusion and the Mekong flood play a role in the aquatic biodiversity and biomass of the study area. The consequence of this result is that an environmental modification permanently favouring one single influence (in particular the freshwater influence) would be detrimental to aquatic resources and to the productivity of the area.

Environmental variability and dominant species

This analysis is comprised of two phases: (i) selection of dominant species for quantitative

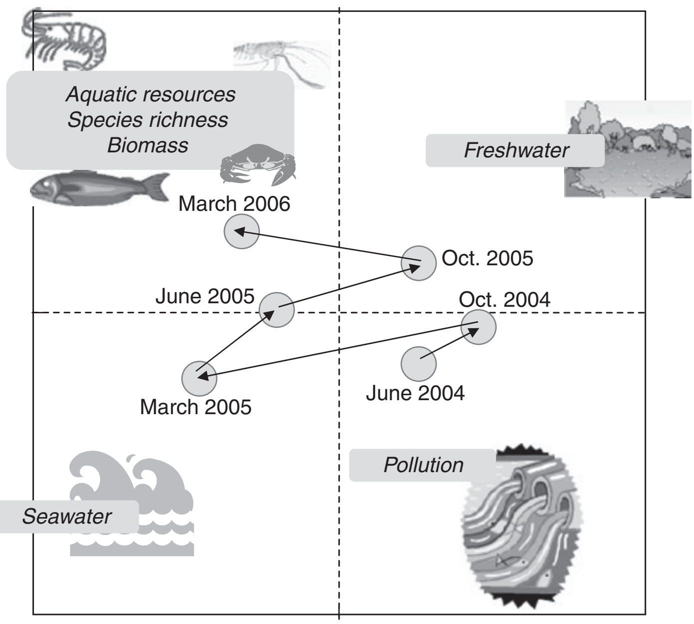

Fig. 2.4. Relationships between major environmental factors and aquatic resources in space and time.

analyses; and (ii) environmental dynamics and corresponding species.

Selection of dominant species for quantitative analyses: the application of a quantitative approach requires the exclusion of the species present only once or twice in the samples, whose nil records bias the calculation of correlation coefficients. Dominant species were identified by considering both their abundance and biomass, so that small but abundant species totalling a low biomass as well as rare but big species were not excluded (Fig. 2.5). Twenty-three species were retained out of 55 species caught by the trawler during the two campaigns. These species represented 89% of the total biomass and 95% of the total abundance in the total catches.

Environmental dynamics and corresponding species: the correspondence analysis indicates a very strong structure, with 89% of the total inertia on the first axis and 93% of the information summarized in the first two axes (Fig. 2.6).

The analysis confirms a clear gradient between marine and freshwater influences similar to that of environmental factors, but this time identifies associated species. In March, when the environment is characterized by high salinity and a high level of dissolved solids, the fish species associated are *Coilia* and *Setipinna*, two abundant *Engraulidae* (anchovies) that are typical of coastal zones. Among shrimps, two wild *Palaemonidae* and a *Penaeidae* characterize the community in tropical coastal zones (there are, however, reservations about the identification of *P. gracillima,* which usually exists only at the straits of Malacca and Borneo).

The middle of the gradient is characterized by high environmental variability, in which the species composition in March at some sites (e.g. Ho Phong) can be similar to that in June at other sites (e.g. coastal area). Species of this environment are typically estuarine, such as gobies, mullets or croakers (respectively, *Glossogobius, Mugil* and *Pennahia*), and alpheid or penaeid shrimps.

October is characterized by fresh water and by salinity-tolerant species originating from the freshwater realm: tilapias (*Oreochromis* sp., usually cultured in ponds) or catfishes (*Mystus gulio*, *Clarias batrachus*). The presence of these species in all sites from Pho Sinh to the coastline highlights the homogenization of the study area in October from a faunal viewpoint.

The river shrimp *Macrobrachium rosenbergi* (tolerant to brackish water) and the tiger

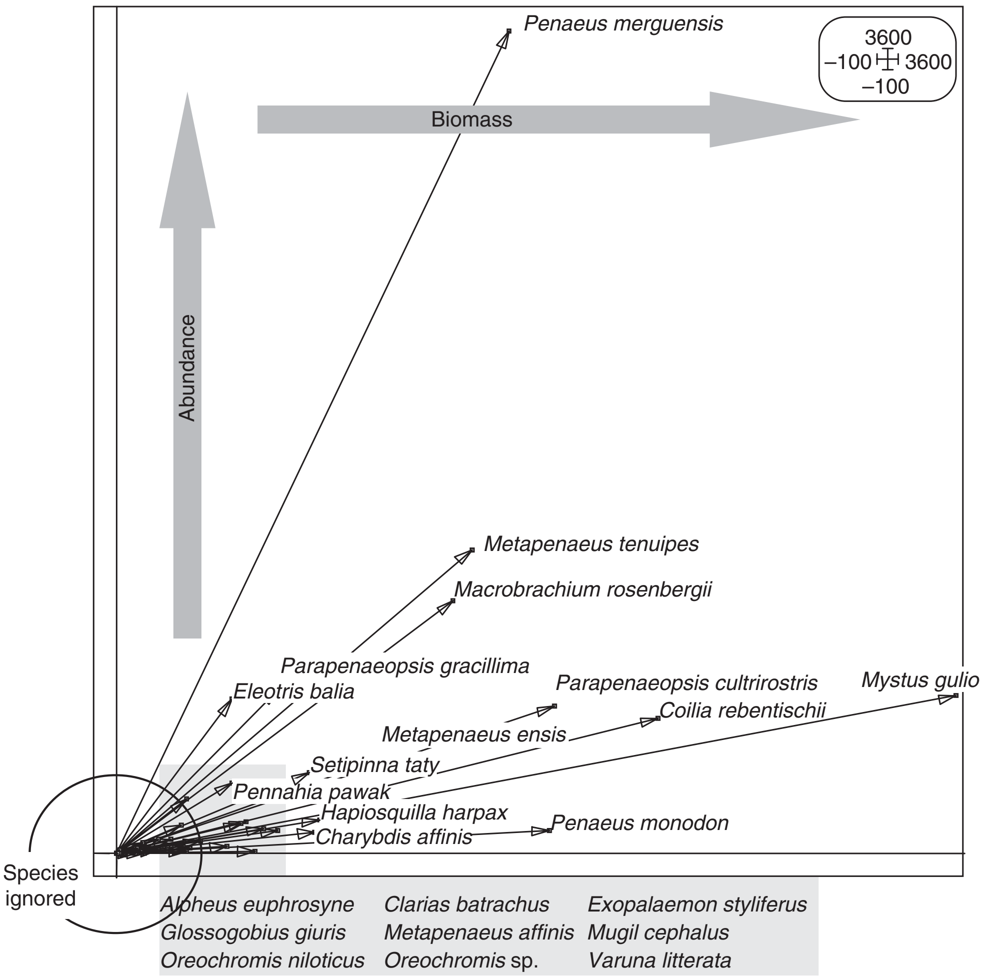

Fig. 2.5. Selection of dominant species based on their total biomass and abundance among the species sampled.

prawn *P. monodon* (tolerant to low salinities) are typical of estuarine waters; these giant decapods probably both originate from aquaculture farms, as underlined by fishers in interviews.

Discussion and Conclusions

This study, which characterizes the aquatic and environmental variability of the area subject to water management in Bac Lieu Province, has highlighted the following points:

- The temporal variability corresponds to three main seasons: March, or dry season, June, or acidic season, and October, or freshwater season. Salinity peaks in March and pH peaks in June, particularly in the north-east corner of the area, when the first monsoon rains release acidity from the acid sulfate soils. This latter area is under the influence of rainfall and freshwater Mekong pulses and approaches freshwater conditions in October during the peak of the monsoon. The study led by Dung *et al*. (2002) confirms that salinity is the parameter that varies most between seasons, but does not highlight the pH peak in June because of lack of sampling in this month.

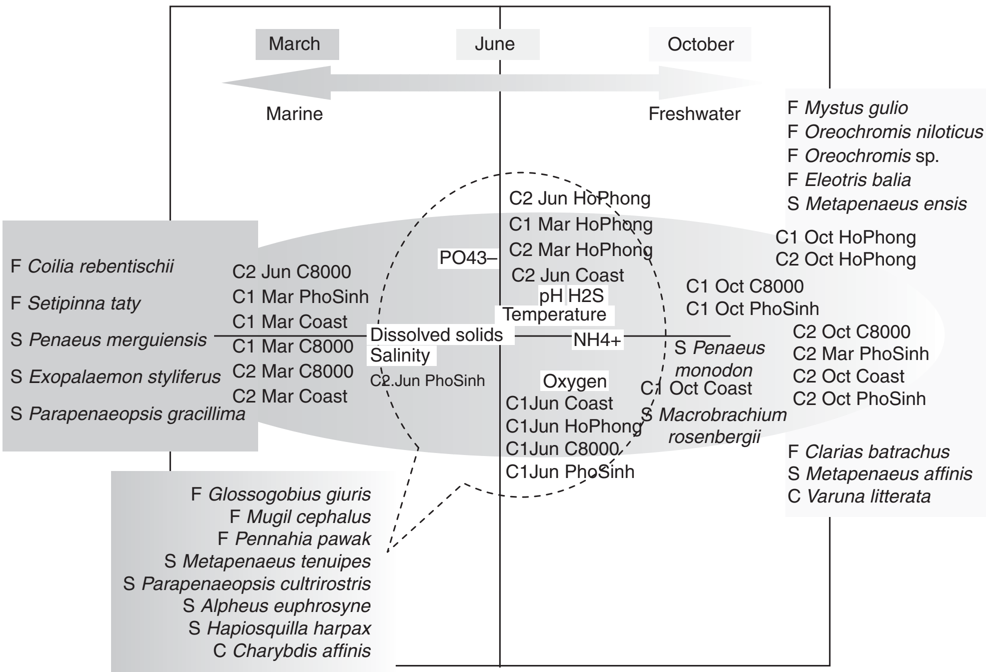

Fig. 2.6. Factorial map of the correspondence analysis combining sites, environmental factors and dominant species (sites are identified by campaign, then month, then zone, and species names are preceded by F for fish, S for shrimps and C for crabs).

- Superimposed on the natural environmental variability is a shorter-term variability induced by the operation of the sluice gates; it is reflected but not fully integrated in the current study. Future environmental studies should definitely integrate sluice gate operation and should also consider interannual variability in order to understand the results fully and improve predictive capabilities.
- The aquatic resources sampled included 78 species, comprising 53 fish species, 16 shrimp species and six crab species. This makes the study site relatively rich, considering its surface area, and this biodiversity results from a succession and overlap of marine, estuarine and freshwater faunas, depending on environmental conditions. Species richness is highest in March during the period of peak salinity when marine species make incursions into the estuarine zone. In 2002, Dung *et al.* sampled only 43 species; however, the number of species collected in each sampling session was similar in both studies. This shows that the greater number of species sampled by the present study (and thus the more representative description provided) is mainly a result of additional sampling in June in our study. Only 14 fish species and six shrimp species were common to both studies; less brackish/marine and no exclusively marine species were sampled by Dung *et al.* in 2002. This relatively low level of congruence between the two studies can be attributed to a strong interannual variability (see below). The causes of this variability can be natural (e.g. influenced by the Mekong flood in each year) or human induced (closing or opening of the sluice gates or pollution in some years, as highlighted in our study).
- In contrast to a high species richness, our study shows that abundance is poor, with an average catch of 55g in gillnets and 373g in trawls after 2h. The individual weight of the fish is also small (46g),

whereas that of shrimp amounts to 39 g; this indicates that the shrimp are, in fact, mainly large prawns that have escaped from aquaculture farms.

- Interannual variation is substantial in the study area, with a 60% difference in fish catches from year to year. Seasonal variation is also high, with a 67% difference between the months of least abundance (June and October) and the month of highest abundance (March). Spatially, there is little variation in abundance among the different sites, with the exception of Canal 8000, where abundance is less; abundance is also lower in secondary canals than in primary canals.
- There is a high correlation between species richness and salinity and/or the concentration of dissolved solids, i.e. with the marine influence, which is often the case in tropical estuarine environments, where tolerant species from the rich marine realm make incursions (Baran, 2000). Overall, species distribution and assemblage composition is influenced largely by salinity; this is confirmed by Dung *et al.* (2002). Among marine species making incursions inland are anchovies (*Coilia* and *Setipinna* species), as well as shrimps *P. merguiensis* and *Exopalaemon styliferus*. The purely estuarine area is characterized, in March and June in particular, by a high environmental variability and by gobies, mullets or croakers, as well as by alpheid or penaeid shrimps (such as *P. monodon*, which probably originates from aquaculture farms). In October, the system is under a strong freshwater influence that spreads over the entire area and homogenizes the ecosystem, which is then characterized by salinity-tolerant freshwater species (e.g. tilapias, catfishes or *M. rosenbergi* prawns).
- A clear negative correlation can also be noted between pollution (in particular in the populated and rice-growing areas) and the abundance and diversity of aquatic resources. Results also show that the Mekong flood itself is not sufficient to dissolve or eliminate the pollution. This intrusion of Mekong water and fauna, on the other hand, contributes, although not dominantly, to the diversity and abundance of aquatic resources in the study area. In fact, it is the *marine* influence that is most beneficial to the abundance and diversity of aquatic resources in that area. Data gathered over 2 years show a situation gradually improving (despite seasonal variations) from pollution in a freshwater context with low diversity and abundance in 2004, towards more abundance and diversity in a more saline and less polluted context in 2006.
- Interviews with local fishers reiterated the impact that the sluice gates had on water quality and on the type and abundance of aquatic resources. It is clear from these interviews that pollution and acidity are two important factors driving fish abundance, and that pollution becomes a problem when the gates remain closed for extended periods of time. According to fishermen, catches are generally best during periods of marine influence, i.e. during the dry season or when the gates are opened. This is particularly true for shrimp, as when the gates are opened, wild marine shrimp enter the system and are targeted by fishers. When the gates are closed, shrimp catches are dominated by individuals that have escaped from aquaculture ponds or are diseased shrimps released from aquaculture ponds being emptied for cleaning. Because of the lack of a detailed operating schedule of the sluice gates during the whole study period, we could not address, unfortunately, the relationship between gate openings and CPUE or species richness. However, our results make it clear that from the perspective of aquatic biodiversity, the permanent closure of the sluice gates is detrimental to both biodiversity and fish abundance in canals.

Finally, this chapter, although mainly descriptive, contributes to the development of a fine-tuned management approach to the Bac Lieu aquatic environment. This environment, and the fish resources it sustains, makes a significant contribution to the province's productivity and food security (Gowing *et al.*, 2006b). However, conflicts between rice, fish and shrimp production requirements call for a better knowledge of all these commodities. Although rice and shrimp production are well known, natural fish production in the canals has been almost undocumented to date, despite its significant contribution to the diet and livelihoods of local communities in the area (Baran *et al.*, 2007b). This highlights the need to integrate in water management models and initiatives, aquatic resources having significant environmental and social dimensions.

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References

Baran, E. (1995) *Spatio-temporal Dynamics of Estuarine Fish Assemblages in Guinea – Relationships with Abiotic Factors. TDM Volume 142*. Éditions ORSTOM, Paris.

Baran, E. (2000) Biodiversity of estuarine fish faunas in West Africa. *NAGA* 23(4), 4–9.

Baran, E. and Chheng, P. (2004) Analysis of Bac Lieu fishery monitoring data (March 2004) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Baran, E., Albaret, J.J. and Diouf, P.S. (1999) Mangrove fish communities in West Africa. In: Cormier-Salem, M.C. (ed.) *Rivières du Sud – Sociétés et Mangroves Ouest-africaines*. IRD Éditions, Paris, pp. 98–117.

Baran, E., Jantunen, T. and Chheng, P. (2006) Developing a consultative Bayesian model for integrated management of aquatic resources: an inland coastal zone case study. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones. Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 206–218.

Baran, E., Jantunen, T., Chheng, P. and Hakalin, M. (2007a) BayFish — Tonle Sap: a model of the Tonle Sap fish resource. Report for the project 'Influence of Built Structures on the Fisheries of the Tonle Sap'. WorldFish Center, Phnom Penh, Cambodia.

Baran, E., Jantunen, T. and Chong, C.K. (2007b) *Values of Inland Fisheries in the Mekong River Basin*. WorldFish Center, Phnom Penh, Cambodia.

Brunet, R. (1980) La composition des modèles dans l'analyse spatiale. *L'Espace Géographique* 4, 253–265.

Brunet, R. (1993) Building models for spatial analysis. In: GIP-RECLUS (ed.) *Two Decades of l'Espace Geographique*. GIP-RECLUS, Montpellier, France, pp. 109–123.

Carrel, G., Barthelemy, D., Auda, Y. and Chessel, D. (1986) Approche graphique de l'analyse en composantes principales normée: utilisation en hydrobiologie. *Acta Oecologica, Oecologia Generalis* 7(2), 189–203.

Chheng, P. (2004a) Analysis of the fishery monitoring data (June 2004) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Chheng, P. (2004b) Analysis of the fishery monitoring data (October 2004) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Chheng, P. and Toan, V.T. (2005a) Analysis of the fishery monitoring data (October 2005) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Chheng, P. and Toan, V.T. (2005b) Analysis of the fishery monitoring data (March 2005) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Dorr, J.A. III, Schneeberger, P.J., Tin, H.T. and Flath, L.E. (1985) *Studies on Adult, Juvenile and Larval Fishes of the Gambia River, West Africa, 1983–1984. Great Lakes and Marine Waters Center International Programs*. The University of Michigan, Ann Arbor, Michigan.

Dudgeon, D. (2000) Large-scale hydrological changes in tropical Asia: prospects for riverine biodiversity. *BioScience* 50(9), 793–806.

Dung, D.T., Cong, N.C. and Prein, M. (2002) Detrend of nectonic species assemblage in the salinity intrusion area of Bac Lieu Province, Mekong Delta, Vietnam. Paper presented at the Mid-term Review of the DfID-CRF R7467C Project, 26–28 June 2002, Bac Lieu, Vietnam.

Esteve, J. (1978) Les méthodes d'ordination: éléments pour une discussion. In: Legay, J.M. and Tomassone, R. (eds) *Biométrie et écologie*. Société Française de Biométrie, Paris, pp. 223–250.

Fagade, S.O. and Olaniyan, C.I.O. (1973) Seasonal distribution of the fish fauna of the Lagos Lagoon. *Bulletin de l'IFAN* 34A(1), 244–252.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006a) Social and environment impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones. Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 48–60.

Gowing, J.W., Tuong, T.P. and Hoanh, C.T. (2006b) Land and water management in coastal zones: dealing with agriculture–aquaculture–fishery conflicts. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones. Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 1–16.

Hoanh, C.T. (1996) Development of a computerized aid to integrated land use planning (CAILUP) at regional level in irrigated areas: a case study for the Quan Lo Phung Hiep region in the Mekong Delta, Vietnam. International Institute for Aerospace Survey and Earth Science (ITC) Publication No 38, Enschede, the Netherlands.

Hoanh, C.T., Tuong, T.P., Kam, S.P., Phong, N.D., Ngoc, N.V. and Lehmann, E. (2001) Using GIS-linked hydraulic model for managing water quality conflict for shrimp and rice production in the Mekong River Delta, Vietnam. In: Ghassemi, F., Post, D., Sivapalan, M. and Vertessy, R. (eds) *Proceedings of International Congress on Modelling and Simulation (MODSIM)*, Canberra, Australia, 10–13 December, 2001. Volume 1: Natural Systems (Part one). Modelling and Simulation Society of Australia and New Zealand, Canberra, Australia, pp. 221–226 (http://www.mssanz.org.au/html/body_publications.html, accessed 10 October 2008).

Hoanh, C.T., Tuong, T.P., Gallop, K.M., Gowing, J.W., Kam, S.P., Khiem, N.T. and Phong, N.D. (2003) Livelihood impacts of water policy changes: evidence from a coastal area of the Mekong river delta. *Water Policy* 5, 475–488.

Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (2006a) *Environment and Livelihoods in Tropical Coastal Zones. Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK.

Hoanh, C.T., Phong, N.D., Gowing, J.W., Tuong, T.P., Hien, N.X. and Dat, N.D. (2006b) Predicting impacts of water management in coastal zones by hydraulic and salinity modeling. In: Voinov, A., Jakeman, A. and Rizzoli, A. (eds) *Proceedings of the iEMSs Third Biennial Meeting 'Summit on Environmental Modelling and Software'*. International Environmental Modelling and Software Society, Burlington, Vermont.

Kam, S.P., Hoanh, C.T., Tuong, T.P., Khiem, N.T., Dung, L.C., Phong, N.D., Barr, J. and Ben, D.C. (2001) Managing water and land resources under conflicting demands of shrimp and rice production for sustainable livelihoods in the Mekong River Delta, Vietnam. Proceeding of the Workshop on 'Integrated Management for Sustainable Agriculture, Forestry and Fisheries', 28–31 August 2001. CIAT, Cali, Colombia.

Kam, S.P., Nhan, N.V., Tuong, T.P., Hoanh, C.T., Be Nam, V.T. and Maunahan, A. (2006) Applying the resource management domain (RMD) concept to land and water use and management in the coastal zone: case study of Bac Lieu Province, Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy. B. (eds) *Environment and Livelihoods in Topical Coastal Zones. Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 293–205.

Khoa, T.T. and Huong, T.T.T. (1993) Freshwater fish classification in the Mekong Delta. Faculty of Fisheries – Can Tho University, Vietnam.

Klippel, A. (2003) Wayfinding choremes. In: Kuhn, W., Worboys, M. and Timpf, S. (eds) *Spatial Information Theory. Foundations of Geographic Information Science*. Springer-Verlag, Berlin, pp. 349–361.

Klippel, A., Tappe, H., Kulik, L. and Lee, P.U. (2005) Wayfinding choremes: a language for modeling conceptual route knowledge. *Journal of Visual Languages and Computing* 16(4), 311–329.

Lévêque, C., Fairhurst, C.P., Abban, K., Paugy, D., Curtis, M.S. and Traore, K. (1988) Onchoceriasis control program in West Africa: ten years monitoring of fish populations. *Chemosphere* 17(2), 421–440.

Nichols, S. (1977) On the interpretation of principal components analysis in ecological contexts. *Vegetatio* 34, 191–197.

Prodon, R. and Lebreton, J.D. (1981) Breeding avifauna of a Mediterranean succession: the holm oak and cork oak series in the eastern Pyrénées. 1-Analysis and modelling of the structure gradient. *Oïkos* 37, 21–38.

Ricklefs, R.E. (1990) *Ecology*. Freeman, New York.

Rottenberry, J.T. and Wiens, J.A. (1981) A synthetic approach to principal component analysis of bird/habitat relationships. In: Capen, D.E. (ed.) *The Use of Multivariate Statistics in Studies of Wildlife Habitat*. USDA Forest Service General Technical Report, RM-87, Rocky Mountain Forest and Range Experiment Station, Fort-Collins, Colorado, pp. 197–208.

Thioulouse, J. and Chessel, D. (1992) A method for reciprocal scaling of species tolerance and sample diversity. *Ecology* 73, 670–680.

Thioulouse, J., Chessel, D., Dolédec, S. and Olivier, J.M. (1997) ADE-4: a multivariate analysis and graphical display software. *Statistics and Computing* 7(1), 75–83.

Toan, V.T. and Chheng, P. (2005) Analysis of the fishery monitoring data (June 2005) and sampling recommendations. Report for the project 'Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh'. WorldFish Center, Phnom Penh, Cambodia.

Tran, Q.B., Nguyen, V.H. and Dehairs, F. (2005) Behavior of nutrients in natural river and shrimp farming area in Bac Lieu Province, Mekong Delta. *Proceedings of the International Symposium 'Sustainable Development in the Mekong River Basin'*, 6–7 October 2005, Ho Chi Minh City, Vietnam. JST–CREST (Japan Science and Technology Agency – Core Research for Environmental Science and Technology project), Tsukuba, Japan, pp. 80–89.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Barr, J. and Ben, D.C. (2003) Impact of seawater intrusion control on the environment, land use and household incomes in a coastal area. *Journal of Paddy and Water Environment* 1(2), 65–73.

Wold, S., Esbensen, K. and Geladi, P. (1987) Principal component analysis. *Chemometrics and Intelligent Laboratory Systems* 2, 37–52.

Yen, M.D. and Trong, N.V. (1988) Species composition and distribution of the freshwater fish fauna of Southern Vietnam. *Hydrobiologia* 160, 45–51.

3 Integrating Aquaculture in Coastal River Planning: the Case of Dagupan City, Philippines

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Abstract

In the Philippines, conflicts between fishing, aquaculture, tourism and other uses of the coastal waters are common because they are not clearly integrated into the management of the coastal zone. Resource use allocation then remains a challenging task for decision makers. Development activities that proceed without proper planning lead to more resource use conflicts and environmental degradation. This chapter presents the findings of a study to identify a strategy for incorporating aquaculture into coastal planning to reduce conflicts in the use of the coastal and river waters of Dagupan City, Philippines. Recommendations to improve coastal planning requirements are discussed. Based on environmental, social, economic and institutional considerations, the river system was subdivided into ten management zones. The zones were further reclassified into priority use zones as 'regulated zone' (Zone 1), 'mariculture and fishing priority zone' (Zones 2–7), 'non-fishery zone' (Zone 8) and 'fishpond priority zone' (Zones 9 and 10). Since unregulated fishpen development was a major concern of the local government, fishpen size and layout were standardized. The output of this study forms part of the legislation, Dagupan City Coastal Fisheries Resources Management Ordinance of Year 2003, Executive Order No 71, Series of 2003. It is intended to promote sustainable aquaculture development, generate livelihood and revenues, institutionalize the production and marketing of milkfish for the domestic and export markets and rationalize the use of coastal resources to ensure social equity and long-term environmental stability.

Introduction

The coastal zone is a place where resources, users and resource use practices interact (Siar, 2003). Thus, coastal management has become increasingly important as different types of use such as fishing, aquaculture, tourism, shipping, etc., compete for space and resources. Resource use allocation then remains a challenging task for decision makers, especially as the current approach to management is unable to protect human health and maintain ecosystem integrity. Development activities and interventions still proceed without proper planning, leading to more resource use conflicts and environmental degradation. This is because resource planning and management decisions are surrounded by uncertainty and complexity (Bennett *et al.*, 2005). Scientific knowledge on which decisions should be based is often difficult to obtain and, when available, it is hardly utilized. In coastal governance, political leaders are often challenged with equitable allocation of limited resources to a number of resource users.

Conflicts over conservation and development intensify as natural resources become limited and areas for human activity become more concentrated (Brody *et al.*, 2004). Thus, proper zoning is crucial in formulating an economically, socially and environmentally sound plan for the management and development of coastal waters.

In the Philippines, the decentralized system of governance mandates the local government to allocate local waters for various uses within 15 km from the shoreline. However, local officials may find it rather difficult to apportion said waters because of their inability or insufficient experience in translating science or technical knowledge into decision making so as to balance resource demand without compromising the integrity of the environment. This is especially true for two important economic activities in the coastal areas, namely fishing and aquaculture. Fishing is categorized either as ‘municipal’ (or small scale) or ‘commercial’, depending on the area of jurisdiction, kinds of fishing boats and types of gears as defined in the 1998 Philippine Fisheries Code (RA 8550). Destructive fishing activities alongside an inefficient regulatory framework have left many of the country’s major fishing grounds and bays overfished and in a critical condition. In effect, the contribution of fishing to food security and poverty alleviation is negligible, despite increasing trends in fish production from both the commercial and municipal sectors. Aquaculture represents a growing enterprise. Although its contribution was only half as much as commercial or municipal fisheries, the average annual increase in fish production from aquaculture from 1997 to 2004 was 6.8% (excluding seaweeds), higher than that of the commercial and municipal fisheries sectors at 3.6% and 2.2%, respectively. The government supports coastal aquaculture, in particular mariculture. However, without proper planning and zoning, this activity can be detrimental to the coastal environment, and ultimately the economy. The potentially deleterious impacts of aquaculture are widely documented (Read and Fernandes, 2003; Feng *et al.*, 2004; Islam, 2005). Boyd (2003) identified conflicts with other resource users and disruption of nearby communities as two of the most serious concerns in aquaculture. In many parts of the country, aquaculture often is in conflict with fishing and other coastal uses because it is not incorporated into the management of the coastal zone.

This chapter is based on a study conducted for the local government of the coastal city of Dagupan, Philippines, in order to provide it with the information necessary to enact measures and implement programmes to promote sustainable aquaculture development and expansion, generate livelihoods from aquaculture and its support industries, generate revenues for the city, institutionalize the production and marketing of the local milkfish for local and export markets and rationalize the use of the river system and coastal waters, taking into consideration social equity and long-term environmental stability.

Objectives

The main objective of this study was to come up with a strategy to incorporate aquaculture into coastal planning so as to reduce conflicts in the use of the resources. Specifically, the study aimed to:

- evaluate the status of capture fisheries and aquaculture in Dagupan, Philippines; and
- recommend a zoning plan for the multiple use of the river.

Methodology

Study area

The coastal city of Dagupan is situated in the northern side of the province of Pangasinan, bordering the southern shore of Lingayen Gulf. It is one of the few cities in the Philippines where a considerable portion of its ‘land area’ is actually water. Out of a total area of 4364 ha, 38.1% comprises ponds and rivers. It is not surprising then that aquaculture and fishing figure prominently in the economy of the city. Dagupan is famous for its *Bonoan bangus* – widely regarded as the tastiest milkfish (*Chanos chanos*) in the country. A confluence of seven river courses that are flooded annually is believed to create the unique environment that allows the production of the *B. bangus*. The capture fisheries sector can be divided into river based and coastal. The river-based fisheries occupy about 536.69 ha of estuarine rivers (City Agriculture Office, 2002), whereas about 15,000 ha of marine waters in Lingayen Gulf comprise coastal fisheries. Brackishwater fishpond development in Lingayen Gulf began in the 1970s and accelerated in the 1980s (Yap *et al.*, 2004).

Sources of data

Secondary data were collected from the literature and from government offices (e.g. Dagupan City Agriculture Office, Fisheries Resource Management Project of the Bureau of Fisheries and Aquatic Resources). Aerial photograph documentation was conducted on 21 March 2002 to estimate the extent of river use. Key informant interviews and surveys (e.g. of local officials, fish farmers and traders) were conducted to validate existing information and the aerial photographs; and to examine the socio-economic characteristics of capture fisheries and aquaculture in the river system. Actual field sampling was done to measure environmental parameters.

Results

Environmental state of coastal and river waters prior to sustainable management

This section analyses the environmental conditions of the coasts and rivers of Dagupan based on available data. It is important to emphasize that these problems are man-made and thus may be mitigated through responsible practices. Similar to other coastal municipalities bordering Lingayen Gulf, the coastal and river waters of Dagupan were already overfished as early as 1985, with catch per unit effort (CPUE) reported as dropping to 1 kg/fisher/day. The rivers used to abound with various fish species, shrimps and crabs because of the extensive mangrove areas. The disappearance of some species, however, is not coincidental but is the result of years of environmental changes (e.g. sublethal levels of dissolved oxygen, ammonia and noxious gases). These changes allowed certain organisms to thrive, yet inhibited others, resulting in a shift in population composition. Shrimps, for example, are unable to tolerate low dissolved oxygen and poor water quality conditions. Loss of biodiversity is caused partly by the destruction of mangroves for charcoal making and conversion to fishponds, industrial sites and human settlements. The records of the Department of Environment and Natural Resources (DENR) show that mangrove areas in Pangasinan used to be 9.9 km^2 but decreased to 4 km^2 in 2000 (MSI, 2002). A large proportion of the 5.9 km^2 lost was in Dagupan.

Padilla *et al.* (1997) classified sources of pollution in Lingayen Gulf as domestic, agricultural and fishery, hog production, aquaculture, manufacturing (e.g. gin bottling, vegetable oil refining, soft drink bottling, galvanized iron sheet, fruit and vegetable processing, gas retailing, electric power generation) and mining. Dagupan receives effluents and industrial by-products from neighbouring towns (e.g. Calasiao) in the form of organic matter/residues. This has resulted in frequent incidents of fish kills in the part of the river that stretches upstream (near the boundary of Calasiao). Mine tailings (e.g. mercury, cadmium, lead) from the provinces of Benguet and Cordillera Autonomic Regions have been transported to Lingayen Gulf through Dagupan via the Agno River since the 1950s. From 1986 to 1995, of the average annual mine wastes of 5.26 million dry metric tonnes (DMT), 4.0 million DMT (or 75%) were used as backfill or for road construction (Padilla *et al.*, 1997).

Modern day commerce endorses the use of plastic products, mainly for packaging purposes. But, plastics create more harm than good when it comes to river management. Being non-biodegradable, they easily clog waterways, drainage systems and even fishpen nets, thus obstructing water exchange, which eventually leads to flooding. When plastics settle on the riverbed, they can create an anoxic bottom condition that generates harmful gases (e.g. hydrogen sulfide and methane) detrimental to aquatic organisms.

The physical structures found in the river also obstruct water circulation. The most important structures are the 95.2 ha of fishpens, occupying about 17.7% of the total river area. In the preferred sections of the river where fish farmers compete for valuable space, fishpens occupy 50–70% of the waterways. Major fish traps occupy only 15.1 ha or 2.8% of the river. Although oyster beds, illegal houses along the riverbank, old abandoned boats and reclaimed intertidal areas for land development and fishponds use much smaller areas compared to fishpens and fish traps, their impacts on the environment can be equally significant if located in hydrographically sensitive areas such as along narrow and shallow tributaries. The reduced tidal water movement can diminish the river's natural process of self-cleaning, and when organic nutrient loads are high, restricted flushing rates can be expected to lead to eutrophication. The rapidly deteriorating water quality, reaching the anoxic state with an increasing level of toxic metabolites (e.g. ammonia, nitrite, hydrogen sulfide and methane), threatens the survival of aquatic organisms and human health.

In pond culture, reduced tidal water exchange may lower the carrying capacity and increase pondwater salinities during the summer months. With slower water currents, siltation often becomes a serious problem in rivers. Soil particles and suspended solids, which should have been flushed into the sea during low tides, become deposited in the lower reaches of the water body. This has been a major problem in Dagupan, where many waterways have become shallower by as much as 1–2 m. The impact of siltation was evident along the river delta where the width in 2002 was at least 50% narrower compared to that in 1996 (Fig. 3.1).

The effect of the considerably reduced river mouth on fisheries production is not known. For a city situated in the Agno River basin, a constricted river mouth and a shallow riverbed cause flooding. The annual flood waters from upstream have affected the low-lying areas of Dagupan. To address the problems of siltation and flooding, dredging the delta along the shallow sections of the river may be necessary.

River-based capture fisheries

Although a variety of fishing gears have been used in Dagupan (e.g. hook and line, gillnet, cast net, push net, lift net, beach seine, fyke nets, baby trawls), gillnet and baby trawl are the most dominant (Calud *et al*., 1989). In 2000–2001, the total number of gillnets and baby trawls was estimated at 388 and 184, respectively (Fisheries Resource Management Project *et al*., 2002). Fish traps such as fyke nets and lift nets are common inside the rivers.

The records of the City Agriculture Office (CAO) showed that the total number of fishers declined from 1190 to 1120 between 1985 and 2001. The 1120 fishers contributed to the annual fisheries production of 1161 t, at an average catch rate of 1 t/fisher/year, or 2.8 kg/fisher/day. Assuming that the CPUE in Lingayen

(a) (b)

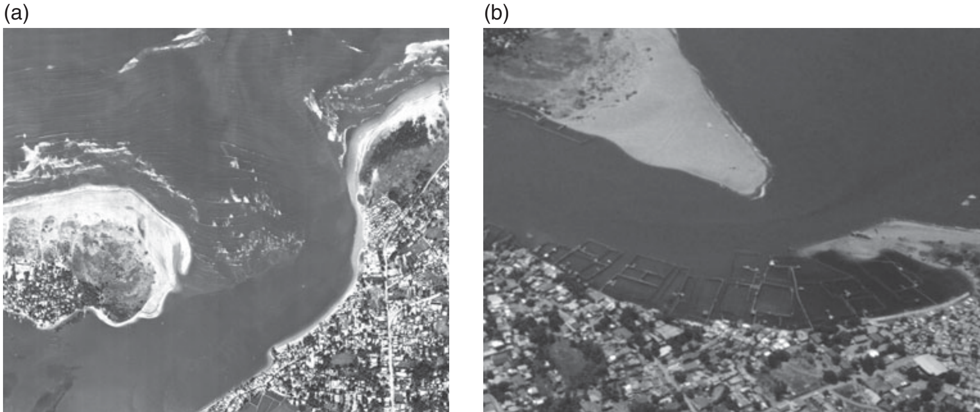

Fig. 3.1. Comparison of the mouth of the Dagupan river system 1996 (left) and 2002 (right).

Gulf has remained constant at 1 kg/fisher/day based on the study of MacManus and Chua (cited in Fisheries Resource Management Project *et al.*, 2002), the catch rate reported by CAO is nearly three times higher. To validate this and establish more baseline information on the socio-economic status of the fishers, key informants (*n* = 34) were interviewed and aerial photographs were analysed. Survey results showed that in 1999 and 2001, major fish traps accounted for 87.8% of the total fish catch. Changes in the use and yield of major fish traps from 1996 to 2002 were estimated from the aerial photographs taken by Certeza Surveying and Aerophoto Systems, Inc, and this study, respectively.

Out of the 1481 major fish traps counted in 1996, 1197 were fyke nets and 284 were lift nets. Assuming that the average fish catch in 1996 was 30% higher than in 2002, the total fish catch from major fish traps was estimated at 721 t. And should they account for 85% of the total catch in the rivers (including gillnet, hook and line, etc.), the total fish catch from river-based capture fisheries in 1996 is estimated at 849 t. The aerial photographs taken in March 2002 estimated that 588 units of fyke nets and lift nets occupied 15% of the river area, yielding a total annual production of 216 t. Assuming they account for 85% of the total catch in the rivers, the total annual yield of river-based city fisheries is about 254 t. Also, it was estimated that about 671 fishers were involved in river capture fisheries, giving a CPUE of 0.4 t/fisher/year, or 1.1 kg/fisher/day. Based on the data, capture fisheries production in the rivers of Dagupan dropped by as much as 70% by volume, from 849 t to 254 t. The number of major fish traps also decreased by about 893 units, or 60%. The average size of fyke nets also decreased from 342 m^2 to 315 m^2. All these changes could have been a direct result of a change in the quantity and quality of fish caught in the rivers, or could have been caused by space limitations resulting from fishpen development.

Milkfish farming in brackishwater ponds

The extensive culture of milkfish in brackishwater fishponds using natural food has been practised for over a century in Dagupan. It involves pond soil management, predator/competitor control, use of organic and inorganic fertilizers and transfer of fish stocks from one pond to another as natural food becomes depleted. Because of the relatively low salinity in Dagupan, the traditional practice of growing milkfish relies heavily on the use of filamentous algae, or *lumot*, as the primary natural food. Although the use of *lumot* in extensive culture is a simple and cost-effective technology, its productivity is low, limiting stocking densities to about 2000 pcs/ha only and production to 600–1000 kg/ha/crop.

Fishpond culture in Dagupan underwent significant changes in the late 1980s with the introduction of feeds and feeding technology. Culture system practices were also reclassified into 'extensive' and 'semi-intensive'. Initially, as stocking was doubled from 2000–3000 pcs/ha to 4000–5000 pcs/ha, feeding was done during the last 4–6 weeks only of the culture, when natural food was no longer available. The increase in stocking density (beyond 7000 pcs/ha) necessitated the use of artificial feeds throughout the culture period. Feeding resulted in higher production levels because it yielded higher stocking densities, bigger harvest sizes and uninterrupted crop cycles all year round. Interviews with milkfish farmers revealed that the average stocking density was 7879 pcs/ha, with a production of 6580 kg/year from 2.9 crop cycles. In 2002, the fishpond industry of Dagupan was believed to have used close to 9000 t of feeds annually, or an average of 23 kg feeds/ha/day. When nearing harvest, the actual consumption is around 56–68 kg feeds/ha/day. Based on studies, 20–30 kg/feed load/day is the maximum limit for a brackishwater pond without a life support system to ensure that the water quality is within the desirable levels (N. Sumagaysay-Chavoso, 2002, personal communication). Beyond this level, dissolved oxygen is depleted and toxic nitrogenous wastes and hydrogen sulfide are generated. In order to remedy this problem, fish farmers should reduce fish stocking densities or adopt the use of aerators. Fishponds provided with adequate aeration allow some degree of waste processing, thus reducing pollutant loads.

It was estimated from the 2001 data of the city that the total fishpond area was about 1051 ha. Juliano (1985) reported that compared to the other provinces in the country, Pangasinan had the most small-sized farms, i.e. 89% of fish farms were between < 1 and 5 ha. This suggested that milkfish farms in Pangasinan were much older since, through the division of inheritance, farms were partitioned to smaller sizes one generation after another. There are more small-sized farms (< 1–5 ha) in this study (i.e. 94%) compared to the findings of Juliano (1985). The average pond depth is 1.3 m, making brackishwater ponds in Dagupan some of the deepest in the country. This would indicate that in the past, many fishponds were 'reclaimed' from the intertidal zone of the river, considering the relatively small sizes of the dykes. The production cost estimates (here estimated in Philippine pesos, or PHP) of milkfish pond operation are higher in Dagupan (PHP55/kg) than in Negros Occidental (PHP45–49/kg), despite higher stocking densities (20,000–50,000 pcs/ha), bigger harvest size (400 g) and the use of life support systems (e.g. pumping and aeration) in the latter. The production inefficiency of Dagupan ponds can be attributed to several factors: (i) *feed expense* – for a harvest size of 3–4 pcs/kg, the feed conversion ratio (FCR) is as high as 2.05, which may be because of poor water quality; (ii) *cost of fingerlings* – farmers in Pangasinan pay 20% more than in other production centres because of higher demand than supply; and (iii) *labour cost* – the ratio of workers to farm area is high (1.2 workers/ha) compared to Negros Occidental (0.5:1).

Milkfish farming in fishpens and cages

In the mid-1990s, when fishing was no longer attractive, the small-scale fishers of Dagupan engaged in fishpen culture operations, as caretakers. Total fish production from fishpens alone increased from less than 1 t to 15,000 t in 2002, surpassing the production of brackishwater fishponds by nearly 400%. The 95-ha fishpens also provided a livelihood to 3400 fish farmers, with an average income of PHP2463/fisher/month. In comparison, fishers who remained reliant on fishing earned less than PHP1500/month.

From a production of less than 3000 t a decade ago, milkfish production in Dagupan increased to 19,000 t. At current wholesale prices, this amounts to a growth of PHP100 million annually. In 2002, Dagupan was producing about 50 t/day of milkfish from pen and cage culture. Although fishpen culture brought economic prosperity to Dagupan, years of unregulated development and lack of sound culture technologies compromised the state of the environment, particularly the river system (Fig. 3.2). Problems such as fish kills, slow fish growth and diseases were prevalent in both fishpen and fishpond culture. Also, all fishpen operations prior to 2003 were illegal.

Because of the lack of experience of the local government managing the fishpen industry, a legal framework for development and expansion was never adopted. In the absence of formal registration, the data available on fishpen/cage areas and production were

Fig. 3.2. Dagupan river congested with fishpens and cages.

unreliable. For the present study, the very limited baseline information available was supplemented with interviews with key fishpen farmers (*n* = 44) from eight barangays (villages) and local officials and aerial photograph documentation. Results showed that about 1484 fishpen units occupied the 95.2 ha river, and the culture practices are summarized in Table 3.1. The annual milkfish production is estimated at 16,043.5 t/year, given the total number of fishpen units, average production of 11.4 t/pen unit/year and assuming that 5% of all fishpens is inactive at any one time because of repairs. At a wholesale value of PHP65/kg, the milkfish pen industry generates an income of over a billion pesos.

Compared to other farming centres in the country, profit sharing is the most common compensation scheme in Dagupan. Of the 44 farms surveyed, 91% entered into profit sharing with an operator/financier, 6.8% adopted a partnership arrangement (normally for family-owned farms) and only 2.3% was based on a fixed salary scheme. Typically, profit sharing starts with a financier (a capitalist who is not necessarily a resident of Dagupan) and an operator who has access to the fishers interested in converting their 'ancestral' fishing areas into aquaculture. Once a business agreement is settled, the operator becomes the supervisor of the project and the fisher becomes the caretaker who provides the day-to-day labour. An operator handles several profit-sharing ventures for the financier, and a financier may have several operators. For his labour and the use of his ancestral waters, a caretaker receives between 40 and 60% of the gross sales, whereas the operator receives a share of the balance. Based on the survey, the average share of the caretaker(s) is 52.3%. Depending on the size, a fishpen may have about one to five caretakers.

The production cost of milkfish consists of fry, feed, pen depreciation, harvest cost and miscellaneous expenses. Of these, feed accounts for the greatest expense at 70%, followed by the cost of fry at 23%. In the absence of labour cost, which is an outright expense, the cost of producing milkfish in Dagupan is PHP50.33/kg. This is not a break-even cost, as the caretaker still has to be compensated for his labour. With known production costs, the gross profit from pen culture is computed at PHP64,979.8/cropping. The average earning of a caretaker is estimated at PHP2462/month. In comparison, fishpen caretakers in the neighbouring municipality of Bolinao receive 6% of the sale after deducting the feed cost (PHP39–42/kg), harvesting and transporting cost (PHP5–6/kg) and marketing commission (5%). On top of this, they also receive a monthly allowance of PHP2000. Thus, fishpen caretakers in Dagupan may be earning less than half that received by their counterparts in Bolinao. This can be attributed to bigger pen sizes in Bolinao (the standard compartment size is 4000 m^2) and a higher net profit/kg of bigger-sized fish.

At a production cost of PHP50.33/kg, the operating capital needed to produce 5690.9 kg is PHP286,423. With good credit standing, a financier can obtain at least a 60-day credit term from feed suppliers to reduce actual cash

Table 3.1. Summary of fishpen culture practices in Dagupan (*n* = 44).

Production aspect	Average figure
Fishpen area	641.6 m^2
Fishpen depth	3.48 m
Fishpen volume	1,998.8 m^3
Stocking density (average dry and wet season)	9 pcs/m^3
Stocking density/pen	17,960 pcs
Survival rate	95%
Harvest size	333 g
Harvest biomass/crop	5,690.9 kg
Crops/year	2
Harvest biomass/year	11,381.8 kg
Harvest biomass/m^3	3.0 kg

outlay to only PHP29.1/kg. Thus, a financier would need to invest only PHP165,605.2 in operating costs to produce 5690.9 kg of milkfish. A financier can make PHP30,995.4/cropping at an average profit share of 47.7%. This amounts to an 18.7% return on the investment for a 6-month cropping period. Some financiers and operators may have profited also from a feed dealership or volume discount scheme provided by the feed distributors and manufacturers. For example, a PHP1/kg discount or rebate on feed would provide the financier with an additional income of PHP13,430.5/cropping (5690.9 kg milkfish × FCR of 2.36 × rebate of PHP1/kg feed). Several financiers are also fingerling traders and fish traders and can generate an additional income of PHP5–6.5/kg of milkfish.

Discussion and Recommendations

This study has applied the available technical information and the authors' years of experience in aquaculture and environmental research to formulate recommendations.

Zoning scheme for the river system

Proper zoning is a crucial component of an economically, socially and environmentally sound plan for management and development because of the multiple uses of Dagupan's rivers. When establishing a zoning plan, it is important to understand several parameters including, but not limited to, the land use plan of the city and adjacent municipalities, the river's hydrography, aquatic ecology and the nature of land ownership along the riverbank. This will allow planners to utilize resources efficiently for the long-term interest of the city and its constituents. However, this is not a priority activity for many local government officials in the country. In the case of Dagupan, very little basic information on river water quality, water depth, current, salinity, natural food productivity and levels of pollutants that directly affect the productivity and profitability of fish farming has been documented.

The aerial photographs taken on 21 March 2002 (this study) and in 1996 by Certeza Surveying and Aerophoto Systems, Inc, provided key geographical information in establishing the zoning plan for the river. A strategy was recommended that divided the river system into ten geographically distinct zones (Zones 1–10), which were convenient and practical to manage (independent of barangay-based boundaries) (Fig. 3.3).

The main consideration in establishing these multiple zones is their suitability for monitoring and evaluating environmental impacts. With ten smaller management areas, it is possible to establish the carrying capacity of the river system relative to each zone. This will also allow optimum use of the water resources for aquaculture with least impact on the environment.

The main river, which is contiguous with the municipality of Binmaley, is divided into four smaller zones (i.e. Zones 1, 5, 6 and 7), whereas Zones 2, 3, 4 and 8 are physically distinct river branches occupying about 200 ha of the river area. Zones 9 and 10 consist largely of upstream secondary rivers and Zone 10 is a common boundary with the adjacent municipalities of Mangaldan and San Fabian. The decreasing salinity as the river goes upstream impacts aquaculture activities and fish capture practices directly. All zones are intended to have their own zone-specific ordinance for efficient and sustainable management. The general location and approximate area of each zone are presented in Table 3.2.

Navigational lanes and buffer zones

These zones are the locations of priority uses of the river traversing all ten zones. These can be identified readily through placement of heavy duty marking buoys or permanent stakes. Navigational lanes (NL) are intended to provide adequate width and depth for the efficient passage and access of watercraft and their cargo; buffer zones (BZ) are unobstructed spaces along the riverbank that serve multiple functions or uses, including fish foraging areas, land access, fishpond security zones and mangrove reforestation. No form of aquaculture or

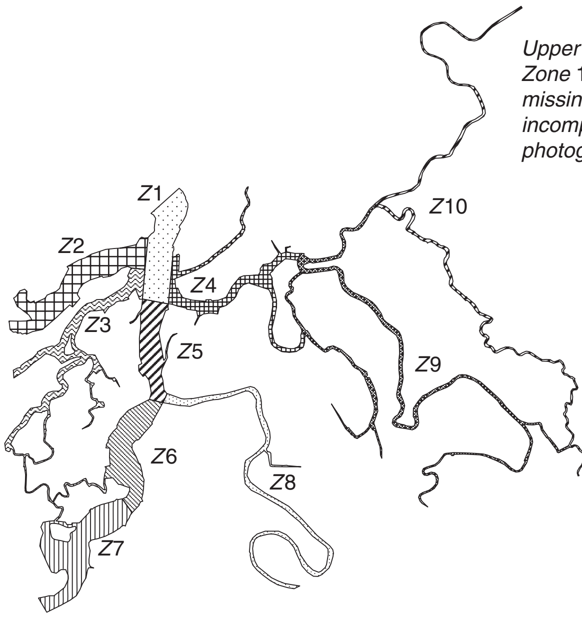

Fig. 3.3. Proposed river zoning.

fixed fishing structures should be allowed in these areas.

By convention, navigational lanes are best situated along the middle of the river. This, however, is not always practical since deeper portions that are suitable for navigation may meander from left to right along the breadth of the river. In areas where the village tends to be located on one side of the riverbank (e.g. Salapingao), the transport of commuters and cargo will be more convenient if the navigational lane passes alongside the settlement. The setting up of navigational lanes needs to be planned carefully, similar to that of road networks, with consideration to future housing and urban development.

Priority use zones

So as to standardize the NL and BZ, four types of 'standardized priority use zones' based on the width of the river and the extent of navigational traffic were recommended (Table 3.3). Zones 1 and 5, which serve as a common waterway for all zones to Lingayen Gulf, are heavily used for navigation, both by municipal and commercial vessels. These zones should have the widest NL (60 m) and BZ (15 m) on both sides. A narrower NL (30 m) and BZ (10 m) may be allocated for Zones 2, 6 and 7, since they have moderate navigational traffic and the widest portions of the river. Zone 8, although relatively narrow, may have a 30 m NL and 10 m BZ, being the busiest passage for commuters and cargo going to and from the Magsaysay area (main port). A 10 m NL and 5 m BZ is adequate for Zones 3 and 4 to provide access to fishponds and fishing communities upstream. The narrowest sections of the river are Zones 9 and 10 – a minimum of 5 m each for NL and BZ is recommended.

Regulated zone (Zone 1)

Zone 1 is classified as a regulated zone. Since this zone is connected directly to Lingayen Gulf, it is very important in maintaining the health of the river system of Dagupan and neighbouring municipalities. Like a gate, the river mouth controls the inflow and outflow of the water. The existence of physical barriers in this area can potentially impact water exchange rates and the carrying capacity of the river. The establishment of aquaculture and fishing structures should be strictly limited to not more than 5% of the area.

Table 3.2. General location and estimated area of the recommended ten river zones.

Zone	Code	Barangays covered	Approximate area	
			Hectares	Total area (%)
Zone 1	Z1	Pugaro, Bonoan Gueset	47.3	8.9
Zone 2	Z2	Pugaro, Salapingao	56.9	10.4
Zone 3	Z3	Salapingao, Lomboy, Carael, Calmay	42.1	8.0
Zone 4	Z4	Bonoan Gueset, Pantal, Bonoan Boquig, Tambac	46.0	8.8
Zone 5	Z5	Calmay, Pantal	36.2	6.9
Zone 6	Z6	Calmay, Poblacion Oeste, Tapuac	49.2	9.3
Zone 7	Z7	Carael, Lucao, Tapuac, Calnmay	69.7	13.0
Zone 8	Z8	Pantal, Poblacion Oeste, Brgy. I–III, Pogo Chico, Herero, Pogo Grande, Bacayao Norte, Lasip Grande, Bacayao Sur, Lasip Chico	41.7	7.8
Zone 9	Z9	Pantal, Tambac, Mamalingling, Bolosan, Mangin, Salisay, Bonoan Boquig	84.9	15.5
Zone 10	Z10	Salisay, Bolosan, Mamalingling, Bonoan Boquig, Bonoan Binloc	62.5	11.4
Total			536.7	100.0

Table 3.3. Recommended navigational lane and buffer zone for the ten river zones.

Type of priority use zone	Navigational lane width (m)	Minimum buffer zone width[a] (m)	Navigational lane + buffer zone (m)	River zones[b]
Type I	60	15	75	1, 5
Type II	30	10	40	2, 6, 7, 8
Type III	10	5	15	3, 4
Type IV	5	5	10	9, 10

[a]Total for both sides, based on low tide; [b]for narrow sections in a river zone, a Type III or Type IV priority use zone shall apply.

Being predominantly marine and relatively deep, Zone 1 is ideal for cage farming of siganids (*Sigannus* spp.), scat (*Scatphagus argus*), snappers (*Lutjanus* spp.) and groupers (*Ephinephelus* spp.). It is recommended that the limited use of this area for aquaculture be prioritized for the culture of high-valued species to ensure some variety in the farmed seafood products of Dagupan. Because the estuaries of Dagupan serve as nursing grounds for the marine fishes and crustaceans in Lingayen Gulf, the establishment of fish traps in this zone should be subjected to the appropriate regulations and close monitoring. Of particular concern is the catching of migrating juveniles and gravid fish.

Aquaculture and fishing priority zones (Zones 2–7)

Zones 2–7 are characterized as having considerable breadth, good water exchange, good salinity range (i.e. brackish water to marine), favourable water quality and low-to-moderate risk of flooding (Table 3.4). These zones have an aggregate area of about 303 ha and account for 95% of all fishpens and cages in the river. With the city's thrust to improve the economic conditions of the fishers through sustainable aquaculture, these zones, which traditionally have been dominated by fish traps, are classified as aquaculture and fishing priority zones. It is recommended to set aside 70% and 30% of the total area in each zone for capture fishing and fish culture, respectively. Although fishpens and cages will occupy only 10% of each zone, the remaining 20% will serve as buffer spaces between fishpens and as fallowing areas in case there is a need to adopt further management strategies in the future. Zones 4–7 are suitable for milkfish, while Zones 2 and 3 are traditionally preferred for siganid and grouper culture.

Of the 70% of the area allotted for capture fishing, a maximum of 10% (or 30.3 ha) is allocated for fish traps and 10% for oyster beds. This leaves 50% of the river's area free for navigation, buffer areas and other uses. Based on the 1996 aerial photographs, 7.3 ha (2.4%) of Zones 2–7 were occupied by fishpens and cages and 3.8 ha (1.25%) were used as oyster beds.

Non-fishery zone (Zone 8)

The most polluted section of the river is Zone 8, which stretches from Poblacion Oeste up to the boundary of Calasiao and directly receives much of the untreated domestic and industrial wastes. Based on previous surveys, Zone 8 is characterized by having the lowest dissolved oxygen levels and the highest faecal coliform counts compared to other parts of the river. It is classified as a non-fishery zone for river-based aquaculture and small-scale fishing because of the risk it poses to aquatic organisms. Unless appropriate pollution measures are put in place, consumption of fish products from this river area poses a health risk. It is strongly advised that this zone be closed to culture and capture activities for a period of at least 2 years, or until the water quality reaches the acceptable levels set by the Fisheries Management Section of the City Agriculture Office. Although the extent to which pollution in this zone affects fishponds is unknown, *Salmonella* spp. are most likely to be found in the waters, especially during the rainy season when the salinity is low. It is further suggested that construction of fishponds in this zone be prohibited because of residential and industrial developments.

Fishpond priority zones (Zones 9 and 10)

Although the zoning plan appears to be directed at river-based fisheries, it is equally applicable to pond-based aquaculture since fishpond productivity is affected ultimately by the water quality conditions in the zone where

Table 3.4. General characteristics of the recommended river zones.

Zone	Tidal water exchange	Water quality	Salinity range	Security from flooding
Z1	**OOOOO**	**OOOOO**	**OOOOO**	**OOOOO**
Z2	**OOOOO**	**OOOO**	**OOOO**	**OOOOO**
Z3	**OOOO**	**OOO**	**OOOO**	**OOOOO**
Z4	**OOOO**	**OOO**	**OOOO**	**OOOO**
Z5	**OOOO**	**OOO**	**OOO**	**OOOO**
Z6	**OOO**	**OOO**	**OOO**	**OOO**
Z7	**OOO**	**OOO**	**OO**	**OOO**
Z8	**OO**	**O**	**O**	**OO**
Z9	**OO**	**OO**	**O**	**O**
Z10	**OO**	**OO**	**O**	**O**

OOOOO, excellent; **OOOO**, good; **OOO**, moderate; **OO**, poor; **O**, very poor.

water is drawn. Similarly, fishpond effluents have a direct impact on the environment into which fishpond water is released. It is in the best interest of the city to classify the fishponds of Dagupan under the same hydrographic divisions in the proposed ten zones.

Zones 9 and 10 consist of a network of long, shallow and narrow winding rivers with poor flushing during the summer months and low salinity and occasional flooding during the rainy season. Considering the small size of these rivers and the extent of fishpond areas dependent on water exchange, it is important that free tidal water exchange is allowed in these zones. Ordinances intended to promote progressive pond culture practices and preserve the traditional *B. bangus* farming system should be formulated. Fishpens and cages should not be permitted in these zones and fish trap operations should be limited to operating only during the rainy season and in no more than 10% of the area.

Although Zones 9 and 10 have very similar characteristics, Zone 10 has been created separately because this stretch of river serves as the common boundary of Dagupan with the municipalities of Mangaldan and San Fabian. Thus, zone-specific fishery regulations may need to be adopted in Zone 10 to harmonize resource management with the neighbouring municipalities.

Standardization of fishpen design and layout

The goal of the city government is to raise the standard of living of fishers engaged in aquaculture. An earnings level of PHP135/day, which is about the minimum wage for Dagupan, should ultimately be the target minimum income level per caretaker. This amounts to PHP24,638/cropping or PHP4106/month at 6 months/cropping. This study recommends a fishpen size of 300 m^2 (10 m × 30 m) as the optimum compromise for the minimum pen size and the maximum number of farmers. At 300 m^2, a farmer should be able to attain the minimum wage-earning capacity with the appropriate culture technology, financing and marketing support. This recommended fishpen size was half the average pen area during the field survey, but 50% bigger than the maximum area of 200 m^2 recommended for Dagupan (Sector 2) by the Fisheries Resource Management Project *et al.* (2002). Assuming that fish farmers continue to rely on financiers and operators, and that the target harvest size is increased to 400 g for the export market, a caretaker will earn PHP4123/month or P137.4/day at 50% profit share.

Prior to the distribution of fishpen plots, it is important to lay out the navigational lane first. The navigational lane should be as straight as possible with the least number of turns to allow the orderly arrangement of fishpens (Fig. 3.4).

The most practical way of laying out the standardized fishpens in a zone is to arrange them in rows, with the long side (i.e. 30 m) parallel to the direction of the water flow. This orientation is important to ensure that the fish have ample time and space to consume broadcasted feed (especially of the floating type) before being carried away by the water current. A narrow width of 10 m is also desirable as a precaution during the rainy season, when flood waters from upstream may cause severe damage to pens. For aesthetic reasons, the rows should be perpendicular to the navigational lane.

A 10 m gap between fishpens in a row is recommended as unobstructed space for tidal water flow. Being identical to the width of the cage, this simplifies the setting up of boundary markers and is convenient for routine verification. A distance of 50 m is recommended; this is farther than the 25 m recommended by the Fisheries Resource Management Project *et al.* (2002), but closer than the 200 m distance indicated in the Fisheries Administrative Order No 214 in the Code of Practice for Aquaculture.

In terms of investment efficiency, bigger fishpens are always cheaper to construct on a per square metre basis because the area increases exponentially with increase in size. Other important advantages of bigger fishpens include efficiency in the use of labour and feed (i.e. less chance of feed ending up outside the fishpen), ease in management and monitoring and is environmentally acceptable since fewer materials are used per unit area (physical obstruction to water flow is reduced, resulting in better water flow through pens and decreased siltation in the river). To take advantage of the economies of scale, a strategy that will retain the individuality of small-scale fish farmers yet improve their cost efficiency through clustering is recommended. The idea is that a third farmer could apply for the

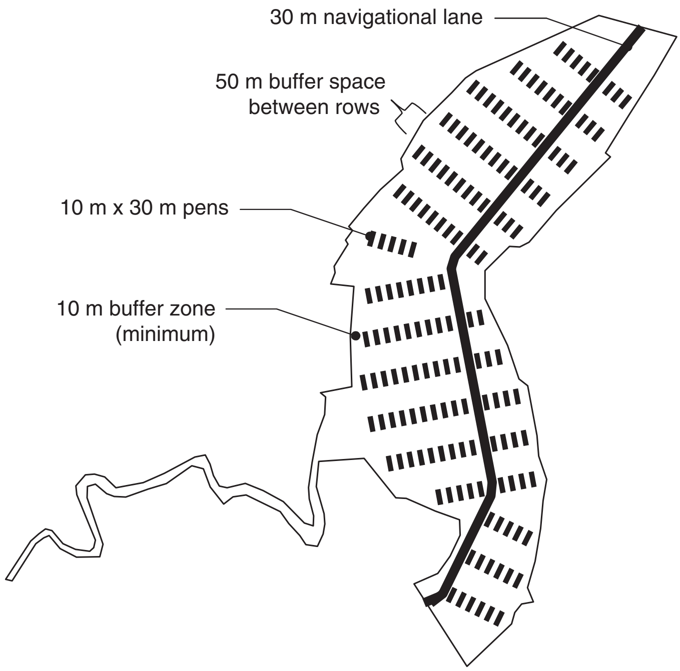

Fig. 3.4. Idealized layout of fishpens for Zone 6 (10% of river area).

buffer space of 10 m × 30 m between two adjacent fishpens. With three adjacent fishpens, it would now be possible to cluster operations into a single 30 m × 30 m compartment with a total area of 900 m^2 (Fig. 3.5). Compared to the average fishpen size of 641.6 m^2 in Dagupan, the clustered pen is 40.3% larger. Through clustering, labour and construction costs are reduced by 33% and 50%, respectively. Under a clustered operation, permit application and renewal should still remain on an individual basis.

Lease terms and fees

Aquaculture Lease Agreement (ALA)

An Aquaculture Lease Agreement (ALA) is recommended to be the legal basis of a time-bounded contract between the lessee and the local government. Initially, a maximum area of 10% of Zones 2–7 shall be identified for the ALA and awarded exclusively to local residents based on the priority guidelines set by the local government. The ALA shall indicate the exact location of a farm plot according to the approved zoning plan. Preferably, the contract should be for a period of 3 years and may be renewed. The 3-year period is sufficient for lessees to recover their investments and gain profit. Depending on the outcome of the management and monitoring of the carrying capacity of the river systems, the number of ALAs may increase or decrease on a per zone basis, as deemed appropriate.

Recommendation on the ALA fee

Given the standard ALA area of 300 m^2, a harvest biomass of 3192 kg should be able to

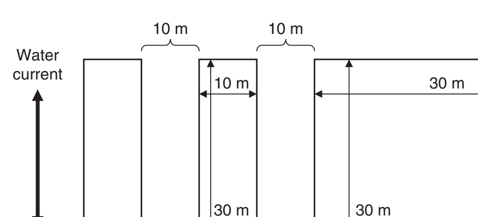

Fig. 3.5. Pen layout with a standard fishpen (10 m × 30 m) and with a clustered fishpen (30 m × 30 m).

generate a gross income of PHP49,476/crop, or PHP98,952/year, assuming a net profit of only PHP15.5/kg. This amounts to a yield of PHP329.8/m^2 pen area/year. A standard fee of PHP20/m^2/year regardless of the depth of the area is recommended for fishpens and fish cages, which is equivalent to PHP6000/year for a standard 300 m^2 ALA. An ALA fee of PHP20/m^2/year is equivalent to only 6.1% of a gross profit of PHP329.8/m^2/year.

As for a clustered pen, the fee for three units of ALA (to be paid individually) is PHP18,000. In Bolinao, the fee for operating either a pen (40 m × 40 m) or a cage (maximum of 18 m × 18 m) is set at PHP10,000/year. This is equivalent to PHP30.1 m^2/year and PHP2.5 m^2/year for cage and pen, respectively. In Taal Lake, water use is charged at PHP750/100 m^2 cage area or PHP7.50/m^2.

In long-established inland fishing communities such as Dagupan, traditional fishing rights have evolved through the years whereby a family claims ownership of a particular section of the river to set up fish traps or oyster culture activities. These 'ownership' claims, like a real estate property, are sold, leased or traded, with transactions generally acknowledged by the fishing community. Although there is no legal basis for this type of arrangement since rivers are public domain, the practice remains common in Dagupan and may need to be considered in the issuance of the ALA.

Recommendation on the number of ALAs to be issued

Section 51 of the Philippine Fisheries Code of 1998 (Government of the Philippines, 1998) states 'that not over ten percent (10%) of the suitable water surface area of all lakes and rivers shall be allotted for aquaculture purposes like fishpens, fish cages and fish traps'. The total area occupied by fishpens and fish cages during this study was already 17.7% of the total area of 536.69 ha. Considering all the environmental problems, the issuance of ALAs should be limited to 1000 permits (to be issued in batches of 200s and 250s, preferably over a 1-year period). With a projected production of 6384 kg/year for a 300 m^2 ALA area (from 3192 kg/crop × 2 crops/year), 1000 ALAs should be able to generate a total yield of 6384 t milkfish/year. Through progressive aquaculture practices, use of high-quality feeds and proactive management of carrying capacity, the number of ALAs may be increased gradually to as much as 1600 permits. This will allow the production of about 10,000 t/year. At this level of expansion, and assuming half of the farms decide to cluster, this is estimated to consume approximately 10% of the entire river area. Whether the proposed number of permits is actually sustainable will depend on the results of an environmental monitoring programme.

Conclusions

In many coastal municipalities in the Philippines, rivers have been used mainly for fishing and small-scale aquaculture. Thus, this is becoming a source of conflict involving many stakeholders in the coastal waters and rivers. There is also considerable apprehension as to social benefits since aquaculture is often viewed as a private sector business using a public resource. However, aquaculture is an important industry in the Philippines and is the fastest growing source of fish protein. Although many local governments support aquaculture, they also recognize their weaknesses in planning for a sustainable aquaculture industry that is locally available and globally competitive.

This chapter presented the case of Dagupan City and focused on how technical knowledge could be used in decision making to improve the state of the aquatic environment. Behind Dagupan's one billion peso milkfish farming industry is a major environmental crisis that seriously threatens the sustainability of farming operations, health of the river ecosystem, economic viability of city fisheries and livelihoods of over 3400 residents. Clearly, should fisheries remain a key socioeconomic pillar of the city, the local government needs to regulate the aquaculture industry strictly and manage it proactively. Through sound and sustainable aquaculture technologies, monitoring of carrying capacity and political will, aquaculture can contribute considerably to income generation and livelihood development. However, any coastal activity or project without careful and proper planning is likely to fail.

Acknowledgements

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References

Bennett, J., Lawrence, P., Johnstone, R. and Shaw, R. (2005) Adaptive management and its role in managing Great Barrier Reef water quality. *Marine Pollution Bulletin* 51, 70–75.

Boyd, C.E. (2003) Guidelines for aquaculture effluent management at the farm-level. *Aquaculture* 226, 101–112.

Brody, S., Highfield, W., Arlikatti, S., Bierling, D.H. and Ismailova, R.M. (2004) Conflict on the coast: using geographic information systems to map potential environmental disputes in Matagorda Bay, Texas. *Environmental Management* 34(1), 11–25.

Calud, A., Rodriguez, G., Aruelo, R., Aguilar, G., Cinco, E., Armada, N. and Silvestre, G. (1989) Preliminary results of a study of the municipal fisheries in Lingayen Gulf. In: Silvestre, G., Miclat, E. and Thia-Eng, C. (eds) *Towards Sustainable Development of the Coastal Resources of Lingayen Gulf, Philippines, ICLARM Conference Proceedings No 17*. Philippine Council for Aquatic and Marine Research and Development and International Center for Living Aquatic Resources Management, Manila, pp. 3–29.

City of Agriculture Office (2002) Unpublished 1996 aerial photograph of Dagupan City, Philippines.

Feng, Y.Y., Hou, L.C., Ping, N.X., Ling, T.D. and Kyo, C.I. (2004) Development of mariculture and its impacts in Chinese coastal waters. *Reviews in Fish Biology and Fisheries* 14, 1–10.

Fisheries Resource Management Project, Bureau of Fisheries and Aquatic Resources, Asian Development Bank, Japan Bank for International Cooperation and Marine Environment and Resources Foundation Inc (2002) Lingayen Gulf RSA Terminal Report. Manila: Fisheries Resource Management Project (ADB Loan Nos 1562/1563-PHI and JBIC Loan No PH-P197). Manila, Philippines.

Government of the Philippines (1998) Republic Act 8550. The Philippine Fisheries Code of 1998, Manila.

Islam, M.S. (2005) Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. *Marine Pollution Bulletin* 50, 48–61.

Juliano, R. (1985) The biology of milkfish, *Chanos chanos* (Forskal) and ecology and dynamics of brackishwater ponds in the Philippines. PhD dissertation, Tokyo University of Fisheries, Tokyo.

MSI (2002) Lingayen Gulf Resource Stock Assessment Terminal Report. Submitted by the Marine Science Institute to the Fisheries Resource Management Project of the Bureau of Fisheries and Aquatic Resources (ADB Loan Nos 1562/1563-PHI and JBIC Loan No PH-P197), Manila.

Padilla, J.E., Castro, L.I., Morales, A.C. and Naz, C. (1997) Evaluation of Economy–Environment Interactions in the Lingayen Gulf Basin: A Partial Area-based Accounting Approach. Philippine Environmental and Natural Resources Accounting Project (ENRAP-Phase IV), Manila.

Read, P. and Fernandes, T. (2003) Management of environmental impacts of marine aquaculture in Europe. *Aquaculture* 226, 139–163.

Siar, S.V. (2003) Knowledge, gender, and resources in small-scale fishing: the case of Honda Bay, Palawan, Philippines. *Environmental Management* 31(5), 569–580.

Yap, L.G., Azanza, R.V. and Talaue-McManus, L. (2004) The community composition and production of phytoplankton in fishpens of Cape Bolinao, Pangasinan: a field study. *Marine Pollution Bulletin* 49, 819–832.

4 Evolution of Shrimp Aquaculture Systems in the Coastal Zones of Bangladesh and Vietnam: a Comparison

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Abstract

Based on on-farm surveys implemented in the Ganges Delta in Bangladesh and the Mekong Delta in Vietnam, the dynamics of shrimp aquaculture in salinity-influenced coastal areas were analysed. Qualitative data were collected through interviewing both individual and group farmers in 2005 and 2006, as well as key informants and value chain stakeholders, to obtain an overview of the dynamics of salinity-influenced aquaculture in these two deltas. The first phase of the coastal area's agroeconomic evolution is related to the policy and infrastructure in the course of agroeconomic transformation. A second phase is characterized by the spread of shrimp aquaculture (in successive levels of technology), causing these coastal zones to become areas of strategic export product generation. Different factors such as government policy, demography and international market demand drove this evolution in both deltas. In a third phase, the risk associated with shrimp farming because of shrimp virus outbreaks led farmers to diversify or intensify the aquaculture farming system. The evolution of shrimp farming systems in both deltas has been toward greater diversification of aquaculture technologies and is dependent on both natural environmental factors such as saltwater period duration and soil quality, technical factors such as access to drainage and socio-economic factors such as investment capacity and market demand. Comparing the coastal area of Bangladesh and the Mekong Delta in Vietnam, the key factors identified were land ownership, access to knowledge for the improvement of shrimp culture technology and diversification of aquaculture production. The alternating rice–shrimp system (i.e. rice in the rainy season, followed by shrimp in the dry season) and diversified brackishwater polyculture show more stable economic returns in comparison to extensive and intensive shrimp monoculture in both areas. In Bangladesh, water management infrastructure, access to information and the development of information networks were highlighted as key factors necessary for the improvement of brackishwater aquaculture. In Vietnam, the higher level of technology used in coastal aquaculture underlined the need for the development of better management practices to reduce the environmental burden and to evolve towards sustainable production systems.

Introduction

Coastal areas include flood plains, mangroves, marshes, swamps, tidal flats and many large and small rivers, canals and creeks. These areas act as a buffer zone between land and sea, with a seasonally affected and variable environment. Coastal areas are under constant change, following different driving forces such as demography, national and international market demands or government planning.

In the Vietnamese Mekong Delta, 1.7–2 million ha are affected annually by salt water, whereas about 1 million ha are affected along the coast of Bangladesh. The land use and colonization of the Mekong Delta and the Ganges Delta evolved differently during the 19th and 20th centuries: from wasteland to rice-based agriculture and subsequently to today's widespread adoption of shrimp farming. Since the last two decades of the 20th century, coastal areas have undergone major changes with the development of shrimp culture. The development of the shrimp industry has transformed the economy of the coastal areas dramatically, as well as the foreign exchange earnings of both Bangladesh and Vietnam. However, since the late 1980s, the spread of disease outbreaks in many of the producing countries in Asia has affected shrimp production and the survival of operations seriously, with a high turnover of ownership and a high risk for all stakeholders in the value chain. Hence, the question arises: what are the actual dynamics of aquaculture production systems in these areas and how do farmers cope with outbreaks of shrimp diseases and environmental changes such as saltwater intrusion?

Given the widespread adoption of shrimp farming in the coastal rice and non-rice cropping areas of South-east Asia in general, and in numerous river deltas in particular, the purpose of this study is to compare and contrast the developments in the Ganges and Mekong deltas. These two cases of salinity-influenced areas were studied to highlight the main factors that fuelled their dynamics and the evolution of human intervention, and to understand how farmers coped with various constraints (e.g. soil quality, variability in salinity, diseases, market forces, infrastructure investment, knowledge availability, access to capital and social conflict). The chapter presents an analysis of the evolution of aquaculture and agriculture production systems in salinity-influenced areas in each delta, and the different options for farmers to develop and evolve these production systems in such variable and diversified environments.

Study Sites and Methodology

Study sites

The climate in Bac Lieu Province located on the Ca Mau peninsula of the Mekong Delta is tropically monsoonal, with a distinct dry season from mid-November to April and a rainy season from May to mid-November. Acid sulfate soils characterize the western part of the province and occupy 60% of the area, mostly in the lowlands (Breemen and van Pons, 1978). In the eastern part, alluvial and saline soils are dominant (Ve, 1988). Bac Lieu Province is part of the saline protected area in the coastal area. A series of sluice gates along the main canals regulate saline intrusion in the dry season and create a gradient of salinity from the eastern to the western part of the province. The different survey sites were chosen in consideration of the duration of the freshwater period (more than 6 months, less than 6 months and no freshwater period) and soil quality (saline soil and acid sulfate soil).

In Bangladesh, Paikgacha Subdistrict is located in Khulna District, in the south-western coastal area of Bangladesh. Two main seasons divide the cropping calendar: a dry season from December to mid-March and a wet season from April to November. Salinity intrusion occurs from January to June, limiting the main season for shrimp farming to 5 or 6 months.

Qualitative semi-structured interviews were conducted with farmer groups on a farmer's personal situation, on household socioeconomics, farm management, production costs and yields, historical aspects, constraints and access to the means of production and to knowledge. The surveys were conducted over 3 weeks in each region between November 2005 and February 2006. We used a randomized survey of 95 shrimp farms in Vietnam (n = 74, Bac Lieu Province) and Bangladesh (n = 21, Khulna District, Paikgacha Subdistrict). The number of shrimp farms surveyed in Vietnam was higher because of the more diversified agroecological environments and the more diversified salinity-influenced aquaculture systems than in Bangladesh. In both study sites, part of the shrimp industry value chain was investigated by interviewing different stakeholders in the value chain, such as shrimp postlarvae nurseries, shrimp traders and middlemen, shrimp buyers, input suppliers and shop owners. The entire value chain was not investigated because of the absence of nursery and processing factories in the survey site in Paikgacha Subdistrict or the non-access to private hatcheries and processing factories in Bac Lieu Province. We focused only on stakeholders directly connected with producers. The participatory approach used in this study was related to that described by Bammann (2007), with key informant interviews and focus group discussions. This value chain analysis focused on the institutional arrangements that linked producers, input retailers and traders. The present study covers the value chain up to the production stage, excluding later steps such as processing and value-addition industries.

The economic net return of the farms was calculated by using the farm's gross return minus farm operating costs. The operating costs included the different inputs, shrimp 'seed' and labour. Investment costs included pond modification and the equipment required (lift pump, nets, feeding trays, etc.).

Coastal Area Development

From wasteland to rice culture

Development in both deltas underwent contrasting evolutionary steps, facilitated by different driving factors such as government policy or national and international market demand. Government policy, although following different respective frameworks, promoted the colonization of the land in the Mekong and Ganges deltas. In Bangladesh, the colonial government policy created an institutional basis for land clearance, peace, order and guaranteed ownership, which encouraged settlement in the 19th century (Richards and Flint, 1990). Whereas in Vietnam, the progression of settlements and the development of rice-based aquaculture followed the dredging of canal networks that were started under the Nguyen dynasty in the 19th century and were continued by the French administration (Catling, 1992; Biggs, 2004). The demand for goods and services by cities such as Calcutta (now called Kolkata) in the Gangetic delta or Saigon (now called Ho Chi Minh city) in South Vietnam developed a market for food grains, timber and fuelwood. From the subsistence agriculture of the first pioneers, deltas rapidly became an export product-generating area (Richards and Flint, 1990; Biggs, 2004). The development of agriculture was not spatially homogeneous in either of these regions. Previously unused marginal wasteland was available and farmers who wanted to develop rice-based agriculture sought the most suitable areas, protected against floods and saltwater intrusion (Russier and Brenier, 1911; Eaton, 1990). Population density and rice culture development was vastly different in the Mekong Delta in comparison to other areas of Vietnam. At the beginning of the 20th century, rice fields covered 60–80% of the total area in the eastern part of the delta in provinces not affected by saltwater intrusion, whereas they covered only 10% in the western part, namely in the Ca Mau (including actual Ca Mau, Kien Giang, Soc Trang and Bac Lieu Provinces) and Ha Tien Provinces, as these areas were affected by saline intrusion (Russier and Brenier, 1911). This dissimilarity of livelihood activity and corresponding population density was still present in the 1980s, with an average of 450 people/km^2 (or 0.22 ha/capita) across the whole delta, whereas Ca Mau and Kien Giang Provinces, under the influence of saline intrusion, had lower densities with less than 200 people/km^2 (or 0.5 ha/capita available land) (Xuan and Matsui, 1998).

In Bangladesh, the delimitation of a protected area for the Sundarbans forest had restricted the space available for colonization and new settlement since 1920 (Richards and Flint, 1990). With the closure of the Sundarbans settlement frontier, agricultural expansion could no longer rely on seemingly limitless wastelands to transform. From 1880 to 1980, the available land per capita dropped from 0.22 to 0.08 ha (Richards and Flint, 1990), equivalent to an increase in population density from 450 to 1250 people/km^2 for the total land area.

After 1940, the main policy of Bangladesh's central government was to increase rice production, even on marginal lands. A new process of agricultural intensification began because of demographic pressure and technical innovation with the introduction of high-yielding rice varieties (HYV) and irrigation (Pingali *et al.*, 1997). In the coastal areas, rice intensification was constrained by salinity intrusion during the dry season. The traditional farming system was a rainfed rice crop in the rainy season followed by a traditional brackishwater aquaculture crop in the dry season, in which wild fish juveniles and crustacean larvae were trapped in ponds and were reared without feeding. In Bangladesh, oil crops (mainly sesame) were also grown during the dry season. In both Bangladesh and Vietnam, the governments planned to increase rice culture to two crops per year by protecting rice land against saltwater intrusion and closing off parts of the delta. In Bangladesh, the coastal embankment project started in 1968, which created 123 polders to enhance crop agriculture productivity in the coastal zone by preventing saline intrusion (PDO-ICZMP, 2005). Between 1990 and 2000, the Vietnamese government planned and constructed new water control infrastructures (sluice gates, embankments) in the saline intrusion area in order to intensify rice cropping (Hoanh *et al.*, 2003). In the case of Bac Lieu Province, the salinity control infrastructure induced land use and livelihood change from 1994 until 2000 (Hossain *et al.*, 2006).

For both countries, the purpose of the infrastructure investments in these areas was to intensify rice culture in order to increase food security (notably rice). Central governments considered brackish water as a constraint and the improvement of traditional brackishwater aquaculture at that time was not regarded as an alternative for the development of the coastal area, although the expansion of the traditional shrimp farming practice under the farmers' own initiative continued. In Bangladesh, private investors from the cities also strongly influenced the development of shrimp aquaculture in coastal areas.

From rice culture to shrimp culture

The spread of shrimp farming occurred in Bangladesh in the early 1980s, followed later by the Mekong Delta in the late 1980s. The development of shrimp culture was driven by an attractive market price and high international demand. The supply of shrimp larvae was, at the beginning, supported mainly by wild catch carried out by coastal communities (mainly children and women) (PDO-ICZMP, 2003a). Hatchery technology for growing giant tiger shrimp (*Penaeus monodon*), which grew considerably larger than the wild species of shrimp, as well as specific feeds and other inputs became available. In a few years, shrimp culture developed exponentially. In Bangladesh, the area dedicated to shrimp farming spread from 51,812 ha in 1983–1984 (DoF, 1986) to 203,071 ha in 2003–2004 (DoF, 2005), with the number of shrimp farms reported by Deb (1998) and Nuruzzaman and Maniruzzaman (2003) increasing from 7578 to 40,000 from 1989 to 2003.

The shrimp culture area in the Mekong Delta grew from 89,605 ha in 1991 to 429,114 ha in 2003 and contributed to 83% of the total exported shrimp value of the country (Vo, 2003). From rice-oriented agriculture, the coastal area of the Mekong Delta became the largest area of saltwater aquaculture in Vietnam.

In these deltas, extensive shrimp farming and rice–shrimp systems were the most common practices. Hatchery reared *P. monodon* postlarvae progressively replaced the traditional system that was based on wild shrimp larvae of a variety of smaller species being trapped when filling ponds or caught with specific netting techniques. In the Mekong Delta, semi-intensive and intensive systems appeared, loaded with technology and financed by private investors (Table 4.1). These intensive monoculture systems remain controversial because of the level of investment and knowledge required. However, much of the growth in production can be attributed to area expansion rather than intensification. In the case of Bac Lieu Province, the shrimp farming area increased from 45,748 ha to 116,428 ha from 2000 to 2005 (source: Department of Agriculture and Rural Development of Bac Lieu), of which 9% accounted for semi-intensive and intensive shrimp farms. Extensive systems in shrimp monoculture, alternating with rice cropping, or integrated concurrent culture of shrimp in mangroves, were adaptations of the traditional systems, characterized by low-input technology, but also low yield. Farmers used fertilizers

Table 4.1. Characteristics of the different shrimp production systems in the Ganges and Mekong deltas before the spread of viral diseases.

Farming pattern	Monoculture			Alternate culture	Integrated culture[a]
System type	Extensive	Semi-intensive	Intensive	Rice–shrimp	Mangrove–shrimp
Pond size (ha)	1–40	1–2	< 1	1–5	1.1–16
Mean stocking rate (ind/m^2)	1–3	5–15	15–40	1–3	0.1–2.9
Input use	Lime, fertilizer	Feed pellets, water treatment	Feed pellets, water treatment	Lime, fertilizer	–
Mean yield (kg/ha)	200–300	100–2000	> 2000	200–300	146–686
Location	Mekong and Ganges	Mekong	Mekong	Mekong and Ganges	Mekong

[a]From Binh *et al.* (1997).

and limestone to improve plankton growth that served as natural food for shrimp and constituted the main portion of the shrimp's diet, supplemented with homemade feed and trash fish to improve the yield (Brennan *et al.*, 2000; Hossain *et al.*, 2004).

The rapid and high profits earned from shrimp farming resulted in a high demand for land in the salinity-affected area. Thus, in a short time period, the transformation of the land use pattern and wide diffusion of shrimp farming driven by an attractive market had several side effects. In Bangladesh, widespread land tenure conflicts appeared with the development of large extensive shrimp farms. Large-scale but absentee farmers coerced small farmers to lease their rice land to culture shrimp (Gupta, 1997; Alauddin and Tisdell, 1998; Karim and Stellwagen, 1998). Through land reform in Vietnam, farmers were issued a land certificate, but this did not permit the development of shrimp farms. Instead, shrimp farm settlement took place in the mangrove areas. The spread of shrimp culture induced a new surge of mangrove clearing in the Mekong Delta (Luttrell, 2006). The area of mangrove forest in the Mekong Delta declined from 117,745 ha in 1983 to 51,492 ha in 1995 (Hong and San, 1993; Phuong and Hai, 1998, in Johnston *et al.*, 2000). Integrated mangrove–shrimp farming systems were established in the form of state forestry–fishery enterprises to reduce deforestation. The status of the Sundarbans mangrove forest in the Ganges Delta protected the forest from massive clearing for shrimp farm settlement, so that integrated mangrove–shrimp farming systems were not developed (Hoq, 2006).

From an initial agricultural constraint to rice-based production, salinity became the enabling factor for shrimp production and the relatively prosperous development of these regions. The attractive business of shrimp culture induced further private investment and new settlement in the mangrove forest areas and on fallow lands (lowland, acid sulfate soil areas) where agriculture was not suitable. Coastal areas, previously the less developed areas in deltas with low rice yield and slow progress in technological development of salinity tolerant HYV, became the most productive areas in terms of income to farmers and revenue to the government, amounting to US$319 millions and US$199 millions for Vietnam and Bangladesh, respectively, in 2000 (FAO, 2003), because of shrimp farming.

Comparison of Different Production Systems

Since the middle of the 1990s, different viral disease outbreaks in shrimp occurred and spread around coastal areas throughout South-east

Asia, causing the shrimp culture business to suffer considerable losses (Flegel, 2006).

In the Mekong Delta, for the period of 1994–1999, only 20–30% of the farms were successful in shrimp farming (Vo, 2003). In the 1994/95 culture season, a disease outbreak in the southern province affected 85,000 ha of shrimp, equivalent to a loss of 294 billion Vietnamese Dong (VND) (MOFI, 1996).

In 1996, shrimp viruses affected 90% of the shrimp farms in the south-western coastal area of Bangladesh, reducing national shrimp production by 20% (Chowdhury and Muniruzzaman, 2003). In the 1997/98 culture season, the total amount of shrimp exported dropped from 25,742 t to 18,630 t after a white spot disease outbreak. Then in 1999–2000, shrimp exportation increased to 28,514 t after a year without severe disease outbreak (DoF, 2002). In 2001, shrimp production fell by 25% compared to the previous years because of white spot disease associated with other viral and bacterial pathogens (Alam *et al.*, 2007a).

Farmers developed different strategies to reduce the economic risk of virus outbreaks, dependent on several factors such as duration of the saltwater period, investment capacity and socio-economic factors (access to knowledge, access to markets or access to production resources such as land, equipment, inputs, etc.).

Stocking strategy

After several crop losses, farmers reduced the level of inputs and changed their shrimp stocking techniques to stocking earlier in the year (before the dry season) to benefit from lower prices of shrimp postlarvae (PL) for the stocking of ponds before the peak stocking period. In addition, instead of stocking every 3 months, farmers switched to a multiple stocking strategy (stocking every month), in which the stocking density varied from 1.5 to 3 PL/m^2, with an average yield of 242 kg/ha/season in Bangladesh and 172 kg/ha/season in the Mekong Delta. In Bangladesh, this evolution is specific to the large shrimp farms (> 6 ha) often run by entrepreneurial farm operators employing several seasonal workers.

Intensification strategy

An intensification strategy was adopted by farmers who specialized in aquaculture production. This involved a higher level of inputs, equipment and knowledge. However, semi-intensive and intensive shrimp farming depends on access to knowledge, to salt water and to investment capacity (Table 4.2). Intensive and semi-intensive shrimp farming require direct access to salt water and to drainage facilities. These techniques also require access to market for inputs and a high level of knowledge and competence on the side of the operators to manage the shrimp ponds successfully. Labour costs are higher for maintenance and guarding of ponds, and also require hired workers on a year-round basis. In addition, management, aeration and water quality monitoring require more equipment. In the Mekong Delta, 83% of the farmers interviewed using semi-intensive (6) and intensive techniques (6) claimed that intensification of their production was facilitated by the presence of a well-developed value chain, thus improving access to inputs and knowledge.

In the south-western coastal area of Bangladesh, intensification of shrimp production has not yet taken place on a large or even medium scale, with only a few farmers stocking postlarvae at a relatively high density (20 PL/m^2). Farmers' lack of access to loans, the lack of advanced technical knowledge, together with an underdeveloped value chain for access to inputs (shrimp feed, water treatment, etc.) act as a constraint on the sector's progress.

With the development of national and international fish markets, farmers tried to diversify their production with the monoculture of high-value fish in semi-intensive or intensive culture in the Mekong Delta. Elongated goby (*Pseudapocryptes elongatus*), sea bass (*Lates calcarifer*) and lately the 'marble goby', also named sand goby or marbled sleeper (*Oxyeleotris marmorata*), are being raised in homestead ponds (0.1–0.2 ha) at various densities (from 0.2 to 15 individuals/m^2) and fed with trash fish or commercial pellets. Recently, attractive prices have resulted in a surge towards the development of fish monocultures in partial replacement of shrimp culture. National market prices are around US$2.6/kg for sea bass and

Table 4.2. Characteristics of the evolution of shrimp farming from extensive over semi-intensive to intensive aquaculture systems in the Ganges and Mekong deltas (found in this survey, 2005/2006).

Item	Extensive shrimp (n = 16)	Semi-intensive shrimp (n = 8)	Intensive shrimp (n = 6)
Labour (man-day/ ha/year)	28–180 x = 73	170–291 x = 213	327–466 x = 402
Level of equipment required	Low	Moderate	High
Saline water duration required	6 months	6 months	6 months
Drainage infrastructure and direct access to water	Preferable	Needed	Essential
Pond area requirement (ha)	Medium to large (2–10 ha)	Small (1–2 ha)	Small (< 1 ha)
Direct access to input markets	Not necessary	Necessary	Essential
Stocking density (ind/m^2)	1.5–3.0 x = 2.1	5.0–15 x = 9.7	15–40 x = 28.3
Yield (kg/ha)	VN: 60–400 x = 172 (n = 10) BD: 10–380 x = 242 (n = 6)	VN: 200–2299 x = 1245 (n = 5) BD: 49–2067) x = 1058 (n = 2)	VN: 300–8000 x = 5460 (n = 5) BD: n.a.
Knowledge requirement	Low	Moderate to high	Very high
Location	Mekong and Ganges	Mekong and Ganges	Mekong

Values are range, x, mean; BD, Bangladesh; VN, Vietnam; n.a., not applicable. Yield range and mean were computed using results from farms without massive mortality due to disease outbreak.

US$3.0/kg for elongated goby, whereas in international markets accessed through export, the price of marble goby has reached US$23.3/kg. However, results were not satisfactory for the farmers because of a longer growth period for sea bass to reach market size (10 months) or high mortality for elongated goby. In the case of marble goby, the introduction of this culture technology in saline-affected areas is too recent to permit any conclusion. However, the emergence and rapid spread of such systems is representative of a dynamic and vibrant aquaculture production environment in which farmers are now seeking niche markets and experimenting with new techniques and species.

Diversification strategy

Diversification of the production system is defined here as the number of different kinds of enterprises on the farm, which include both agriculture (rice) and aquaculture products (shrimp, fish and mud crab). There are different options for diversification of aquaculture production (Table 4.3) in the form of either brackishwater polyculture or alternating rice–shrimp systems. The choice between these two main kinds of production system depends on the duration of freshwater availability during and after the rainy season.

When the freshwater period exceeds 6 months, farmers located on higher land with access to drainage can implement the alternating rice–shrimp system. The level of shrimp yield ranges between 73 kg/ha and 294 kg/ha, with a shorter shrimp culture period (only in the dry season) than in the extensive system. The next evolutionary step of this system is the integration of the aquaculture component during the rice crop in the form of a concurrent rice–fish system. Fish species such as Nile tilapia (*Oreochromis niloticus*), carps (various species) or crustaceans such as the giant freshwater prawn (*Macrobrachium rosenbergii*) stocked at

Table 4.3. Characteristics of evolution of shrimp farming from extensive shrimp farming to rice–fish–freshwater prawn/brackishwater shrimp culture in the Ganges and Mekong deltas (found in this survey, 2005/2006).

Rainy season / Dry season	Extensive shrimp (year-round) (*n* = 16)	Extensive shrimp and extensive mud crabs (year-round) (*n* = 26)	Extensive shrimp and extensive mud crabs and fish[a] (*n* = 10)	Rice / shrimp (*n* = 21)	Rice + aquaculture[b] / shrimp[c] (*n* = 8)
Labour (man-day/ ha/year)	28–180 *x* = 73	28–58 *x* = 43	28–60 *x* = 43	35–152 *x* = 98	35–152 *x* = 113
Level of equipment required	Low	Low	Low	Low	Low
Saline water duration required	6 months	6 months	6 months	Salinity < 4 ppt during 6 months	Salinity < 4 ppt during 6 months
Drainage infrastructure and direct access to water	Preferable	Preferable	Preferable	Preferable	Needed
Pond area requirement (ha)	Medium (> 2 ha)	Medium (> 2 ha)	Medium (> 2 ha)	Small to medium (1–2 ha)	Small to medium (1–2 ha)
Access to markets	–	–	Preferable for fish output		Preferable for prawn seeds and fish output
Stocking density (ind/m^2)	1.5–3	Shrimp: 0.50–2.90 *x* = 1.87 Mcrab: 0.01–0.05 *x* = 37	Gcarp: 0.05–0.60 *x* = 0.17 Sbass: 0.003–0. 03 *x* = 0.02 Egoby: 0.26–1.92 *x* = 0.61 Scat: 0.07–0.25 *x* = 17	Shrimp: 0.80–4. 81 *x* = 2.47	Tilapia: 0.10–0. 16 *x* = 0.13 Prawn: 0.15–0.50 *x* = 0.33 Ccarp: 0.09– 0.2 *x* = 0.15
Yield (kg/ha)	VN: 60–400 *x* = 172 BD: 10–380 *x* = 242	Shrimp 126–444 *x* = 271 (*n* = 21)[d] Mcrab: 25–83 *x* = 53 (*n* = 18)[d]	Gcarp: 219–222 *x* = 220 Sbass: 40–125 *x* = 82 Egoby: 12–106 *x* = 65 Scat: 50–150 *x* = 102	VN: 130–294 *x* = 205 BD: 73–268 *x* = 160	VN: Prawn: 45–60 *x* = 52 Tilapia: 88–112 *x* = 99 BD: Tilapia: 200–285 *x* = 232 Prawn: 50–60 *x* = 54 Ccarp: 300–369 *x* = 334

Continued

Table 4.3. Continued.

Rainy season / Dry season	Extensive shrimp (year-round) ($n = 16$)	Extensive shrimp and extensive mud crabs (year-round) ($n = 26$)	Extensive shrimp and extensive mud crabs and fish[a] ($n = 10$)	Rice / shrimp ($n = 21$)	Rice + aquaculture[b] / shrimp[c] ($n = 8$)
Knowledge requirement	Low	Low	Moderate	Moderate	Moderate
Location	Mekong and Ganges	Mekong	Mekong	Mekong and Ganges	Mekong and Ganges

[a]Yield and stocking density data for shrimp and mud crab are similar to extensive shrimp + extensive mud crab system, Gcarp and Egoby only in rainy season, other fish mentioned are raised all year round; [b]aquaculture = in rainy season, concurrent culture of paddy rice with various fish and crustacean species; [c]yield and stocking density data for shrimp are similar as alternate rice/brackishwater shrimp system; [d]yield range and mean were computed using results from farms without massive mortality due to disease outbreak or mortality. Abbreviations: BD, Bangladesh; VN, Vietnam; Shrimp, giant black tiger shrimp (*Penaeus monodon*); Mcrab, mud crab (*Scylla* spp.); Egoby, elongated goby (*Pseudapocryptes elongatus*); Scat, spotted scat (*Scatophagus argus*); Prawn, giant freshwater prawn (*Macrobrachium rosenbergii*); Tilapia, Nile tilapia (*Oreochromis niloticus*); Sbass, sea bass (*Lates calcarifer*); Ccarp, common carp (*Cyprinus carpio*); Gcarp, grass carp (*Ctenopharyngodon idella*).

low density in irrigated or flood-controlled rice fields (Table 4.3) produce average yields ranging from 88 kg/ha to 369 kg/ha, depending on the species and the stocking density. In the case of the giant freshwater prawn, the adoption of this species depends mainly on knowledge and the availability of postlarvae or juveniles on the market. Freshwater prawn production was recorded at low levels (45–60 kg/ha) both in Bangladesh and Vietnam, because of low stocking density and relatively short growing periods (5–6 months). The abundance of wild fish species (snakehead *Channa* sp., catfish *Clarias* sp., climbing perch *Anabas testudineus*, Mozambique tilapia *Oreochromis mossambicus*, etc.) trapped in relatively small ponds or rice fields together with low market prices for some of these fish, are not enough to convince farmers towards wider adoption of concurrent rice–fish culture in both countries, with average yields of only 60–80 kg/ha of these and other wild fish species. In addition, in Bangladesh, the land tenure system (where leasing contracts for rice fields do not allow the digging of refuges for fish) is also constraining the development of such a farming system.

In the Mekong Delta, in areas with longer periods of saltwater intrusion (more than 6 months) or with severe soil constraints (acid sulfate soils), diversification of production is oriented towards extensive polyculture of *P. monodon*, mud crab (*Scylla* sp.) and fish (sea bass, spotted scat, elongated goby and grass carp). The choice of species for diversification depends on the salinity period, knowledge level of the farmer, availability of postlarvae for stocking and the farmer's investment capacity. In some cases, farmers stock certain fish species at low density (0.003 ind/m^2 to 0.05 ind/m^2) with the intention of serving a sanitary function, namely cleaning the pond bottom (e.g. grass carps – the response of 8% of those interviewed) or to control virus outbreaks by eliminating weak shrimp using predatory fish (e.g. sea bass – the response of 6% of those interviewed). Some Asian shrimp farmers also claim that tilapia markedly inhibit outbreaks of shrimp diseases when stocked together with shrimp in ponds (5% of those interviewed). Most of these statements are the result of the work of the extension services.

Shrimp production (126–444 kg/ha) is within the same range of the extensive system (69–400 kg/ha). Mud crab (25–83 kg/ha) and elongated goby (12–106 kg/ha) production also appear to be highly variable in comparison to other types of fish production, particularly as a result of high mortality.

The different shrimp production systems described in the Mekong and Ganges deltas cover a wide range of economic investment and operational costs (Table 4.4). In terms of start-up investment, semi-intensive and intensive systems can be separated from other systems based on the low level of technology and investment, such as in extensive or rice–shrimp systems. Intensification of shrimp production requires investments that are 6–12 times higher than in extensive systems, principally for pond construction and essential equipment. However, in Bangladesh, the semi-intensive system observed uses a lower level of technology (no paddlewheel aerators, no night lights surrounding the ponds, fewer lift pumps for water management installed per hectare, etc.) than in the Mekong Delta. In the Ganges Delta, the operational cost of the semi-intensive system is 7.4 times higher than the extensive system. In the Mekong Delta, the operational costs of the semi-intensive and intensive systems are 20 and 41 times higher than the extensive systems, respectively. The allocation of the cost is also different, with feed representing 60–80% of the operational cost respectively in semi-intensive and intensive systems, whereas the main costs of extensive systems are for shrimp postlarvae. However, even loaded with technology, intensive and semi-intensive systems present a high economic risk, with crucial investments (that have to be implemented and then operated correctly, requiring expertise) and also a 20–30% risk of disease outbreak in the intensive system and a 50–60% risk of disease outbreak in the semi-intensive system, as has been recorded in the Mekong Delta. These results reflect the differences between shrimp production systems, in terms of risk (disease outbreak occurrence) and investment, despite the sample size.

Comparing operational costs between extensive farms in the Ganges and Mekong deltas reveals a higher cost for labour and postlarvae in the south-western coast of Bangladesh. *Penaeus monodon* postlarvae cost US$1.30–2.60/1000 PL in the Mekong Delta compared to US$5.30–9.20/1000 PL in the south-western coast of Bangladesh. In addition, the extensive system in Bangladesh employs more hired labour (28 man-days/ha in Vietnam versus 80 man-days/ha in Bangladesh), including farm operators and several workers.

In addition, these extensive farms rely on larvae of wild shrimp species trapped in the ponds during initial filling and top-up of salt water at high tides (Islam *et al*., 2005; Alam *et al*., 2007a). However, this low-cost sourcing of shrimp larvae (which are often already carriers of pathogens) comes with the associated

Table 4.4. Investment and operational cost of the different shrimp production systems in the Mekong and Ganges deltas from surveys in 2005–2006, in US$/ha (mean and standard deviation of the mean).

Item	Investment (US$/ha)	Operational cost (US$/ha)
Extensive shrimp		
Ganges Delta (n = 6)	338 ± 94	562 ± 131
Mekong Delta (n = 10)	279 ± 116	287 ± 206
Semi-intensive shrimp		
Ganges Delta (n = 2)	581 ± 97	4154
Mekong Delta (n = 6)	1834 ± 1174	5339 ± 2838
Intensive shrimp		
Mekong Delta (n = 6)	3564 ± 1267	11,880 ± 8324
Shrimp–mud crab		
Mekong Delta (n = 26)	289 ± 108	429 ± 264
Shrimp–mud crab–fish		
Mekong Delta (n = 10)	289 ± 72	528 ± 132
Rice–Shrimp		
Ganges Delta (n = 9)	338 ± 74	623 ± 169
Mekong Delta (n = 12)	334 ± 44	485 ± 158
Rice–aquaculture/shrimp		
Ganges Delta (n = 4)	462 ± 31	930 ± 472
Mekong Delta (n = 4)	384 ± 61	528 ± 231

high level of disease outbreaks and low survival rate of *P. monodon* (Milstein *et al*., 2005; Alam *et al*., 2007a). Other extensive systems with brackishwater polyculture do not improve the stability of the farm economy, where 66–75% of the farms record at least one disease outbreak during the shrimp crop. In addition, culture operations of mud crab and high-value fish such as elongated goby are considered to be risky activities, with several cases of mass mortality.

The most economically stable production systems in both study sites were the systems based on the alternating rice–shrimp farming system. In some cases, these incorporated the additional integration of an aquaculture activity (e.g. freshwater prawn, Nile tilapia or various carp species) during the rice crop in the rainy season. The otherwise high risk of disease outbreak in shrimp production was reduced to 28% by seasonal rotation of rice and aquaculture production in the Mekong Delta. The integration of an aquaculture component in the rice field required a higher cost in Bangladesh, with necessary modification of the field, such as the raising of bunds and the excavation of refuges for fish or crustaceans, whereas in Vietnam farmers had already transformed their fields when they initially started shrimp cultivation. This difference explains the higher investment required in Bangladesh for the rice–shrimp farming system.

The production results of all the systems based on shrimp farming vary widely because of disease outbreaks. We have seen that intensification of production increases the risk of bankruptcy because of considerable levels of required investments when compared to extensive systems. The risks associated with shrimp farming drive farmers to secure farm incomes by diversifying their production with high-value fish or other crustaceans. In the 2007 survey in Vietnam, we observed that in areas with periods of freshwater lasting longer than 6 months, the rice–shrimp system was more profitable and the occurrence of disease outbreaks seemed to be lower.

Diversification of production can be progressive and species stocked in ponds evolve according to market demands. These production systems are less restrictive than intensification processes, with lower investment cost, lower labour cost and less knowledge requirement.

Factors affecting the evolution of shrimp production systems

The evolution of coastal aquaculture depends on different socio-economic and environmental factors. The Mekong and Ganges deltas have followed different pathways in adopting shrimp farming. Besides the technical aspects, several keys factors influence the evolution of coastal aquaculture in these two specific areas.

Development of the shrimp value chain

The survey included not only study grow-out ponds but also a part of the shrimp value chain, with interviews of postlarvae nursery operators, shrimp buyers and traders and input retailers (Table 4.5). It revealed the notable differences of *P. monodon* postlarvae supply markets, which were US$1.30–2.60/1000 PL in the Mekong Delta compared to US$5.30–9.20/1000 PL in the Ganges Delta. The higher price of postlarvae in Bangladesh could be explained by several factors such as transport and less competitive larvae supply markets. The south-western coast of Bangladesh can be considered as a 'grow out' area, with almost all the postlarvae produced in hatcheries located along the south-eastern coast and these have to be transported to the south-western coast, where 70% of the Bangladesh grow-out shrimp farms are located and 77% of the Bangladesh shrimp production occurs (Alauddin and Tisdell, 1998; PDO-ICZMP, 2003b). The south-western coastal area can be considered only as a value-adding area, importing 2.1 billion PL (at a value of US$9.5 million) and exporting 23,000 t shrimp (valued at US$187 million) (Alauddin and Tisdell, 1998; PDO-ICZMP, 2003b).

In Vietnam, only 48 hatcheries were present in the Mekong Delta in 1999, producing 5.4% of the country's total shrimp PL production. In 2005, 38.8% of the *P. monodon* PL production came from the 1261 hatcheries in the Mekong Delta. A survey implemented in

Table 4.5. Shrimp value chain stakeholders investigated in this study and main outcomes in the Mekong Delta, Vietnam (VN) and the south-western coast of Bangladesh (BD).

Stage of value chain	Study sites	Indicators	Outcomes
Nursery operators	VN/BD	PL price, PL origin	Difference of PL price between VN and BD
Postlarvae traders	VN/BD	PL price, PL origin	Difference of PL price between VN and BD
Input retailers	VN	Diversity of products sold	Importance of input retailers as source of knowledge and wide spread of technique. Role of retailers in informal loans for access to manufactured feeding pellets
Shrimp producers	VN/BD	Yield, operational cost, stocking density, etc.	Process of intensification or diversification of aquaculture production systems
Shrimp buyers	VN/BD	Kind of contract, origin and destination of products	Absence or presence of verbal contract with producers
Shrimp traders	VN/BD	Kind of contract, origin and destination of products	Absence or presence of verbal contract with buyers

Bac Lieu Province in 1997/98 (Brennan *et al*., 2000) highlighted the shortage of PL during the peak stocking period, and a price of US$10–15/1000 PL compared to US$1.30–2.60/1000 PL in 2006. The distinctly increased availability of PL on the market during the peak season and the subsequent lowering of the PL price enabled the evolution of the shrimp production system, with far less reliance on wild-caught larvae of shrimp and fish.

The PL price and quality in Bangladesh were highlighted during the survey as constraints for farmers who needed to engage in contractual loans (at 30–50% interest rate) with nursery operators and PL traders. Together with other factors such as access to land, loans and knowledge, the higher cost of PL in Bangladesh reduces the investment capacity of farmers to modify their production system.

In the Mekong Delta, the widespread diffusion of technologies was supported by the development of a dense network of input retailers. In comparison to Bangladesh where access to chemicals, probiotics or even manufactured feed pellets is difficult, in Vietnam several input retailers are located in each village, thus allowing widespread accessibility of diverse products. Although farmers can benefit from competition between input retailers, a recent development is the provision of informal loans to farmers, notably in semi-intensive and intensive shrimp production areas. These loans are mainly for manufactured feed pellets. Even when severe losses occur as a result of disease outbreaks, loans are contracted by input retailers only after 60–80 days of grow-out, in order to limit the risk for the input retailer. Input retailers also play a crucial role in access to knowledge, as they organize training courses for farmers.

In both study sites, the number of shrimp buyers and shrimp traders was important, with several layers and intermediaries between the farm and the processing factories. Rules and agreements between the different stakeholders in the value chain are diverse, where sometimes contracts are established between buyers and producers, or between buyers and traders in the two study sites. A common aspect was found in the form of verbal contracts between buyers and traders, or sometimes between producers and buyers or traders, for exclusive sale of the harvest. In the latter case, the moneylender defines the selling price. These contracts are the collateral of a loan for start-up investment in the case of shrimp buyers, or to cover the operational costs in the case of shrimp producers.

It appears that links and institutional arrangements between the different components of the value chain connected to the shrimp producer are diverse, complex and cannot be generalized. In addition, oral contracts and informal loans are extremely variable and depend on several factors, such as the personal relationship between the two contractors or the economic results of the farm in previous years. Larger sample sizes in both countries would be needed for a more detailed analysis of the value chain.

Water management and land ownership

Access to water is also one of the main factors that differ between these two case study sites. In Vietnam, the development of an elaborate canal network in the Mekong Delta since the 19th century has enabled private access to water for each pond. In Bangladesh, the absence of such canal network severely constrains farmers who do not have direct access to rivers for filling their pond with water and must do so by taking in water via neighbouring intermittent pond(s), thereby increasing considerably the potential of viruses spreading and restricting water exchange (Masudur Rahman, 1999).

The variations in access to water between the Ganges Delta and the Mekong Delta reflect the consequences not only of two different water management development plans but also of differences in land tenure. In Vietnam, ownership of the land allows farmers to modify their pond according to the needs of the production systems (inlet and outlet canals, higher dykes and refuges for shrimp and fish in the rice field). In contrast, in Bangladesh, large numbers of farmers are leasing land on a contractual basis of 3 years, as found in a socio-economic survey in Paikgacha Subdistrict with 63% of the 60 shrimp farms (Joffre *et al.*, 2007). Therefore, modification of the pond is almost impossible, as the landowners would not permit this to be undertaken. This situation does not enable improvement of the water management infrastructure, and consequently the evolution of the production systems.

Sources of knowledge

Vietnamese aquaculture in the coastal area appears to be more diversified and dynamic than in the south-western coast of Bangladesh, with the frequent emergence and rapid spread of technical innovations and development of new production systems such as high-value fish culture or extensive mud crab farming. In addition, most Vietnamese farmers have some knowledge of water quality management and monitoring. For example, in the acid sulfate soil area, pH monitoring using pH paper or even a pH meter is common.

In Paikgacha Subdistrict, only farmers located near the town are able to join training courses from extension services and engage in the integrated rice–aquaculture system or in semi-intensive shrimp culture. The average number of different sources of new technical knowledge was only 0.8 in Paikgacha Subdistrict but was 2.1 in Bac Lieu Province. In Vietnam, aside from the government extension services, television and radio broadcasts regularly present aquaculture technologies, and even the private sector is engaged in training courses for farmers, leading to diversified accessibility to knowledge for the farmers.

Information networks are more developed and diversified in the Mekong Delta compared to the Ganges Delta, where information flows from farmers and government agencies only. This situation can explain the difference in terms of evolution and the numbers of different farming systems between the two study areas and the rapid spread of new technology and new production systems in the Mekong Delta.

Conclusions

The development of shrimp culture has modified drastically the development and economy of the coastal areas. However, the Mekong and Ganges deltas present major differences. In Vietnam, development of the shrimp industry, with hatcheries, processing plants and feed factories, has occurred within the production areas. In contrast, in Bangladesh, the major production area is geographically separated from other components of the shrimp industry. This difference, with other factors such as land tenure, credit availability and/or water management infrastructure, leads to two distinct dynamics. Compared to the south-western coast of Bangladesh, the Mekong Delta in Vietnam has a more diversified shrimp value chain, with lower costs of postlarvae and more diversified sources of knowledge for farmers. In this delta, the wide spread of shrimp viral diseases has led to diversification of the brackishwater aquaculture systems, with the development of market-oriented brackishwater polyculture or alternate culture of rice and shrimp, to secure and diversify farm incomes. This most recent evolutionary step within the coastal area highlights their potential use, characterized by the seasonal variation of the environment and the possibility to alternate freshwater and brackishwater production.

In Bangladesh, land tenure, water management infrastructure, lack of knowledge and the high price of postlarvae are the major constraints for such evolution. In Vietnam, the development of the shrimp industry with more access to advanced technology has enabled, but also driven, a process of intensification. This evolution towards intensification may lead to important environmental change and may jeopardize the sustainability of the economic growth of these areas. It seems important for policy makers and development agencies to regulate and steer such farming system evolution through the development of alternative production systems with more benign environmental and social characteristics for adoption by farmers. For example, in areas where the freshwater period exceeds 6 months, rice–shrimp farming achieves more sustainable results than shrimp monoculture, with a lower percentage of disease outbreak. In this system, a rice crop is considered as a ‘sanitary’ crop between two shrimp crops. In Bangladesh, the results of the experiments of Project No 10 of the CGIAR Challenge Program on Water and Food (CPWF) in the south-western coastal area achieved promising results with rice–freshwater prawn and Nile tilapia (GIFT strain), followed by a shrimp crop. When freshwater prawn PL were stocked at the end of the dry season, the net returns of the rice-integrated aquaculture system were 330–422% higher than the locally practised rice monoculture (Alam *et al.*, 2007b).

In areas where rice culture is impeded by saltwater intrusion, diversified brackishwater aquaculture can improve the farm economy without important environmental cost. Moreover, these systems do not require a significant investment and have potential for wider adoption. However, the development of such production systems will be effective only with the involvement of national and local agencies. In Bangladesh, water management infrastructures at the pond polder level have to be improved for better water management (for both rice and shrimp culture) and to reduce the exchange of water between ponds.

In Vietnam, intensive and semi-intensive practices have to be standardized to reduce the environmental burden of intensive shrimp farming, for example, with the development of good management practice (GMP). Coordination among state agencies should be reinforced to elaborate well-accepted land use planning, thus reducing conflict between rice–shrimp and semi-intensive and intensive shrimp farmers for water resources. In addition, as in Bac Lieu Province, intensive shrimp farming should be restricted by local government to areas with suitable environmental characteristics (water flows, water salinity, soil structure, etc.) for shrimp farming, to reduce the risk of crop failure and environmental degradation of the surrounding environment.

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References

Alam, N.S.M., Pokrant, B., Yakupitiyage, A. and Philips, M.J. (2007a) Economic returns of disease-affected extensive shrimp farming in southwest Bangladesh. *Aquaculture International* 15(5), 337–350.

Alam, M.J., Islam, M.L., Joffre, O. and Tuong, T.P. (2007b) Managing Water and Land Resources for Sustainable Livelihoods at the Interface Between Fresh and Saline water Environments in Vietnam and Bangladesh (CPWF No 10). Activity 3.2.2 Shrimp-based system. Report of CPWF No 10 project. WorldFish Center, Dhaka.

Alauddin, M. and Tisdell, C. (1998) Bangladesh's shrimp industry and sustainable development: resource-use conflict and the environment. *Asian Fisheries Science* 11, 97–110.

Bammann, H. (2007) Participatory value chain analysis for improved farmer incomes, employment opportunities and food security. *Pacific Economic Bulletin* 22(3), 113–125.

Biggs, D. (2004) Between rivers and tides: a hydraulic history of the Mekong delta, 1820–1975. PhD Thesis, University of Washington, Washington, DC.

Binh, C.T., Philips, M.J. and Demaine, H. (1997) Integrated shrimp–mangrove farming systems in the Mekong Delta of Vietnam. *Aquaculture Research* 28, 599–610.

Breemen, N. and van Pons, L.J. (1978) *Acid Sulphate Soils and Rice*. *Soil and Rice*. International Rice Research Institute, Los Baños, Laguna, Philippines, pp. 739–761.

Brennan, D., Clayton, H. and Be, T.T. (2000) Economic characteristics of extensive shrimp farms in the Mekong Delta. *Aquaculture Economics and Management* 4(3/4), 127–184.

Catling, D. (1992) *Rice in Deep Water*. Macmillan, London.

Chowdhury, M.B.R. and Muniruzzaman, M. (2003) Shrimp disease and its consequence for coastal shrimp farming in Bangladesh. *Technical Proceeding BAU-NORAD Workshop*. *Environmental and Socio-economic Impact of Shrimp Farming in Bangladesh*, BARC Centre, Dhaka, Bangladesh, Bangladesh Agricultural University, Mymensingh.

Deb, A.K. (1998) Fake blue revolution: environmental and socio-economic impact of shrimp culture in the coastal area of Bangladesh. *Ocean Coastal Management* 41, 63–88.

DoF (1986) Fisheries Information Bulletin, Vol. 3, No 1. Department of Fisheries, Ministry of Fisheries and Livestock, Matshya Bhaban, Dhaka, Bangladesh.

DoF (2002) National fish fortnight publication 2002. Department of Fisheries, Ministry of Fisheries and Livestock, Dhaka, Bangladesh.

DoF (2005) *Fishery Statistical Yearbook of Bangladesh 2003–2004*. Fisheries Resources Survey System, Department of Fisheries, Ministry of Fisheries and Livestock, Matshya Bhaban, Dhaka.

Eaton, R.M. (1990) Human settlement and colonization in the Sundarbans, 1200–1750. *Agriculture and Human Values* 7(2), 6–16.

FAO (2003) *Review of the State of World Aquaculture*. FAO, Rome.

Flegel, T.W. (2006) Detection of major penaeid shrimp viruses in Asia, a historical perspective with emphasis on Thailand. *Aquaculture* 258, 1–33.

Gupta, M.V. (1997) Social and policy issues involved in adoption of integrated agriculture–aquaculture–livestock production system in Bangladesh. *Proceeding of the Integrated Fish Farming Conference, 11–15 October 1994*, Wuxi, Jiangsu Province, People's Republic of China, pp. 231–244.

Hoanh, C.T., Tuong, T.P., Gallop, K.M., Gowing, J.W., Kam, S.P., Khiem, N.T. and Phong, N.D. (2003) Livelihood impact of water policy changes: evidence from a coastal area of the Mekong river delta. *Water Policy: Official Journal of the World Water Council* 5(5/6), 475–488.

Hong, P.C. and San, H.T. (1993) *Mangroves of Vietnam*. IUCN, Bangkok.

Hoq, M.E. (2006) An analysis of fisheries exploitation and management practices in Sundarbans mangrove ecosystem, Bangladesh. *Ocean Coastal Management* 50(5/6), 411–427.

Hossain, M., Ut, T.T. and Bose, M. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 30–47.

Hossain, S., Nazmul, A.S.M., Lin, K.C., Demaine, H., Sharif, Y., Khan, A., Das, N.G. and Rouf, M.A. (2004) Integrated management approach for shrimp culture in the coastal environment of Bangladesh. *World Aquaculture* 35(1), 35–67.

Islam, M.S., Milstein, A., Wahab, M.A., Kamal, A.H.M. and Dewan, S. (2005) Production and economic return of shrimp aquaculture in coastal ponds of different sizes and with different management regimes. *Aquaculture International* 13(6), 489–500.

Joffre, O., Islam, M.L. and Alam, M.J. (2007) Socio-economic aspects and dynamics of salinity based farming systems in the south-west coastal region of Bangladesh. Report of the CGIAR Challenge Program on Water and Food, Project No 10. WorldFish Center, Dhaka.

Johnston, D., Trong, N.V., Tien, D.V. and Xuan, T.T. (2000) Shrimp yield and harvest characteristics of mixed shrimp–mangrove forestry farms in southern Vietnam: factors affecting production. *Aquaculture* 188, 263–284.

Karim, M. and Stellwagen, J. (1998) Shrimp aquaculture. Fourth Fisheries Project. Final Report. Department of Fisheries, Dhaka, Bangladesh.

Luttrell, C. (2006) Adapting to aquaculture in Vietnam: securing livelihoods in a context of change in two coastal communities. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 17–29.

Masudur Rahman, M. (1999) Policies for sustainable shrimp culture in Bangladesh. In: *Papers presented at the FAO Technical Consultation on Policies for Sustainable Shrimp Culture*, Bangkok, Thailand, 8–11 December 1997. FAO Fisheries Report No 572, Suppl., pp. 41–50.

Milstein, A., Islam, M.S., Wahab, M.A., Kamal, A.H.M. and Dewan, S. (2005) Characterization of water quality in shrimp ponds of different sizes and with different management regimes using multivariate statistical analysis. *Aquaculture International* 13(6), 501–518.

MOFI (1996) *Aquaculture Development Strategy for the Period of 1995–2000*. Ministry of Fisheries, Vietnam.

Nuruzzaman, M. and Maniruzzaman, M. (2003) *Impact of Shrimp Industry on the Coastal Communities. Present Status of Coastal and Marine Resources of Bangladesh and Future Potential of Poverty Alleviation*. Bangladesh Fisheries Research Forum, Dhaka, Bangladesh.

Pingali, P.L., Hossain, M. and Gerpacio, R.V. (1997) *Asian Rice Bowls: The Returning Crisis*? CAB International, New York and International Rice Research Institute, Manila.

PDO-ICZMP (Program Development Office for Integrated Coastal Zone Management Plan) (2003a) *A System Analysis of Shrimp Production*. Working Paper 14, Ministry of Water Resources (MoWR), Dhaka.

PDO-ICZMP (Program Development Office for Integrated Coastal Zone Management Plan) (2003b) *Coastal Livelihood. Context and Situation*. Working Paper 15, Ministry of Water Resources (MoWR), Dhaka.

PDO-ICZMP (Program Development Office for Integrated Coastal Zone Management Plan) (2005) *Coastal Development Strategy – Unlocking the Potentials of the Coastal Zone*. Ministry of Water Resources (MoWR), Dhaka.

Phuong, N.T. and Hai, T.N. (1998) Coastal aquaculture and environmental issues in the Mekong Delta, Vietnam. In: Macintosh, D.J. (ed.) *Proceedings of a Workshop on Coastal Environmental Improvement in Mangrove/Wetland Ecosystems*, held on 18–23 August 1998 in Ranong, Thailand. Centre for Tropical Ecosystems Research, University of Aarhus, Denmark.

Richards, J.F. and Flint, E.P. (1990) Long-term transformation in the Sundarbans wetlands forest of Bengal. *Agriculture and Human Values* 7(2), 17–33.

Russier, H. and Brenier, H. (1911) *L'Indochine française*. Edition Armand Colin, Paris.

Ve, N.B. (1988) *Soil Map of Trans-Bassac Area*. University Cooperation Project (VH10 and 60 B) between Wageningen Agricultural University, the Netherlands, and University of Can Tho, Vietnam.

Vo, L.T.T. (2003) *Quality Management in Shrimp Supply Chain in the Mekong Delta, Vietnam: Problems and Measures*. Discussion Paper Series 43. Centre for ASEAN Studies, Antwerp, Belgium.

Xuan, V.T. and Matsui, S. (1998) *Development of Farming Systems in the Mekong Delta of Vietnam*. Saigon Times Group, Vietnam Asia Pacific Economic Center, Ho Chi Min City Publishing House, Can Tho, Vietnam.

5 Ecological Risk Assessment of an Alien Aquatic Species: a Case Study of *Litopenaeus vannamei* (Pacific Whiteleg Shrimp) Aquaculture in the Bangpakong River, Thailand

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Abstract

Although aquaculture promises economic and social benefits, escaped organisms can pose ecological risks to the receiving aquatic environments and undermine the sustainability of aquaculture and small-scale fisheries. In this chapter, we present a framework for evaluating the ecological risks of *Litopenaeus vannamei*, a shrimp species introduced to Thailand for aquaculture. A risk analysis framework comprising three steps was employed: (i) identification of hazards; (ii) assessment and prediction of the likelihood and severity of the harm; and (iii) characterization of risk. This case study focused on step (i) and parts of step (ii) of the risk analysis framework and addressed releases of *L. vannamei* from farms, their survival and their ability to reproduce in the wild. Potential impacts included the spread of an alien pathogen carried by *L. vannamei* to local shrimp species and competition for food with local shrimp species. Data for this study were generated by combined field surveys, geographic information systems and experiments. Field data on the composition of Penaeid shrimp species in the Bangpakong estuary indicated that *L. vannamei* were persistent in the wild. Toxicity experiments indicated that *L. vannamei* could tolerate the range of environmental conditions that occurred in the Bangpakong estuary. We detected the presence of an alien pathogen, Taura Syndrome Virus, in at least seven local shrimp species (3.30–25.75% of individuals tested). Feeding experiments also indicated that *L. vannamei* might be better at seeking food than selected local species. Our proposed framework can serve as a model for assessing the ecological risks of *L. vannamei* introduced elsewhere and of other alien aquatic species.

Introduction

Although aquaculture promises economic and social benefits, aquaculture escapees can pose ecological risks to the receiving aquatic environments (see De Silva, 1989; Naylor *et al*., 2001; Miller *et al*., 2004; De Silva *et al*., 2006). Certain ecological impacts such as reducing aquatic biodiversity or spreading alien pathogens may undermine the sustainability of aquaculture and small-scale fisheries. The incorporation of science-driven risk assessment before new

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

introductions, and integration of risk monitoring into the management of alien species already introduced for aquaculture, may prevent such undesirable ecological outcomes.

Although the potential ecological impacts of alien aquatic species have received international attention, very little data are available from developing countries (see Bartley *et al.*, 2005; De Silva *et al.*, 2006). A large body of literature on biological invasions suggests dramatic impacts of a few alien species on local communities (e.g. Nile perch, *Lates niloticus*, introduction in Lake Victoria, Witte *et al.*, 1992; zebra mussel, *Dreissena polymorpha*, in eastern USA, Johnson and Padilla, 1996; green crab, *Carcinus maenas*, in western USA, Grosholz *et al.*, 2000). However, there is some debate whether the spread of alien species is responsible for the extinction of local species (Gurevitch and Padilla, 2004; De Silva *et al.*, 2006). Because the type and magnitude of ecological harm is specific to the interactions between alien species and the receiving ecosystems, site-specific data are crucial for both the prediction and assessment of potential harm (i.e. risk assessment) and monitoring for realized harm or lack thereof (i.e. risk management).

It is important to use a systematic framework to identify the most important ecological data needed to inform the risk assessment and management of the introduction of a specific alien species. An appropriate framework allows for the generation and prioritization of relevant questions and the integration of research findings into decision making about the risk of the alien introduction. In addition, a systematic identification of subcomponents giving rise to an ecological effect can help determine whether to accept a specific, worst-case assumption (e.g. alien species escapees will survive in the receiving environment). This strategy would allow analysts to focus limited resources on assessing other subcomponents.

Existing data on the ecological impacts of alien aquatic species stem largely from retrospective analyses (see Witte *et al.*, 1992; Johnson and Padilla, 1996). Although these analyses are insightful, management decisions regarding the introduction of alien species to a new ecosystem still require site-specific data *prior to* the introduction. In this chapter, we present a conceptual framework to guide the formulation of scientific research questions relevant to ecological risk assessment of the introduction of an alien aquatic species. The framework is then illustrated using a case study of the introduction of Pacific whiteleg shrimp (*L. vannamei*) for aquaculture in Thailand, highlighting our relevant findings. Our research has both retrospective and predictive components as *L. vannamei* is already present in Thailand. We do not intend to present an extensive review of the potential ecological impacts of alien aquatic species nor reach a risk assessment conclusion. The chapter provides a guiding approach for research that feeds into the analytical component of risk assessment and management of alien aquatic species.

Elements of Ecological Risk Assessment and Management

A comprehensive biosafety framework (Table 5.1) consists of risk assessment and risk management (Stern and Fineberg, 1996; Miller *et al.*, 2004).

Risk can be defined as the likelihood of harm occurring as a result of an action or inaction (Stern and Fineberg, 1996). Harm refers to undesirable consequences to humans or components of valued ecosystems (Hayes *et al.*, 2007). Hazard refers to an act or phenomenon that, under certain circumstances, could lead to harm (Royal Society, 1983) or, alternatively, as a substance's or activity's tendency to produce harm (Stern and Fineberg, 1996). Hayes *et al.* (2007) suggested that it might be useful to conceptualize hazard as a function of both the intrinsic properties of a substance (or activity) and circumstance.

Risk assessment (items 1 and 2 in Table 5.1) is a process for determining the frequency and consequences of harmful events. It starts with the identification of a hazard, followed by the risk analysis, consisting of analytical steps to determine and predict the likelihood of harm, as well as to estimate the severity of the harm. An outcome of the risk assessment is risk characterization, which can be illustrated in a matrix of the likelihood of realized hazards and the likelihood and severity of the harm (Fig. 5.1).

Risk assessment is a generic approach to all kinds of risks, including hazardous substances

Table 5.1. Systematic steps in risk assessment and management (modified from Kapuscinski, 2002).

Step in risk assessment and management	Key question addressed at this step
1. Hazard identification	What event posing harmful consequences could occur?
2. Risk analysis	How likely is the hazard? What harm might be realized and how severe might it be? What is the risk assessment, i.e. a matrix of likelihood plotted against severity of harm? Each cell of the matrix should be accompanied by a qualitative assessment of the response and level of assurance needed to reduce harm if the cell's conditions were to occur How certain is the knowledge used to identify the hazard, estimate its likelihood and predict harm?
3. Risk reduction planning and implementation	What can be done to reduce risk, either by reducing the likelihood or mitigating the consequences of the hazard once they are realized?
4. Risk tracking (monitoring)	How effective are the implemented measures for risk reduction? Are they as good, better or worse than planned for? What follow-up/corrective action/intervention will be pursued if findings are unacceptable? Did the intervention resolve the concern(s) adequately?

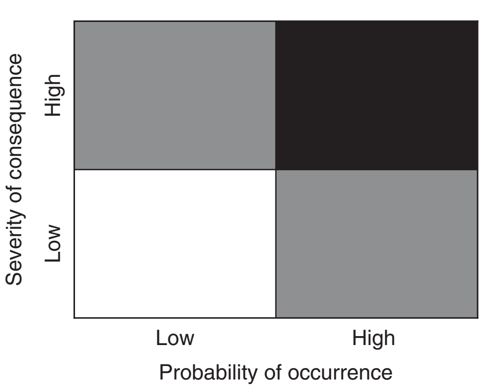

Fig. 5.1. Schematic of a risk assessment matrix (from Miller *et al.*, 2004).

or activities that are harmful to human health (e.g. fatalities and injuries). Ecological risk assessment is a specific form of risk assessment that centres on ecosystem health rather than human health. Even though risk assessment is an analytical part of a risk decision-making process, several authors have called for the participation of multiple stakeholders (Hayes *et al.*, 2007). A participatory process will allow all concerns to be recognized. Hazards and harm identified and prioritized through a participatory process will help stakeholders reach meaningful risk assessment outcomes.

In ecological risk assessment, hazards and their subsequent ecological effects (i.e. harm) are part of a chain of events. Figure 5.2 illustrates an example of cascading events after alien species enter an aquatic ecosystem. The selection of hazards is an important step because it focuses the rest of the analysis and management procedures. In ecological risk analysis, assessment end points focus on ecological changes that the relevant parties have agreed are undesirable (e.g. population declines in endangered species). Analysts often need to develop measurement

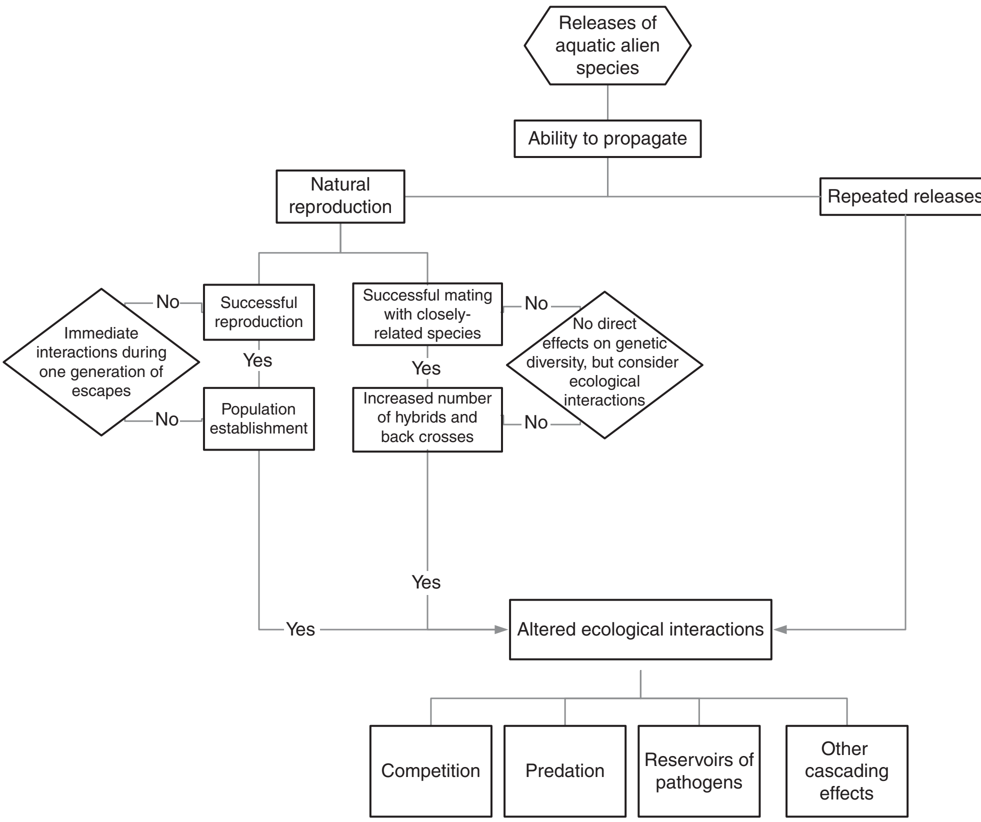

Fig. 5.2. Potential cascading ecological changes from the spread of released alien species.

end points (what they can actually measure) for each assessment end point (what they are trying to protect) and extrapolate to the end point for risk assessment.

Each assessment end point in the cascading ecological events after a species introduction may require a varying amount of effort to measure. For example, it may be more straightforward to measure the presence/absence of an alien species in the wild than to measure subsequent ecological interactions (or indicators of ecological interactions). Ecological changes occurring over a long time frame (e.g. several generations after the releases) usually involve several ecosystem components and processes, and such changes may be because of factors other than the spread of alien species (e.g. other anthropogenic induced changes). To define appropriate end points and levels of effort needed, a team of analysts should consist of relevant expertise, such as marine biologists, ecologists, population ecologists, statisticians and GIS specialists.

Risk management (items 3 and 4 in Table 5.1) usually involves the design and implementation of risk reduction measures, either by reducing the likelihood of harm or mitigating the severity of harm, and risk tracking. In many aquaculture situations, reducing the number of escapees to acceptable levels (as agreed on by multiple stakeholders in the deliberative part of the risk assessment process) may require more than one type of barrier (NRC, 2004; Kapuscinski, 2005; Mair *et al.*, 2007). Measures to mitigate the severity of harm (e.g. removing alien species from an ecosystem), on the other hand, have proved to be non-effective. Risk tracking is an important element of risk management because it allows detection of the inadequacy of risk reduction measures and measurement of realized harm (identified prior to the releases). The key elements of a monitoring programme are well-defined sets of assessment and measurement end points and appropriate baseline data on the status of an ecosystem prior to any releases (Senanan *et al.*, 2007a).

Assessing Ecological Risks of Alien Aquatic Species

Ecological risk assessment of the introduction of alien aquatic species may start with the analysis of pathways by which alien species enter an aquatic ecosystem (Fig. 5.2). Subsequent ecological harm can occur at both population and ecosystem levels. Depending on whether closely related species are present, the most immediate harm may be genetic impacts on local populations of closely related species or the establishment of a population of the released alien species. Increased numbers of alien individuals in the wild, either through natural reproduction or through persistent releases, may trigger other cascading ecological interactions. Each alien species will have different ecological interactions, depending on their ecological roles in the receiving environment. For example, a predator, such as the Nile perch (*L. niloticus*), may prey on local fish species (Witte *et al.*, 1992), whereas an omnivorous species, such as the common carp (*Cyprinus carpio*), may consume excessive amounts of macrophytes that provide an important nursing habitat for other species (Koehn, 2004).

Released alien species may start interacting with the receiving aquatic communities on their arrival. For example, individuals carrying alien pathogens can spread these pathogens to native species even within a single generation of the release. However, the magnitude of most ecological changes resulting from the spread of released individuals will increase as the numbers of alien species increase. Moyle and Light (1996) hypothesized that alien fish species would have observable impacts on the receiving aquatic communities if they successfully: (i) established a population; (ii) integrated themselves into aquatic communities; and (iii) altered interactions in the communities.

Hazard identification

Alien species used for aquaculture can enter aquatic ecosystems via either unintentional or intentional releases. Animals may escape or be released during the production cycle and during natural disasters, such as floods. The numbers of individuals escaping in these situations can be vastly different; the first scenario may allow frequent releases, with small numbers of individuals per event, whereas the second scenario may cause less frequent releases, but with large numbers of individuals per event. Both the numbers of individuals released per event (propagule size) and the frequencies of release events (propagule number) facilitate population establishment and geographic spread of alien species (Marchetti *et al.*, 2004; Lockwood *et al.*, 2005). In addition to initial releases, the numbers of alien species in the wild may be maintained through natural reproduction or repeated releases.

In addition to our proposed hazards (i.e. the release of alien aquatic species), analysts sometimes focus on a particular aspect of the introduction, such as health-related issues. Bartley *et al.* (2006) chose as hazards the spread of pathogens specific to alien aquatic species used for stock enhancement. Some pathogens considered in their analysis included White Spot Syndrome Virus (WSSV), specific to marine shrimp, and the parasitic cestode, *Callotetrarhynchus japonicus*.

Risk analysis

A challenge in analysing the ecological risks of alien species is the difficulty in predicting harm, estimating the likelihood of harm occurring and the severity of the harm, because these parameters are species- and ecosystem-specific and are often difficult to measure. Figure 5.3 summarizes a systematic approach to identify and assess likely harm scenarios for a given species introduction. Briefly, analysts would describe the ecosystem components (abiotic and biotic) and relevant processes, life-history characteristics of the alien species and the relevant interactions between the two, drawing on existing data and literature, as well as specific experiments and field surveys.

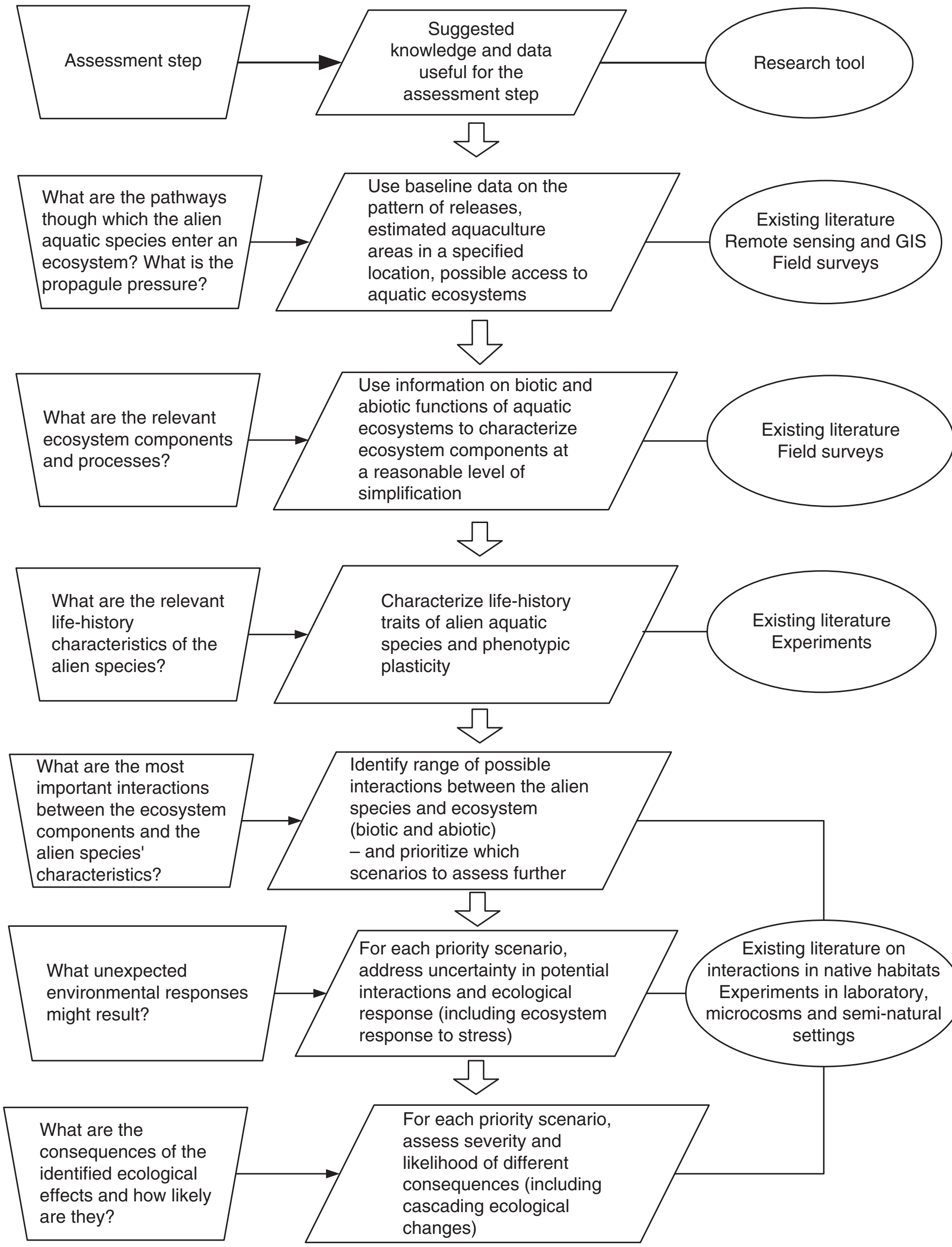

Fig. 5.3. Analytical steps and data required for ecological risk assessment of alien aquatic species used for aquaculture (adapted from Devlin *et al*., 2007).

Existing data on realized ecological impacts induced by aquatic alien species in specific locations can assist identification of the potential harm of an alien species introduction in a new geographic location. Data were usually generated from field surveys and specific experiments. Potential types of harm at a population level include hybridization with closely related species (Bartley and Gall, 1991; Allendorf *et al.*, 2001; Hitt *et al.*, 2003; Na-Nakorn *et al.*, 2004; Senanan *et al.*, 2004) and establishment of a population (De Silva, 1989; Witte *et al.*, 1992; Koehn, 2004). Examples of harm at an ecosystem level include increased predation pressure on local prey species (Witte *et al.*, 1992), increased competition for food or space (Byers, 2000; Rossong *et al.*, 2006), displacement of some local species (Robinson *et al.*, 2005), harbouring alien pathogens (Bartley *et al.*, 2006), alteration of habitat characteristics (Koehn, 2004) and other cascading ecological interactions (Goldschmidt *et al.*, 1993; Grosholz, 2005).

To estimate the likelihood of harm occurring and the severity of that harm, analysts have begun to develop mathematical models, drawing on the available data on some invasive species (Kolar and Lodge, 2002; Koehn, 2004; Zambrano *et al.*, 2006). These models suggest that successful invaders are generally highly fecund, highly tolerant to extreme environmental conditions, provide extensive care for young and have diverse natural diets. Unfortunately, most models focus on invasive species in temperate regions. To generate similar models for tropical species, we still need more relevant data.

Figure 5.4 illustrates the use of a fault-tree analysis to help partition assessment end points (hazards and harms) into subcomponents. Subcomponents entering the AND or OR gates are factors contributing to an ecological event. An event following an AND gate requires all the subcomponents to occur, whereas one following an OR gate requires only one subcomponent to occur. For example, for released individuals to survive, all subcomponents are necessary, namely large propagule pressure, availability of natural diets, avoidance of predation and an environment with suitable physical and chemical characteristics. To develop a comprehensive list of ecological harm, analysts will need to describe possible events (Fig. 5.4 is not a comprehensive diagram) and partition each event into subcomponents (see Devlin *et al.*, 2007 and Kapuscinski *et al.*, 2007). A comprehensive list of ecological harm and the subcomponents allows prioritization of the harm to evaluate the introduction of a given species.

Risk assessment of the introduction of *Litopenaeus vannamei*

Marine shrimp (*Penaeus* spp.) are important commodities for several Asian countries, including Thailand (Briggs *et al.*, 2004). Thailand introduced the Pacific whiteleg shrimp (*L. vannamei*, Boone, 1931) for aquaculture in the late 1990s to replace *P. monodon*, a native species that faced several problems, including disease outbreaks. The production of *L. vannamei* has surpassed *P. monodon* since 2004, with an estimated 2007 annual production of 441,451 t, contributing to 99.26% of total marine shrimp production in Thailand (DOF, 2009). *Litopenaeus vannamei* is native to the Pacific coasts of Central and South America (Perez Farfante and Kensley, 1997). Aquaculture of *L. vannamei* has expanded rapidly because of the species' fast growth, the low incidence of native diseases and the availability of domesticated strains.

The Bangpakong River is one of the largest and most important waterways in eastern Thailand. Many people rely on the river for small-scale fishing activities, agriculture and aquaculture. Urban development and agriculture comprise the majority (over 80%) of land use in the Bangpakong watershed (Panutrakul *et al.*, 2000). It is an ideal site for this study because: (i) its watershed harbours the largest area of shrimp farming in eastern Thailand (8900 ha of Chacheangsao Province in 2004, according to DOF, 1999–2005); (ii) its estuarine conditions provide viable habitats for released *L. vannamei*; and (iii) already installed stationary stow nets in the main channel are quite effective in capturing wild shrimp, enabling *L. vannamei* to be caught in the wild.

The chain of cascading ecological events may include the release of *L. vannamei* from farms, the survival of released individuals in the wild and the reproduction of survivors in the wild (by either establishing a self-sustaining population or by interbreeding with closely related species). Attributes specific to *L. vannamei* may heighten some ecological interactions, leading to the alteration of aquatic communities. These interactions may include serving as a reservoir for alien pathogens, competing with other species for food or for space

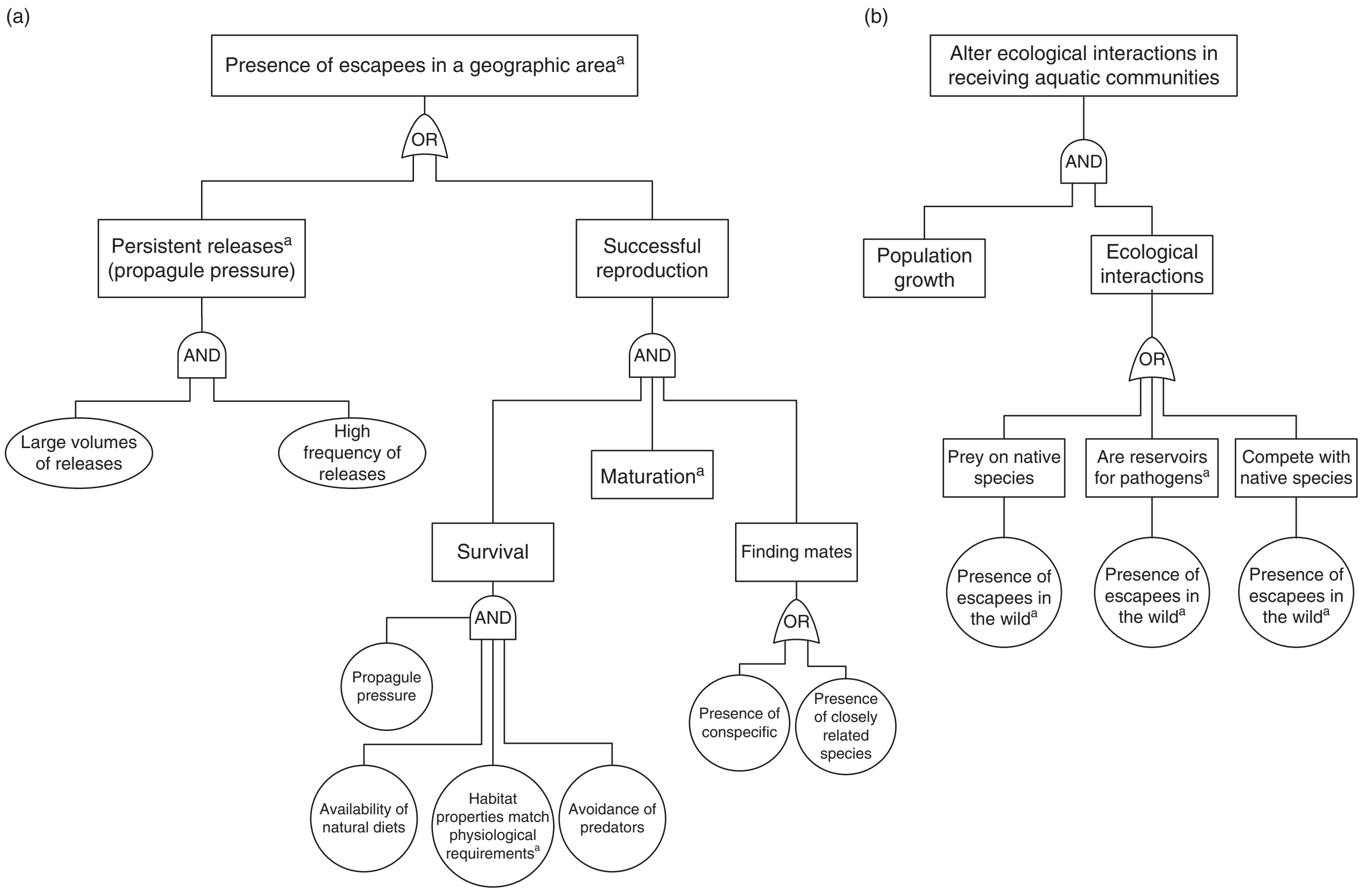

Fig. 5.4. Fault-tree analysis of possible mechanisms through which released alien species could (a) be sustained in the wild and (b) alter ecological interactions with other species. [a] Foci of this research.

and predating on other species (Fig. 5.4). Our research programme addresses some of these hazards and their harm, as indicated by asterisks (*) in Table 5.2, and the following sections will illustrate our approach in defining the research questions outlined in Table 5.2. Hazards in the *L. vannamei* case may include releases of *L. vannamei* from farms (Hazard I), their survival in the receiving ecosystem (Hazard II) and their ability to sustain a population (Hazard III). The realization of these hazards will determine the magnitude of ecological harm.

Risk analysis: frequency/exposure analysis

Hazard I: releases of L. vannamei *from farms*

Litopenaeus vannamei can enter the Bangpakong estuary at various life stages, including postlarvae (produced in hatcheries), juveniles and subadults (cultured in ponds). Postlarvae may escape from hatcheries during production. A moderate size hatchery produces millions of nauplius and PL_{15} (15-day-old postlarvae) every few days. Juveniles and subadults may be released

Table 5.2. Research questions relevant to risk assessment of *Litopenaeus vannamei* releases.

	Research questions relevant to risk analysis	
Hazard identification	Frequency/exposure analysis	Harm/effect analysis
I. Releases of *L. vannamei* from farms, grow-out ponds and hatcheries into local environment	1. How often and how many *L. vannamei* (all life stages) escape into natural aquatic ecosystems?[a,*] (What is the propagule pressure?) 2. Are the released individuals present in the wild?*	1. Can survivors establish a self-sustaining population? 2. Does *L. vannamei* have genetic impacts on populations of native species? (Increased numbers of hybrid and backcross offspring.)
II. Survival of escaped *L. vannamei* in the wild	1. What are the physiological limits of *L. vannamei* compared to selected native shrimp species?* 2. How do these physiological requirements fit the physical and chemical properties of the local environment?* 3. Can we detect the presence of *L. vannamei* for a sustained period?*	3. Are there pathogens specific to *L. vannamei*?[a,*] 4. Can these pathogens spread to other local shrimp species?* 5. Do alien pathogens cause an outbreak in local shrimp species? 6. What are the life-history traits of *L. vannamei* in its native ecosystems?
III. Reproduction of *L. vannamei* in the wild	1. Can *L. vannamei* reproduce in captivity?[b] 2. What is the correlation between the levels of gonad maturation and size of individuals raised in captivity?* 3. What are the levels of gonad maturation of individuals captured from the wild?* 4. Are the larvae and juveniles present in natural habitats? 5. Is the abundance of *L. vannamei* in the wild adequate to maintain a population? 6. Could *L. vannamei* hybridize with a local shrimp species? 7. If so, how successfully?	7. How do whiteleg shrimp compete for food with local shrimp species?* 8. Is *L. vannamei* territorial? 9. Does *L. vannamei* prey on other species? 10. What are other cascading interactions?

*Indicates research questions addressed by our research programme; [a]indicates information from the government database; [b]indicates information present in published journal articles.

from farms during a production cycle (3–4 months/cycle; 2–3 cycles/year), via pond cleaning after disease infections, routine water exchange in ponds or during harvests, or after a large flooding event. No large flooding events have occurred in this area since the mid-2000s.

To assess propagule pressure, we estimated the active areas from shrimp farming along the bank of the Bangpakong River using remote sensing and GIS techniques. Production-related estimates come from questionnaires and the government database. Our estimation of shrimp pond areas in the Bangpakong watershed in 2006 was 119.5 and 828.3 ha for active and inactive shrimp ponds, respectively, using a fusion technique to combine information from low-resolution and high-resolution satellite images taken in that year. These values were much lower than those estimated by the Department of Fisheries because our estimates included only water surface areas for shrimp ponds and excluded pond areas used for other purposes, such as reservoirs, fishponds and abandoned shrimp ponds. Also, our study focused only on areas within 10 km of each bank of the river. Our GIS mapping and analysis of satellite images indicates that approximately 70% of shrimp ponds are located within 5 km of the river.

Propagule pressure from shrimp aquaculture in this area can be substantial, given the high stocking densities, the lack of formal regulations to minimize escapes and the possibility of flooding. *Litopenaeus vannamei* are raised at a very high density (typical stocking density of PL_{15} = 80,000–150,000 individuals/1600 m^2; 500,000–937,500 individuals/ha), yielding 2–3 t shrimp/pond/production cycle. A typical pond size ranges from 2400 m^2 to 4000 m^2. The active pond areas alone can hold about 60–100 million individuals/production cycle. A small percentage of pond escapes per cycle could translate to significant numbers of individuals entering the ecosystem. Even though releases through flooding may not be a major factor in the Bangpakong River, this may not be true in some flood-prone shrimp farming areas in Thailand, such as some provinces further south, along the coast of the Gulf of Thailand.

The realization of this hazard was indicated by the presence of *L. vannamei* in the wild. *Litopenaeus vannamei* were captured from the wild in all the sampling periods of a 2-year field survey in the Bangpakong River (see Senanan *et al.*, 2007b; Panutrakul *et al.*, Chapter 6, this volume). The mean proportion of *L. vannamei* to total numbers of Penaeid shrimp/net ranged from 0.005 (July 2005) to 0.16 (January 2006). The proportion of nets containing *L. vannamei* ranged from 0.16 (3/19 nets, July 2005) to 1 (20/20 nets per sampling period, January 2006 and November 2006).

Hazard II. Survival of released L. vannamei *in the Bangpakong River*

Figure 5.4 identifies factors contributing to survival, including: (i) propagule pressure (resulting from Hazard I); (ii) the match between the physiological requirements of *L. vannamei* and habitat qualities in the Bangpakong estuary; (iii) the availability of natural diets; and (iv) the ability to avoid predation. Our research programme focused on factors (i) and (ii). To evaluate the match between the physiological requirements of *L. vannamei* and the habitat conditions of the Bangpakong River, we drew on existing data in published reports on the water quality of the Bangpakong River (Panutrakul *et al.*, 2000; Department of Marine and Coastal Resources, 2005; Senanan *et al.*, 2007b), as well as data from our experiments. The type of toxicological experiments conducted by Panutrakul *et al.* (Chapter 6) can illustrate the physiological limits of *L. vannamei* to extreme water quality changes compared to local shrimp species. Strategic decisions have to be made on the choice of candidate species using variables that reflect physiological tolerance and important water quality parameters. In our case, Panutrakul *et al.* (Chapter 6) estimated LC_{50}, a concentration of a chemical that kills 50% of tested animals within a given time (96 h) for *L. vannamei* and *P. monodon* exposed to rapid changes in salinities and pH. These water quality parameters are known to influence species distribution in an estuarine/marine ecosystem (Primavera, 1998; Rowe, 2002). In terms of salinity tolerance, juvenile *L. vannamei* could tolerate a wider range and more extreme changes of salinity than juvenile *P. monodon* (upper and lower salinity LC_{50} values were 0.02 and 44.85

part per thousand (ppt) for *L. vannamei* and 0.517 and 43.08 ppt for *P. monodon*). For the levels of pH tolerance, postlarvae of *L. vannamei* were more tolerant to low pH compared to postlarvae of *P. monodon* (upper and lower pH LC_{50} values were 4.56 and 8.71 for *L. vannamei* and 4.96 and 9.37 for *P. monodon*).

These data suggest that both life stages of *L. vannamei* could adapt to the estuarine conditions of the Bangpakong River where water quality, especially salinity, can fluctuate dramatically (Panutrakul *et al.*, 2000; Department of Marine and Coastal Resources, 2005; Senanan *et al.*, 2007b). Water temperature in the Bangpakong River ranges from 26.0 to 34.4°C; dissolved oxygen concentration ranges from 0.7 to 13.3 mg/l; pH ranges from 6.0 to 8.0. During the dry season (December–May), salinity ranges from 1.6 to 30.2 ppt; during the rainy season (June–November), salinity approaches zero at most sites. From existing data on the water quality of the Bangpakong River and the physiological and abundance data of *L. vannamei* in the wild, we conclude that *L. vannamei* are likely to survive in the Bangpakong River. However, it is still premature to conclude that the persistence of *L. vannamei* is because of natural reproduction (addressed in the following section).

Hazard III. Natural reproduction of L. vannamei

The persistence of *L. vannamei* in the wild could be because of repeated releases or natural reproduction. Natural reproduction would require released adults to be sexually mature and a high probability that mature adults could find mates (Fig. 5.3). Our research focused on evaluating the gonadal development of subadult shrimp captured in the wild (factor (i) above). To achieve this research objective, we first developed a baseline on the correlation between body size and stages of gonad development of individuals raised in captivity in Thailand (Senanan *et al.*, 2008). We then chose individuals larger than 10 cm for histology analysis (ongoing). Existing data in the published literature on the reproductive biology of this species are also valuable.

We compared the gonad histology of shrimp caught in the wild with those bred in captivity. Spawners used in commercial hatcheries in Thailand typically weigh 50–65 g (age > 1 year; unpublished data). Our preliminary baseline data on the gonad development of mature adults bred in captivity indicated that males were sexually mature at 11 months after PL_{15} (average length = 15.04 ± 9.6 cm and average weight = 34.3 ± 4.1 g), whereas females of a similar age and size had approximately 50% mature oocytes in their ovaries (Type III ovary based on the criteria developed by Kao *et al.* (1999)). A wild-caught female (21 g) had a Type II ovary consisting of primary and developing oocytes. Currently, we are increasing the sample size for this part of the study.

Although we have no evidence that the shrimp present in the wild could reach maturation in the Bangpakong River, we have observed evidence of gonadal development (from Type I ovary in an 11.64 g female to Type II ovary in a 21 g female). The typical size of spawners in captivity elsewhere is greater than 35 g (Palacios *et al.*, 2000; Ceballos-Vázquez *et al.*, 2003). However, there are no data on the minimum size of spawners in the wild. More data on the correlation of body size and stages of gonad development will allow us to extrapolate the reproductive capacity of individuals captured from the wild.

Risk analysis: harm/effect analysis

Spread of alien pathogens

This harm is pertinent to the health of wild shrimp populations and individuals raised on farms. A major disease outbreak on farms can result in significant economic loss (Rosenberry, 1995). A disease outbreak is an intersection of the presence of pathogens, inductive environmental conditions and susceptibility of host organisms. Outbreaks of Taura Syndrome Virus (TSV), a pathogen specific to *L. vannamei*, have been identified in cultured *L. vannamei* in China since 1999 (Tu *et al.*, 1999) and in Thailand since late 2002 (Nielson *et al.*, 2005).

Our study examined the presence of TSV in wild populations of local shrimp species in the Bangpakong River over two dry seasons (December–March) and two wet seasons (June–August) in both 2005 and 2006. We detected the presence of TSV using nested RT-PCR (IQ2000™ TSV Detection and Prevention System from Farming IntelliGene Tech Corp, Taiwan). TSV was found to be present in *L. vannamei* captured from the wild, as well as in several local shrimp species, namely *P. monodon*, *P. semisucatus*, *P. merguiensis*, *Metapenaeus affinis*, *M. brevicornis*, *M. tenuipes*, *Parapenopsis hungerfordi* and *Macrobranchium rosenbergii* (Table 5.3). The occurrence of TSV differed by season, with a lower incidence of the pathogen in the wet season. The overall occurrence of TSV in local shrimp species was 25.75% (dry season, 2005), 3.30% (wet season, 2005), 12.08% (dry season, 2006) and 8.72% (wet season, 2006). We also detected the presence of TSV in *L. vannamei* captured in 2006 from the Bangpakong River, with an occurrence of TSV of 23.88% and 2.22% for dry and wet seasons, respectively. The presence of TSV in wild shrimp species raises a concern over the increased virulence of this pathogen and outbreaks in local shrimp species. A combination of monitoring the prevalence of TSV as well as the outbreaks will be important for appropriate management and conservation strategies.

Food competition

An alien species could also potentially interact with local species through food competition, either by exploitative or interference competition. The better competitor of the former type can utilize more of the limited food resources compared to others. On the other hand, a better competitor of the second type exhibits behaviours, such as territoriality or biting, that interfere with other species' ability to utilize resources. Analytical steps to address this potential harm were to: (i) determine natural diets; (ii) select candidate native species potentially competing for food with *L. vannamei*; (iii) observe feeding behaviour; and (iv) perform competition experiments in laboratory and natural settings. Our research focuses on steps (i)–(iii). Panultrakul *et al.* (Chapter 6) present more detailed methods and results. Briefly, to determine natural diets, Panutrakul *et al.* (Chapter 6) analysed the gut contents of *L. vannamei* and local shrimp species (*P. merguiensis*, *P. monodon*, *Metapenaeus* spp., *Macrobrachium* spp.). Specimens used for the gut content analyses were subsets of individuals sampled in abundance surveys (Senanan *et al.*, 2007b); the selected specimens were collected at the same site in January 2005. Stomach content data indicated that *L. vannamei* ingested the same diet types (phytoplankton,

Table 5.3. Taura Syndrome Virus (TSV) in captured feral *L. vannamei* and native shrimp species.[a]

		2004–2005		2006	
Family	Species	Dry season 2004	Wet season 2005	Dry season	Wet season
Penaeidae	*Litopenaeus vannamei*	N/A	N/A	+32/134	+1/45
	Penaeus monodon	+2/17	+0/15	+1/4	+1/25
	P. merguiensis	N/A	+2/10	+0/10	+0/16
	P. semisucatus	N/A	N/A	+3/3	N/A
	Metapenaeus brevicornis	+4/10	+1/10	+2/28	+8/27
	M. tenuipes	N/A	N/A	N/A	+0/11
	M. affinis	+3/10	+1/10	N/A	+0/26
	Parapeneopsis hungerfordi	+1/10	+1/10	+5/11	+0/6
Caridae	*Macrobrachium rosenbergii*	+3/3	+0/28	+0/25	+10/92
	Macrobrachium spp.	+2/6	+0/10	+0/10	+0/11
Prevalence in *L. vannamei* (%)		N/A	N/A	23.88	2.22
Prevalence in local shrimp species (%)		25.75	3.30	12.08	8.72

[a] Values in each cell indicate the number of samples that tested positive for TSV to total numbers of individuals screened (N/A indicates no data available).

appendages of crustacean zooplankton and detritus materials) and in similar proportions to several local shrimp species. These data, however, are insufficient to suggest that *L. vannamei* can outcompete local shrimp species for food.

Panutrakul *et al*. (Chapter 6) also attempted to evaluate feeding behaviours that might lead to food competition. They conducted a set of experiments to determine the feeding interactions of *L. vannamei* and other local species in a microcosm setting. The local shrimp and crab species chosen for the experiments co-occur with *L. vannamei* in the Bangpakong River. The shrimp species included in the experiments were *P. merguiensis*, *P. monodon*, *M. brevicornis* and *M. ensis*. In the experiments, a small piece of shrimp meat (0.5 g) was offered to one individual of *L. vannamei* and one individual of a local species (four combinations, ten trials for each combination). For each species combination, *L. vannamei* approached the food faster than the local species in most trials (> 80%). Although these results imply *L. vannamei*'s competitive advantage over some native shrimp species for food in the wild, it is still premature to draw a conclusion on the potential ecological impacts. Additional experiments in microcosms and semi-natural conditions will be needed to determine possible mechanisms (i.e. exploitative versus interference) and the impacts of the competition (e.g. growth differential and survival).

Conclusions

Our data contribute to the risk assessment of *L. vannamei* as follows: (i) the data indicate realized hazards in an important river basin in Thailand and an early sign of realized harm (i.e. the presence of TSV in wild shrimp populations); (ii) the research programme generates necessary baseline data (e.g. location of aquaculture areas in the Bangpakong, physiological tolerance of *L. vannamei* and its reproductive capacity); and (iii) the programme lays out a foundation for data generation for risk assessment of *L. vannamei* in Thailand and elsewhere. However, further data must be generated to complete the analytical component of the risk assessment decision-making process. We emphasize the use of a systematic framework, as well as existing literature and well-designed experiments and surveys. Some analytical steps only require extensive reviews of grey and published literature and existing databases. For example, if it is likely that *L. vannamei* can be released into the wild (considering the geographic connection between aquaculture facilities and natural water bodies) and if water quality parameters (from published literature or government databases) are within the tolerance range of *L. vannamei* (from existing literature such as ours), researchers may forego extensive experiments on physiological limits and focus their limited resources on assessing subcomponents giving rise to important ecological interactions, such as food and habitat competition.

To avoid severe ecological damage, it is ideal to plan risk assessment and risk management prior to an alien species introduction. Unfortunately, several alien species had already been introduced in many aquatic ecosystems before data became available. In locations where *L. vannamei* have already been introduced, data generated from a monitoring programme and a retrospective risk analysis, such as ours, can be valuable to inform risk assessment elsewhere. This type of data can also serve as baseline data for risk reduction and mitigation measures. For Thailand, our results indicate a need to reduce escapes. Even though we have not found direct evidence of the reproduction of *L. vannamei* in the Bangpakong River, reducing propagule pressure will limit the opportunities for survivors to find mates, and thus limit natural reproduction (Fig. 5.4). The reduction of releases may range from reducing escapes during production cycles to implementing additional barriers. An indicator for effective release reduction measures may include reduced frequency of encounters compared to our abundant data.

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References

Allendorf, F.W., Leary, R.F., Spruell, P. and Wenburg, J.K. (2001) The problems with hybrids: setting conservation guidelines. *Trends in Ecology and Evolution* 16, 613–622.

Bartley, D.M. and Gall, G.A.E. (1991) Genetic identification of native cutthroat trout (*Oncorhynchus clarki*) and introgressive hybridization with introduced rainbow trout (*O. mykiss*) in streams associated with the Alvord Basin, Oregon and Nevada. *Copeia* 3, 854–859.

Bartley, D.M., Bhujel, R.C., Funge-Smith, S., Olin, P.G. and Phillips, M.J. (eds) (2005) International mechanisms for the control and responsible use of alien species in aquatic ecosystems. Report of an Ad Hoc Expert Consultation, Xishuangbanna, People's Republic of China, 27–30 August 2003. FAO, Rome.

Bartley, D.M., Bondad-Reantaso, M.G. and Subasinghe, R.P. (2006) A risk analysis framework for aquatic animal health management in marine stock enhancement programmes. *Fisheries Research* 80, 28–36.

Briggs, M., Funge-Smith, S., Subasinghe, R.P. and Phillips, M. (2004) *Introductions and Movement of* Penaeus vannamei *and* Penaeus stylirostris *in Asia and the Pacific*. RAP Publication 2004/10. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand.

Byers, J. (2000) Competition between two estuarine snails: implications for invasions of exotic species. *Ecology* 81, 1225–1239.

Ceballos-Vázquez, B.P., Rosasc, C. and Racotta, I.S. (2003) Sperm quality in relation to age and weight of white shrimp *Litopenaeus vannamei*. *Aquaculture* 228, 141–151.

De Silva, S.S. (1989) Exotics – global perspective with special reference to finfish introduction to Asia. In: De Silva, S.S. (ed.) *Exotic Aquatic Organisms in Asia. Proceedings of the Workshop on Introduction of Exotic Aquatic Organisms in Asia*. Asian Fisheries Society Special Publication 3. Asian Fisheries Society, Manila, pp. 1–6.

De Silva, S.S., Nguyen, T.T.T., Abery, N.W. and Amarasinghe, U.S. (2006) An evaluation of the role and impacts of alien finfish in Asian inland aquaculture. *Aquaculture Research* 37, 1–17.

Department of Marine and Coastal Resources (2005) *Bangpakong Estuary Ecosystem*. Eastern Marine and Coastal Research Center, Department of Marine and Coastal Resources. Chulalongkorn University Printing House, Bangkok.

Devlin, R.H., Sundström, L.H., Johnsson, J.I., Fleming, I.A., Hayes, K.R., Ojwang, W.O., Bambaradeniya, C. and Zakaraia-Ismail, M. (2007) Chapter 6: Assessing ecological effects of transgenic fish prior to entry into nature. In: Kapuscinski, A.R., Hayes, K.H., Li, S. and Dana, G. (eds) *Environmental Risk Assessment of Genetically Modified Organisms, Volume 3: Methodologies for Transgenic Fish*. CAB International, Wallingford, UK, pp. 151–187.

DOF (Department of Fisheries) (1999–2005) Fisheries statistics of Thailand (1999–2004). Fishery Information Technology Center, Department of Fisheries. Ministry of Agriculture and Cooperatives, Bangkok.

DOF (Department of Fisheries) (2009) Status of production, price and trade of Thai shrimp. Fisheries Economics Division, Bangkok (http://fishco.fisheries.go.th/fisheconomic/Shrimp_magazine_Quarter1_52.php, accessed November 2009).

Goldschmidt, J., Witte, F. and Wanink, J. (1993) Cascading effects of the introduced Nile perch on the distritivorous/phytoplantivorous species in the sublitoral areas of Lake Victoria. *Conservation Biology* 7, 686–700.

Grosholz, E.D. (2005) Recent biological invasion may hasten invasional meltdown by accelerating historical introductions. *PNAS* 102, 1088–1091.

Grosholz, E.D., Ruiz, G.M., Dean, C.A., Shirley, K.A., Maron, J.L. and Connors, P.G. (2000) The impacts of a non-indigenous marine predator in a California bay. *Ecology* 81, 1206–1224.

Gurevitch, J. and Padilla, D.K. (2004) Are invasive species a major cause of extinction? *Trends in Ecology and Evolution* 19, 470–474.

Hayes, K.H., Kapuscinski, A.R., Dana, G., Li, S. and Devlin, R.H. (2007) Introduction to environment risk assessment for transgenic fish. In: Kapuscinski, A.R., Hayes, K.H., Li, S. and Dana, G. (eds) *Environmental Risk Assessment of Genetically Modified Organisms, Volume 3: Methodologies for Transgenic Fish*. CAB International, Wallingford, UK, pp. 1–28.

Hitt, N.P., Frissell, C.A., Muhlfeld, C.C. and Allendorf, F.W. (2003) Spread of hybridization between native westslope cutthroat trout, *Oncorhynchus clarki lewisi*, and non-native rainbow trout, *Oncorhynchus mykiss*. *Canadian Journal of Fisheries and Aquatic Sciences* 60, 1440–1451.

Johnson, L.E. and Padilla, D.K. (1996) Geographic spread of exotic species: ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha*. *Biological Conservation* 78, 23–33.

Kao, H.C., Chan, T.Y. and Yu, H.P. (1999) Ovary development of the deep-water shrimp *Aristaeomorpha foliavea* (Risso, 1826) (Crustacea: Decapoda: Aristeidae) from Taiwan. *Zoological Studies* 38, 373–378.

Kapuscinski, A.R. (2002) Controversies in designing useful ecological assessments of genetically engineered organisms. In: Letourneau, D. and Burrows, B. (eds) *Genetically Engineered Organisms: Assessing Environmental and Human Health Effects*. CRC Press, Boca Raton, Florida, pp. 385–415.

Kapuscinski, A.R. (2005) Current scientific understanding of the environmental biosafety of transgenic fish and shellfish. *Revue Scientifique et Technique de l'Office International des Epizooties* 24, 309–322.

Kapuscinski, A.R., Hard, J.J., Paulson, K.M., Neira, R., Ponniah, A., Kamonrat, W., Ojwang, W.O., Bambaradeniya, C. and Zakaraia-Ismail, M. (2007) Approach to assessing gene flow. In: Kapuscinski, A.R., Hayes, K.H., Li, S. and Dana, G. (eds) *Environmental Risk Assessment of Genetically Modified Organisms, Volume 3: Methodologies for Transgenic Fish*. CAB International, Wallingford, UK, pp. 112–150.

Koehn, J.D. (2004) Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways. *Freshwater Biology* 49, 882–894.

Kolar, C.S. and Lodge, D.M. (2002) Ecological predictions and risk sssessment for alien fishes in North America. *Science* 298, 1233–1236.

Lockwood, J.L., Cassey, P. and Blackburn, T. (2005) The role of propagule pressure in explaining species invasions. *Trends in Ecology and Evolution* 20, 223–228.

Mair, G.C., Nam, Y.K. and Solar, I.I. (2007) Risk management: reducing risk through containment of transgenic fish. In: Kapuscinski, A.R., Hayes, K.H., Li, S. and Dana, G. (eds) *Environmental Risk Assessment of Genetically Modified Organisms, Volume 3: Methodologies for Transgenic Fish*. CAB International, Wallingford, UK, pp. 209–238.

Marchetti, M.P., Moyle, P.B. and Levine, R. (2004) Invasive species profiling? Exploring the characteristics of non-native fishes across invasion stages in California. *Freshwater Biology* 49, 646–661.

Miller, L.M., Kapuscinski, A.R. and Senanan, W. (2004) Biosafety approach risks posed by aquaculture escapees. In: Gupta, M.V., Bartley, D.M. and Acosta, B.O. (eds) *Use of Genetically Improved and Alien Species for Aquaculture and Conservation of Aquatic Biodiversity in Africa*. WorldFish Center, Penang, Malaysia, pp. 56–65.

Moyle, P.B. and Light, T. (1996) Biological invasions of fresh water: empirical rules and assembly theory. *Biological Conservation* 78, 149–161.

Na-Nakorn, U., Kamonrat, W. and Ngamsiri, T. (2004) Genetic diversity of walking catfish, *Clarias macrocephalus*, in Thailand and evidence of genetic introgression from introduced farmed *C. gariepinus*. *Aquaculture* 240, 145–163.

Naylor, R.L., Williams, S.L. and Strong, D.R. (2001) Aquaculture – a gateway for exotic species. *Science* 294, 1655–1656.

Nielson, L., Sang-oum, W., Cheevadhamarak, S. and Flegel, T. (2005) Taura syndrome virus (TSV) in Thailand and its relationships to TSV in China and the Americas. *Diseases of Aquatic Organisms* 63, 101–106.

NRC (National Research Council) (2004) *Biological Confinement of Genetically Engineered Organisms*. National Academic Press, Washington, DC.

Palacios, E., Ibarra, A.M. and Racotta, I.S. (2000) Tissue biochemical composition in relation to multiple spawning in wild and pond-reared *Penaeus vannamei* broodstock. *Aquaculture* 185, 353–371.

Panutrakul, S., Musika, S. and Mokkongpai, P. (2000) Behavior of heavy metals in the Bangpakong River. Technical report to the National Research Council of Thailand [in Thai]. Department of Aquatic Science, Burapha University, Chonburi, Thailand.

Perez Farfante, I. and Kensley, B. (1997) *Penaeoid and Sergestoid Shrimps and Prawns of the World. Keys and Diagnoses for the Families and Genera*. Memories du Museum National D'Historie Naturelle, Paris.

Primavera, J.H. (1998) Mangroves as nurseries: shrimp populations in mangrove and non-mangrove habitats. *Estuarine, Coastal and Shelf Science* 46, 457–464.

Robinson, T.B., Griffiths, C.L., McQuaid, C.C. and Rius, M. (2005) Marine alien species of South Africa – status and impacts. *African Journal of Marine Science* 27, 297–306.

Rosenberry, B. (ed.) (1995) Taura, Taura, Taura. *Shrimp News International* 20, 1–10.

Rossong, M.A., Williams, P.J., Comeau, M., Mitchell, S.C. and Apaloo, J. (2006) Agonistic interactions between the invasive green crab, *Carcinus maenas* (Linnaeus) and juvenile American lobster, *Homarus americanus* (Milne Edwards). *Journal of Experimental Marine Biology and Ecology* 329, 281–288.

Rowe, C.L. (2002) Differences in maintenance energy expenditure by two estuarine shrimp (*Palaemonetes pugio* and *P. vulgaris*) that may permit partitioning of habitats by salinity. *Comparative Biochemistry and Physiology Part A* 132, 241–351.

Royal Society (Great Britain), Study Group on Risk (1983) Risk assessment: report of a Royal Society Study Group. The Royal Society, London.

Senanan, W., Kapuscinski, A.R., Na-Nakorn, U. and Miller, L.M. (2004) Genetic impacts of hybrid catfish farming (*Clarias macrocephalus* x *C. gariepinus*) on native catfish populations in central Thailand. *Aquaculture* 235, 167–184.

Senanan, W., Hard, J.J., Alcivar-Warren, A., Trisak, J., Zakaraia-Ismail, M. and Lorenzo Hernandez, M. (2007a) Risk management: post-approval monitoring and remediation. In: Kapuscinski, A.R., Hayes, K.H., Li, S. and Dana, G. (eds) *Environmental Risk Assessment of Genetically Modified Organisms, Volume 3: Methodologies for Transgenic Fish*. CAB International, Wallingford, UK, pp. 239–271.

Senanan, W., Tangkrock-Olan, N., Panutrakul, S., Barnette, P., Wongwiwatanawute, C., Niphonkit, N. and Anderson, D.J. (2007b) The presence of the Pacific whiteleg shrimp (*Litopenaeus vannamei*, Boone, 1931) in the wild in Thailand. *Journal of Shellfish Research* 26, 1187–1192.

Senanan, W., Barnette, P., Ponsombut, K. and Tangkrock-Olan, N. (2008) Gonadal development of Pacific whiteleg shrimp (*Litopenaeus vannamei*) raised in captivity and caught from the wild. In: Panutrakul, S. and Senanan, W. (eds) *Aquaculture Management Strategies for the Pacific Whiteleg Shrimp* (Litopenaeus vannamei) *in the Bangpakong River basin and the East Coast of Thailand*. Burapha University, Chonburi, Thailand [in Thai], pp. 51–75.

Stern, P.C. and Fineberg, H.V. (eds) (1996) *Understanding Risk: Informing Decisions in a Democratic Society*. Committee on Risk Characterization, Commission on Behavioral and Social Sciences and Education, National Research Council. National Academy Press, Washington, DC.

Tu, C., Huang, H.T., Chuang, S.H., Hsu, J.P., Kuo, S.T., Li, N.J., Hsu, T.L., Li, M.C. and Lin, S.Y. (1999) Taura syndrome virus in Pacific white shrimp *Penaeus vannamei* in Taiwan. *Diseases of Aquatic Organisms* 38, 159–161.

Witte, F., Goldschmidt, T., Wanink, J., Van Oijen, M., Goudswaard, K., Witte-Maas, E. and Bouton, N. (1992) The destruction of an endemic species flock: quantitative data on the decline of the haplochromine cichlids of Lake Victoria. *Environmental Biology of Fishes* 34, 1–28.

Zambrano, L., Martinez-Meyer, E., Menezes, N. and Peterson, A.T. (2006) Invasive potential of common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in American freshwater systems. *Canadian Journal of Fisheries and Aquatic Sciences* 63, 1903–1910.

6 Ability of *Litopenaeus vannamei* to Survive and Compete with Local Marine Shrimp Species in the Bangpakong River, Thailand

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Abstract

Potential ecological damage caused by the introduction of *Litopenaeus vannamei* (Pacific whiteleg shrimp) for aquaculture in Thailand's Bangpakong watershed depends on its ability to survive environmental conditions and compete for food with local shrimp species. To examine this, we determined: (i) the physiological tolerance of *L. vannamei* and *Penaeus monodon* to extreme pH and salinity; (ii) the persistence of *L. vannamei* in the wild; (iii) the stomach contents of *L. vannamei* and local shrimp species; and (iv) the ability of *L. vannamei* to compete for food with selected local shrimp species in aquaria. Toxicity experiments showed that *L. vannamei* could tolerate a wider range of salinity and pH than *P. monodon. Litopenaeus vannamei* were captured in all sampling periods and the mean proportion of *L. vannamei* to total numbers of Penaeid shrimp per net ranged from 0.005 (July 2005) to 0.16 (January 2006). Stomach content analyses indicated diet overlap between wild-caught *L. vannamei* and local shrimp species (*Metapenaeus brevicornis, M. tenuipes, M. ensis, P. merguiensis* and *P. monodon*) and food competition experiments showed that *L. vannamei* approached food more quickly than local species. Our results suggest that a sustained population of *L. vannamei* may pose a threat to local biodiversity. Information generated from our study will be important for designing in-depth risk assessment experiments in semi-natural settings and for defining monitoring end points to detect ecological harm.

Introduction

Shrimp farming in Thailand shifted from the extensive cultivation of species such as *P. merguiensis*, *P. indicus* and *M. monoceros* to the production of black tiger (*P. monodon*) during the mid-1980s after the importation of intensive shrimp production technology from Taiwan (Tookwinas, 1993). Black tiger shrimp farming expanded rapidly into saltpans and mangroves along the lower Chao Phraya Delta and to the eastern and southern coasts of Thailand. A crash of black tiger shrimp farming occurred in the early 1990s when outbreaks of White Spot Syndrome Virus (WSSV) and Yellow Head Virus (YHV) were created by self-pollution and general environmental degradation. To solve these problems, low salinity shrimp farming techniques were developed and expanded quickly to inland agricultural areas such as rice fields in the Chao Phraya Delta (Tiensosngrusmee, 2000; Szuster, 2001). Further disease outbreaks, poor growth performance and declining prices for *P. monodon* led to the introduction of *L. vannamei* (Pacific whiteleg shrimp) into Thailand in 1998 (Briggs

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

et al., 2005; Ekmaharaj, 2005). *Litopenaeus vannamei* is native to the Pacific coasts of Central and South America (Perez Farfante and Kensley, 1997) and is known for its tolerance to a wide salinity range and its fast growth rate in brackish water (Holthuis, 1980).

The Bangpakong River is one of the most important rivers in eastern Thailand. It is formed by the Nakornayok and Prachinburi rivers and runs through Bangklah, Meung, Baan Poh and Bangpakong Districts of Chachoengsao Province, with a total length of 122 km (Fig. 6.1).

The estuarine condition of the river allowed the conversion of rice fields in Bangpakong watershed to low salinity black tiger shrimp farms and, during the dry season, fields can be flooded with brackish water from the river. The boom of low salinity shrimp farming along the Bangpakong River in Chachoengsao Province started in the early 1990s. Between 1999 and 2001, the total area of black tiger shrimp farms in this province was about 50,000 rai (8000 ha) and about 30,000 t of black tiger shrimp were produced annually. The area used for black tiger shrimp farming in Chachoengsao Province dropped to about 38,000 rai (6000 ha) in 2002 as a result of viral disease outbreaks, but a drastic increase in *L. vannamei* culture occurred in 2003, with this species suddenly increasing to more than 80% of the total shrimp production (Department of Fisheries, 1999–2005).

Rapid expansion of *L. vannamei* aquaculture and improper management of farms led to the escape of this alien species into the Bangpakong River (Senanan *et al*., 2007). The ability of escaped individuals or their offspring to survive in the wild is a key factor affecting the magnitude of ecological change associated with the spread of *L. vannamei*. This chapter

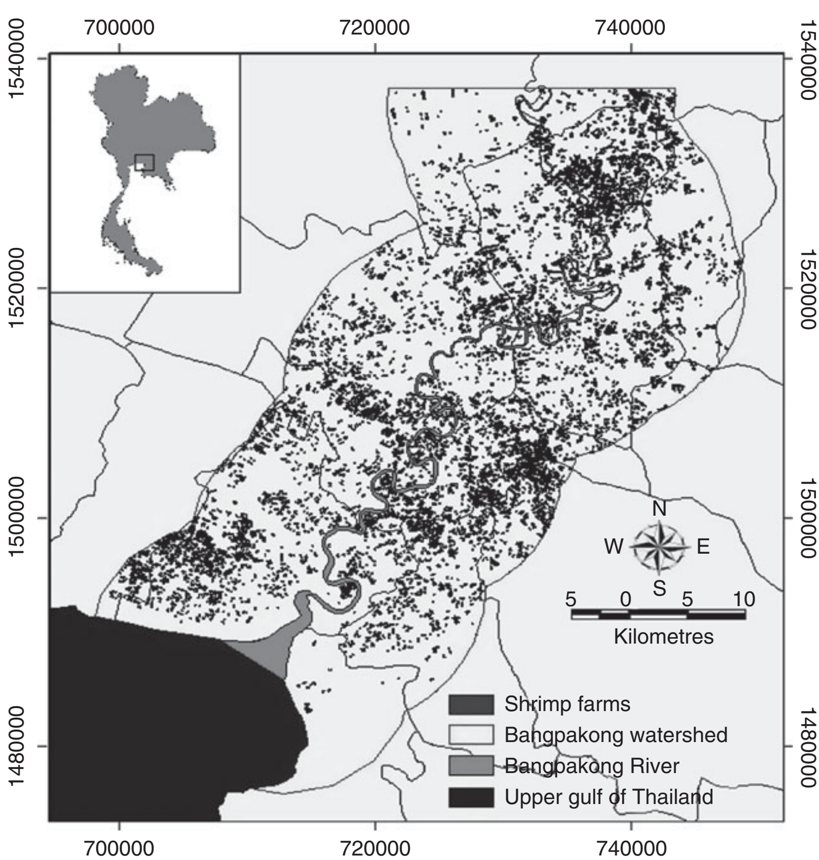

Fig. 6.1. Bangpakong River and shrimp farming areas (*P. intacharoen*).

presents the results from several related studies that address the question of the survival of *L. vannamei* and potential food competition with local shrimp species in the Bangpakong River. We compare the tolerance of *L. vannamei* and *P. monodon* to extreme pH and salinity and support these findings with a 2-year field survey of *L. vannamei* persistence and abundance relative to local shrimp populations. We also compare the stomach contents of *L. vannamei* and some local shrimp species collected from the Bangpakong River and evaluate the ability of *L. vannamei* to compete for food with selected local shrimp species in aquaria. These data represent important inputs to a risk assessment of *L. vannamei* introduced outside of their native range, and the outcome of the risk assessment is essential for management planning for *L. vannamei* aquaculture in coastal Thailand.

Materials and Methods

Effects of changing salinity and pH on survival

Postlarvae (P_{10} to P_{15}) and juveniles (1–2 months old) of *L. vannamei* and *P. monodon* were obtained from hatcheries and shrimp farms in Chonburi and Chachoengsao Provinces. The total length and weight of the postlarvae were 10–15 mm and 0.1–0.3 g, respectively, whereas the total length and weight of the juveniles were 5–7 cm and 1.0–2.0 g, respectively. Test animals were acclimated in 25‰ seawater for 5 days in the laboratory prior to experimentation. During this acclimation period, postlarvae and juveniles were fed twice daily with brine shrimp and commercial pellets, respectively. Seawater and fresh water used in the experiment were sterilized with calcium hypochlorite ($Ca(OCl)_2$) and aerated for 1 week to eliminate chlorine residue. The desired salinities of 0, 5, 10, 15, 20, 25, 30, 35 and 40‰ were obtained by diluting seawater with fresh water or by adding sea salt. Citric acid-1-hydrate and $Na_2HPO_4.2H_2O$ solutions were added to 25‰ seawater to prepare seawater with pH ranging from 3 to 8. The alkaline seawater (pH 9 and 10) was prepared by adding $NaHCO_3$ and NaOH solutions to 25‰ seawater to obtain the desired pH.

A 96-h semi-static bioassay technique was used to test the effect of changing salinity and pH on postlarvae and juveniles of *L. vannamei* and *P. monodon*. We followed a generic protocol for conducting tropical acute toxicity tests with fish and invertebrates (CIDA, 1993). Individual postlarvae and juvenile shrimp were placed in vessels containing 250 ml and 1000 ml of test solution, respectively. Test organisms were starved during the entire test period. About 75% of the test solution was replaced by fresh test solution every 24 h until the end of the experiment. Water temperature, salinity, pH and dissolved oxygen content were measured each day before and after changing the test solution. Mortality of test organisms was recorded at 4, 12, 24, 48, 72 and 96 h and each experiment was carried out in triplicate. Ninety-six-hour LC_{50} was calculated using EFFL software (CIDA, 1993).

Abundance of *L. vannamei* in the Bangpakong River

Shrimp samples were collected from three to four sites in the Bangpakong River, representing the upstream to downstream portions, between January 2005 and November 2006 (see Fig. 6.1).

This encompassed three districts of Chachoengsao Province: Bangklah (one site, 69 km from the river mouth), Muang (one site, 45.8 km from the river mouth) and Bangpakong (two sites, 10.5 and 6.5 km from the river mouth). Shrimp sampling methods are described in Senanan *et al*. (Chapter 5, this volume). Wild shrimp were captured during the hours of the ebb of a major tide using stow nets (5 m deep × 25 m long with 2.5 cm mesh), which were set for 6 h. The nets were set along the main channel of the river. Shrimp were collected in seven sampling periods, with three occurring in 2005 (January–March, June and September–November) and four in 2006 (January, May, July and November). The numbers of nets at each site during the 2006 sampling season ranged from five to ten, depending on the conditions of the river (i.e. flow rates, depth and width). The total number of nets ranged from 20 to 25 in each sampling period.

Penaeid shrimp were sorted from other crustaceans, molluscs, fish and debris at the laboratory at Burapha University (Thailand), with each shrimp identification based on Penaeid keys for South-east Asia and Australia (Grey *et al.*, 1983; Dall *et al.*, 1990; Leelapiyanart, 1992; Perez Farfante and Kensley, 1997) to the lowest possible taxon. We quantified the presence of *L. vannamei* in terms of the number of this species in relation to other Penaeid shrimp in each net (i.e. proportion per net) and the frequency of encounter (number of nets containing *L. vannamei* to the total number of nets collected in the sampling period). Measurements for each captured *L. vannamei* included: total length (cm) and postorbital carapace length (PO-CL is the distance between the postorbital eye socket and posterior median edge of the cephalothorax) to the nearest 0.1 mm using calipers. The total lengths of individuals captured between January and March of 2005 ($n = 29$) were approximated by the regression of the standard length (cm) and total length (cm) of individuals of similar size captured in other sampling periods. We tested for changes in the means of proportions and body lengths through time using ANOVA.

Stomach content analysis

Specimens were collected for gut content analysis between January and March 2005 in the Bangpakong River using the same methods described in Senanan *et al*. (Chapter 5). All specimens were collected at the same location, with gut content analysis conducted on 30 individuals of similar size (PO-CL = 1.4–3.0 cm) per species of the following: *L. vannamei*, *M. brevicornis*, *M. tenuipes*, *M. ensis*, *P. merguiensis* and *P. monodon*. The percentage of different foods was determined by spreading the contents of each stomach evenly on a 100-point grid using a dissecting microscope to identify diet types on each point. Diet types were categorized into five main groups: phytoplankton, appendages of crustaceans, vegetal matter (macroalgae, seagrass and plant tissues), shells of molluscs and digested matter (small particles that could not be identified). One-way ANOVA was performed to examine differences in the percentage of each diet type among shrimp species.

Food competition

In the laboratory experiments to evaluate food competition between native and non-native species, *M. brevicornis*, *M. ensis*, *P. merguiensis* and *P. monodon* were used as representatives of native shrimps. *M. brevicornis*, *M. ensis* and *P. merguiensis* were collected by pushnet from the Bangpakong River or an extensive shrimp rearing pond. *Litopenaeus vannamei* and *P. monodon* were obtained from shrimp farms. All animals were acclimated in the laboratory for at least 2 weeks prior to experimentation. Individuals were fed with fresh shrimp meat during the acclimation period and this was also used during the food competition experiment. Individuals were starved for 1 day prior to the start of experiment trials in which each aquarium received one individual of a native shrimp species and one individual of *L. vannamei*. A piece of fresh shrimp meat (0.5 g) was placed in the middle of the aquarium to allow for visual observations and the experiment was recorded by video camera. Observers noted which individual was first to approach and reach the food item. Four treatments were used to compare *L. vannamei* with the other shrimp species, with each treatment having ten replicates. In each trial, the animal that caught and ate the food item first was considered to outcompete the animal with which it was paired. Results from the ten trials for each treatment (species pairing) were converted to percentages.

Results

Effects of changing salinity

The average 96-h LC_{50} of a rapid change in salinity for postlarvae of *L. vannamei* was 0.4‰ at low salinity (0–25‰) and 30.23‰ at high salinity (20–40‰) (Figs 6.2 and 6.3). Juveniles of *L. vannamei* tolerated a wider range of salinity than postlarvae. The average 96-h LC_{50} of changing salinity for juveniles of *L. vannamei* was 0.02‰ at low salinity and 44.85‰ at high salinity. The postlarvae of *P. monodon* tend to tolerate slightly higher salinity than postlarvae of *L. vannamei*. The average 96-h LC_{50} of changing salinity on postlarvae of *P. monodon*

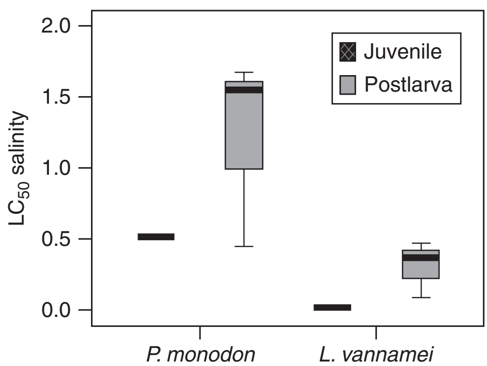

Fig. 6.2. 96-hour LC_{50} of low salinity (0–20‰) for postlarvae and juveniles of *L. vannamei* and *P. monodon.*

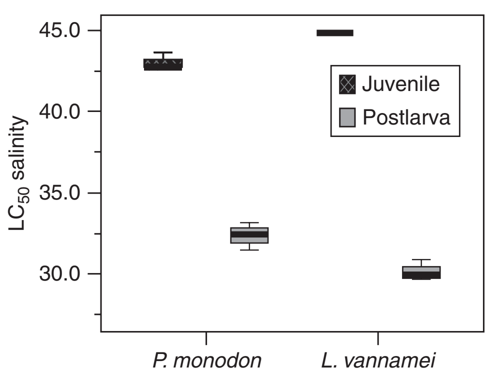

Fig. 6.3. 96-hour LC_{50} of high salinity (20–40‰) for postlarvae and juveniles of *L. vannamei* and *P. monodon.*

was 1.22‰ at low salinity and 32.42‰ at high salinity. Juveniles of *P. monodon* tolerated a wider range of salinity than postlarvae. The average 96-h LC_{50} of changing salinity on juveniles of *P. monodon* was 0.52‰ at low salinity and 43.08‰ at high salinity.

Effect of changing pH

The average 96-h LC_{50} of changing pH on postlarvae of *L. vannamei* was 4.96 at low pH and 9.37 at high pH. Juveniles of *L. vannamei* tolerated higher pH than postlarvae. The average 96-h LC_{50} of changing pH on juvenile *L. vannamei* was 5.11 at low pH and 8.76 at high pH. The average 96-h LC_{50} for a rapid change in pH on postlarvae of *P. monodon* was 4.56 at low pH (3–8) and 8.71 at high pH (7–10) (Figs 6.4 and 6.5). Juveniles of *P. monodon* tolerated a narrower pH range than postlarvae.

The average 96-h LC_{50} of changing pH on juvenile *P. monodon* was 5.7 at low pH and 9.51 at high pH.

Abundance and size distribution

Litopenaeus vannamei were captured in all sampling periods, with the mean proportion of *L. vannamei* per net ranging from 0.005 (July 2005) to 0.16 (January 2006) (Fig. 6.6). Local shrimp species in the samples included *P. monodon*, *P. merguiensis*, *M. ensis*,

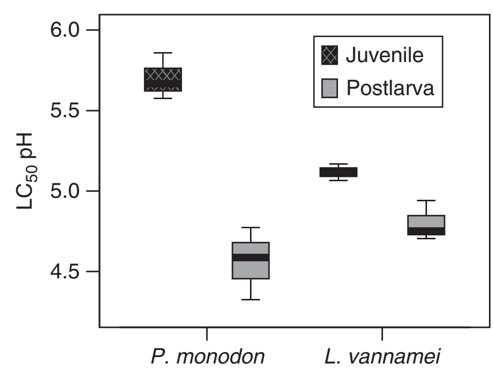

Fig. 6.4. 96-hour LC_{50} of low pH (3–8) for postlarvae and juveniles of *L. vannamei* and *P. monodon.*

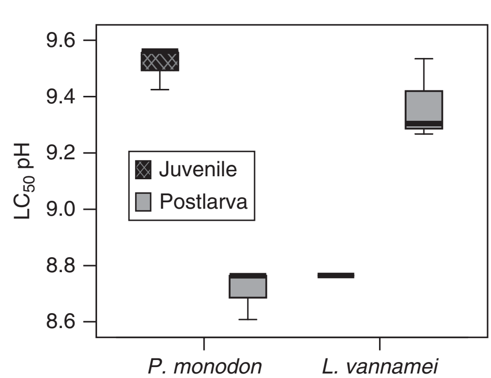

Fig. 6.5. 96-hour LC_{50} of high pH (7–10) for postlarvae and juveniles of *L. vannamei* and *P. monodon.*

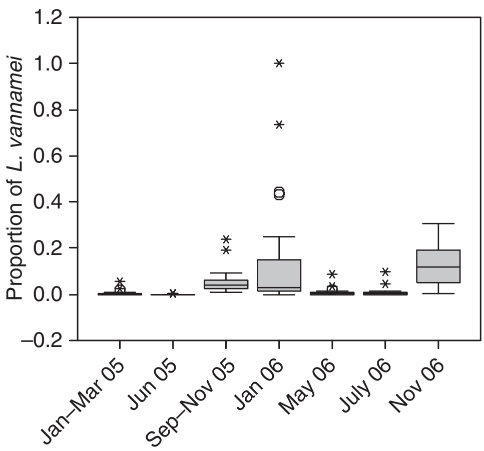

Fig. 6.6. *Litopenaeus vannamei* abundance relative to total number of Penaeid shrimp species in Bangpakong River (January 2005–November 2006).

M. affinis, *M. brevicornis*, *M. tenuipes*, *M. moyebi*, *Parapenaeopsis hungerford* and *Macrobrachium* spp. The proportion of nets containing *L. vannamei* ranged from 0.16 (3/19 nets, July 2005) to 1 (20/20 nets per sampling period in January 2006 and November 2006). The relative abundance estimated for 2006 (0.06 ± 0.142) was significantly higher than for 2005 (0.02 ± 0.04; $p = 0.013$). The size of *L. vannamei* caught in the Bangpakong River ranged from 5.5 to 17.2 cm for total length (Fig. 6.7) and from 1.13 to 3.74 cm for carapace length (PO-CL).

The mean total length was 9.64 ± 1.60 cm (2.24 ± 0.40 cm PO-CL) and 10.34 ± 1.46 cm (2.12 ± 0.60 cm) for individuals captured in 2005 and 2006, respectively. The mean total length of *L. vannamei* collected in 2006 was significantly higher than that of *L. vannamei* collected in 2005 ($p < 0.001$).

Stomach content analysis

Our results show five diet types in shrimp stomachs: (i) phytoplankton (e.g. diatom, centric diatom and triceratium); (ii) appendages of crustaceans; (iii) vegetal matter (including macroalgae, seagrass and plant tissues); (iv) shells of molluscs; and (v) digested matter (Fig. 6.8). Digested matter was the major diet type found in the stomachs of both native and non-native shrimps (from 41.72 to 55.37% of the total contents). There was a statistically significant difference in the percentage of digested matter among shrimp species ($p < 0.05$), with *L. vannamei* possessing the highest mean percentage of digested matter (55.37%) compared to other local shrimp species. There was also a significant difference in the percentage of appendages of crustaceans found in the stomachs of different shrimp species ($p < 0.05$). *Litopenaeus vannamei* had the lowest percentage of appendages (13.33%) and *M. ensis* had the highest (28.28%). There was, however, no difference in the percentage of phytoplankton and vegetal matter in the stomachs of different shrimp species. Mollusc shells were found in the stomachs of *P. monodon* only.

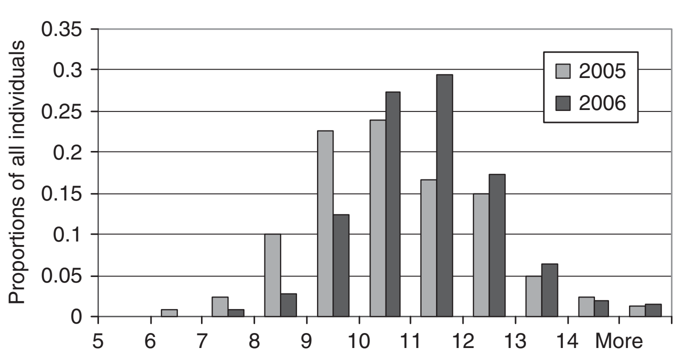

Fig. 6.7. Length-frequency distribution of *L. vannamei* caught in Bangpakong River during 2005 and 2006.

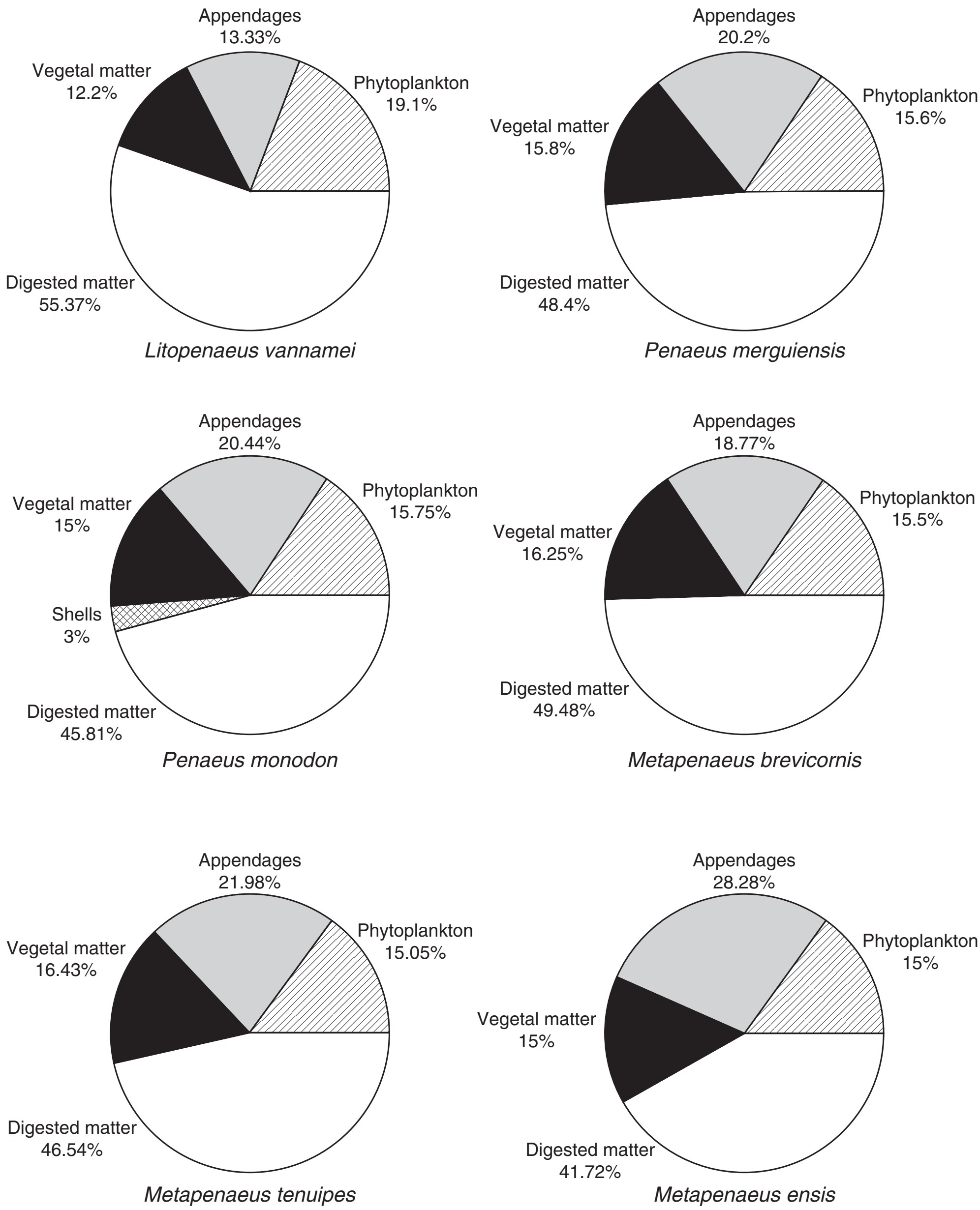

Fig. 6.8. Stomach contents of *L. vannamei* and native shrimp species.

Competing for food with local shrimp species

The results from the food competition experiments showed that *L. vannamei* approached and captured foods faster than all other native shrimp species, including *M. brevicornis*, *M. ensis*, *P. merguiensis* and *P. monodon*. All *L. vannamei* individuals captured food faster than individuals of *M. brevicornis*, *M. ensis* and *P. merguiensis* (100% outcompeting) and 80% of *L. vannamei* individuals captured foods faster than *P. monodon* (Fig. 6.9). There was

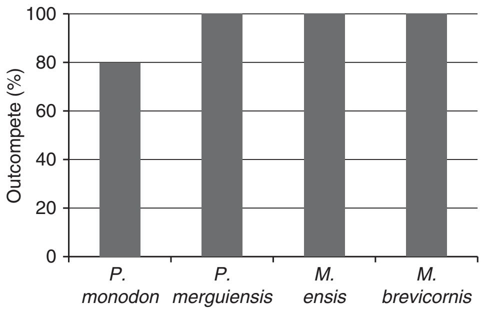

Fig. 6.9. Percentage of *L. vannamei* outcompeting native shrimp species for food in aquaria.

no significant difference in the durations of time that *L. vannamei* used to approach and capture food among treatments (1–3 min).

Discussion

Ability to adapt to the Bangpakong River

The types and magnitude of ecological harm associated with the spread of *L. vannamei* introduced for aquaculture purposes in the Bangpakong River watershed depend on their ability to occupy the same ecological niche as local species. Results from this study show that postlarvae and juveniles of *L. vannamei* can tolerate a wider range of salinity than postlarvae and juveniles of *P. monodon*, especially at low salinity. Pante (1990) suggested that *L. vannamei* could tolerate a wide salinity range, from brackish water of 1–2‰ to hypersalt water of 50‰. Boyd (1989) suggested that salinity of 15–25‰ was ideal for *L. vannamei* culture. Salinity in the Bangpakong River varies seasonally. Rainy season salinity is near 0% along all upstream segments to the river mouth as a result of high freshwater discharge. During the dry season, discharge decreases dramatically and tidal influences can extend 120 km upstream (Panutrakul *et al.*, 2000). Upstream salinity can be up to 10‰ during the dry season and up to 32‰ at the river mouth. The results of this study and the salinity pattern in the Bangpakong River suggest that the dry season is the most favourable period for *L. vannamei* growth.

Postlarvae and juveniles of native shrimp species such as *P. monodon*, *P. merguiensis*, *P. indicus* and most of *Metapenaeus* spp. can also tolerate wide ranges of salinity (FAO, 1978). Optimal growth of *P. monodon* has been obtained at 15–22‰ (Tiensosngrusmee, 2000), but *P. monodon* and most *Metapenaeus* spp. can survive in near freshwater conditions. *Penaeus merguiensis* and *P. indicus* require more saltwater (above 10‰), with optimal growth of *Penaeus merguiensis* obtained at 27‰. Saldanha and Achuthankutty (2000) carried out experiments on the effect of varying salinity levels (5, 10, 15, 20, 30 and 40‰) on the growth of *P. merguiensis* juveniles. They found that growth of *P. merguiensis* increased with increasing salinity and individuals raised at 40‰ displayed the highest growth rate. Enamul Hoq *et al.* (2001) reported high abundance of *Penaeus monodon* postlarvae in Bangladesh's Sundarbans mangrove between October and February, which was linked to moderate salinity (5–15‰) in the study area. *Penaeus monodon* and *P. merguiensis* were found in high abundance in riverine mangroves in the dry season, when salinity varied between 15 and 30‰, whereas *M. ensis* were found in high abundance year-round (Primavera, 1998). Medina-Reyna (2001) report the growth and emigration of Pacific white shrimp in the Mar Muerto Lagoon, which is one of the largest nursing grounds for this species in Mexico. The highest catch and abundance of *L. vannamei* juveniles in the Mar Muerto Lagoon occurs during the dry season, when salinity in the lagoon varies from 40 to 60‰ and temperature ranges from 28 to 32°C. Growth rates in the rainy season drop when salinity falls to 5–20‰ and temperatures range between 28 and 34°C, which is significantly higher than the dry season. Data on the salinity preferences of Thailand's native shrimp species and *L. vannamei* indicate an overlap between *L. vannamei*, *P. monodon* and *P. merguiensis*.

Results from the LC_{50} experiments of rapid pH change indicated a shift in pH tolerance from lower pH (4.56–8.71) in *L. vannamei* postlarvae to higher pH (5.7–9.51) in juveniles. There is little published information on the effect of pH on the survival and optimal growth of *L. vannamei*, but most papers on *L. vannamei* aquaculture report that the domesticated strains can grow in water with pH between 5.5 and 9.5 (Holthuis, 1980; Zhang *et al.*, 2006). The difference of LC_{50} of changing pH found in this study may indicate the shifting preference from fresh water to seawater when *L. vannamei* postlarvae develop to juveniles. This was supported in a study by Zarain-Herzberg *et al.* (2006), who reported high *L. vannamei* production in floating cages in Mexico, where salinity and pH ranges were 30–39‰ and 8.0–8.6, respectively. Postlarvae of *P. monodon* tolerate a wider range of pH than juveniles, and juveniles of *P. monodon* tend to tolerate a lower pH range than *L. vannamei* juveniles. Wickins (1976) suggested that the optimal pH for *P. monodon* growth was between 8 and 8.5, with low pH producing stress and causing a soft shell and poor survival. It has been demonstrated that survival of *P. monodon* larvae is not affected by pH as low as 6.4, although the growth rate is reduced.

The pH of the Bangpakong River varies seasonally and, during the rainy season, water chemistry is governed by freshwater inputs. In our study, rainy season pH ranged between 6 and 6.8 and dry season pH rose to 7.3–7.6 because of mixing with alkaline seawater. Water in the Bangpakong River tends to have rather low pH, which may favour juveniles of *P. monodon* rather than *L. vannamei*. An intensive study on the status of fisheries resources in freshwater, brackish and seawater zones of the Bangpakong River in 2004 found *P. monodon, P. merguiensis*, *M. brevicornis*, *Metapenaeus* spp. and *M. rosenbergii* distributed in every zone of the river, whereas *L. vannamei* was found only in the seawater zone (Department of Marine and Coastal Resources, 2005). This may be a result of the different pH preferences of the species. The water temperature of Bangpakong River generally varies between 28 and 32°C, which is within the range of tolerance of *L. vannamei* (Medina-Reyna, 2001). Thus, the physical and chemical conditions of the Bangpakong River seem to suit *L. vannamei*'s physiological requirements.

Occurrence in the Bangpakong River

We detected the presence of both *L. vannamei* juveniles and subadults (total length 6.7–17.20 cm) in the wild during all sampling periods (Figs 6.6 and 6.7). *Litopenaeus vannamei* individuals in those samples may represent recent escapes from farms or the survival of released individuals. Our data suggest that both factors may be important. Higher numbers of *L. vannamei* sampled in November through March may be explained by a higher number of escapes, since this is a peak production period for cultured shrimp and wastewater releases from farms are more frequent. On the other hand, the increase in mean total length and the proportion of larger individuals (total length > 13 cm) sampled over time suggest that some percentage of escaped *L. vannamei* can survive in the wild (Fig. 6.7).

Lower abundance of *L. vannamei* in the main channel of the Bangpakong River during the rainy seasons for both years may reflect higher mortality in this environment or migration to more favourable habitats. As salinity in the Bangpakong River approaches zero at most sites during the rainy season (Panutrakul *et al.*, 2000; Senanan *et al.*, Chapter 5), *L. vannamei* may migrate to coastal areas where salinity is higher than 15‰. Trawl surveys suggest increased numbers of juveniles, and adults of several marine shrimp species may inhabit adjacent coastal areas rather than the river during the rainy season (Senanan *et al.*, 2008). Pérez-Castañeda and Defeo (2001) reported that salinity (seaward, middle and inner zones) and the types of habitats (presence and absence of aquatic vegetation) had varying degrees of influence on the spatial distribution of four *Farfantepenaeus* spp. (Family Penaeidae).

There are other cases in which an alien Penaeid shrimp species has been reported in geographic areas outside its native range. *Penaeus monodon*, which is a species native to South-east Asia, was introduced on the Atlantic coast in 1988 through an accidental water release at the Waddell Mariculture Center. Commercial shrimpers later captured *P. monodon* as far south as Florida, but there was no conclusive evidence that a *P. monodon* population was self-sustaining in the USA (McCann *et al.*, 1996). In the case of *L. vannamei*, a large number were released accidentally from a shrimp farm in Texas in 1991 and the escapees were caught up to 65 miles from the shore (Texas Parks and Wildlife Department, 1997). Wenner and Knott (1991) also reported the presence of *L. vannamei* in commercial catches in South Carolina (3% and 0.16% occurrence in 1989 and 1990, respectively). In the case of the Bangpakong River, toxicological and field data suggest that *L. vannamei* is likely to survive the physical and chemical conditions, but there is still no direct evidence that the persistence of *L. vannamei* in the wild is because of natural reproduction.

Litopenaeus vannamei as a potential competitor

The stomach content study suggests a diet overlap between native shrimp species and *L. vannamei* that have escaped from shrimp farms. Both farmed and wild shrimp species in the Family Penaeidae are opportunistic omnivores (Marte, 1980) that can consume phytoplankton, plants, animals and dead organisms (see Wassenberg and Hill, 1987; Laokiatsophon *et al.*, 2006). Panikkar (1952) observed that the food of young penaeids consisted of organic detritus, algal material and other extremely small organisms contained in the mud. Hall (1962) found that the food of *P. monodon* consisted of large crustaceans, vegetable matter, polychaetes, molluscs and fish. Large crustacean food items were mostly of brachyuran origin. The stomach contents of *L. vannamei* from semi-intensive farms were analysed microscopically for shrimp between 2 and 10 g. Plant matter contributed more than 30% of the total stomach content of 6 g, 8 g and 10 g shrimp, with detritus and digested matter representing 58 and 62% of the total stomach content of 2 g and 4 g shrimp, respectively (decreasing to 33–43% at greater shrimp weights). These differences may be because of an adaptation of enzymatic activity to different diets (Gamboa-delgado *et al.*, 2003). *Litopenaeus vannamei* was also found to be more aggressive than native shrimp species and outcompeted native shrimp for food in aquaria. During the experiment trials, we observed that certain aggressive *L. vannamei* individuals ate the other live native shrimp after consuming the presented food item. Moreover, native shrimp were not able to retain food items, even if in some cases they reached the food item first. *Litopenaeus vannamei* individuals were able to take the food from the native shrimp and consume it. Native shrimps were not observed consuming *L. vannamei* during our experiments. Results from this experiment suggest that surviving *L. vannamei* may possess a competitive advantage over native shrimp species of the Bangpakong River, but it is premature to extrapolate these results to the natural setting. The degree of antagonistic behaviour in food or habitat competition may vary among species (Dingle and Caldwell, 1969; Herberholz and Schmitz, 1998), sizes and sexes (Moss and Moss, 2006). Moss and Moss (2006) showed that males of *L. vannamei* had a competitive advantage over females in acquiring food, even though the males were typically smaller in size. Alien shrimp species may, however, induce cascading ecological effects. Spencer *et al.* (1991) showed that the introduction of opossum shrimp (*Mysis relicta*) induced cascading changes through the food web and contributed to the collapse of an important native planktivorous fish population. The potential impacts of alien shrimp species in the Family Penaeidae in several receiving ecosystems have, however, not been proven conclusively because of a lack of long-term monitoring (McCann *et al.*, 1996; Briggs *et al.*, 2005).

Conclusions

Results from toxicological experiments and field surveys suggest *L. vannamei* may be able to survive water conditions in the Bangpakong River. *Litopenaeus vannamei* shows the ability to tolerate salinity and pH levels that are well within the natural range of conditions in the Bangpakong River. Although the presence of *L. vannamei* in the Bangpakong River might reflect recent escapes, the increased abundance and mean size of captured *L. vannamei* over time suggest that escaped *L. vannamei* can survive and grow in the wild. In addition, wild-caught *L. vannamei* were shown to be able to consume natural diets available in the Bangpakong River. Dietary overlap between *L. vannamei* and native shrimp species, as well as *L. vannamei*'s ability to outcompete native shrimp species for food in aquaria, implies a potential competitive advantage of *L. vannamei* over local shrimp species. Our research provides some of the data necessary for risk assessment, but additional studies are needed to complete a full risk analysis for the introduction of this species. Long-term monitoring of abundance and changes of size structure could determine if *L. vannamei* can sustain a wild population. Furthermore, additional laboratory and semi-natural competition experiments could aid our understanding of the mechanisms through which *L. vannamei* competes with native shrimp species for common resources and the implications of this for receiving aquatic communities. The full implications of using an exotic species such as *L. vannamei* for aquaculture in Thailand are not yet clear, but the results of this research suggest that negative impacts are possible. This supports the generally agreed on position that proper risk assessments must be undertaken prior to introducing any exotic species for aquaculture purposes. Risk assessment results can then be used to develop proper planning and management programmes that support sustainable coastal aquaculture.

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References

Boyd, C.E. (1989) Water quality management and aeration in shrimp farming. In: *Fisheries and Allied Aquacultures Departmental Series*, Vol. 2. Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama.

Briggs, M., Funge-Smith, S., Subasinghe, R.P. and Phillips, M. (2005) Introductions and movement of two penaeid shrimp species in Asia and the Pacific. FAO Fisheries Technical Paper No. 476. Food and Agriculture Organization of the United Nations, Rome.

CIDA (1993) A generic protocol for conducting tropical acute toxicity tests with fish and invertebrate. ASEAN-Canada, CPMS II (CIDA Project No 149/15464), Vancouver, Canada.

Dall, W., Hill, B.J., Rothlisberg, P.C. and Staples, D.J. (eds) (1990) *The Biology of the Penaeidae. Advances in Marine Biology, Volume 27*. Academic Press, London.

Department of Fisheries (1999–2005) Fisheries statistics of Thailand, 1999–2004. Fishery Information Technology Center, Department of Fisheries. Ministry of Agriculture and Cooperatives, Bangkok.

Department of Marine and Coastal Resources (2005) *Bangpakong Estuary Ecosystem*. Eastern Marine and Coastal Research Center, Department of Marine and Coastal Resources. Chulalongkorn University Printing House, Bangkok.

Dingle, H. and Caldwell, R.L. (1969) The aggressive and territorial behaviour of the mantis shrimp *Gonodactylus bredini*. *Behaviour* 33, 115–136.

Ekmaharaj, S. (2005) Aquaculture of white shrimp (*Penaeus vannamei*) in South-east Asia countries and China. *Thai Fisheries Gazette* 58, 107–111.

Enamul Hoq, M., Islam, M.N., Kamal, M. and Wahab, M.A. (2001) Abundance and seasonal distribution of *Penaeus monodon* postlarvae in the Sundarbans mangrove, Bangladesh. *Hydrobiologia* 450, 97–104.

FAO (1978) *Manual on Pond Culture of Penaeid Shrimp*. A project of the Association of South-east Asian Nations (ASEAN) with the assistance of the FAO/UNDP South China Sea Fisheries Development and Coordinating Programme (SCSP), Manila.

Gamboa-delgado, J., Molina-poveda, C. and Cahu, C. (2003) Digestive enzyme activity and food ingesta in juvenile shrimp *Litopenaeus vannamei* (Boone, 1931) as a function of body weight. *Aquaculture Research* 34(15), 1403–1411.

Grey, D.L., Dall, W. and Baker, A. (1983) *A Guide to the Australian Penaeid Prawns*. Department of Primary Industries of the Northern Territory, Darwin, Australia.

Hall, D.N.F. (1962) Observations on the taxonomy and biology of some Indo-west Pacific Penaeidae (Crustacea, Decapoda). *Fishery Publications Colonial Office* 17, 1–229.

Herberholz, J. and Schmitz, B. (1998) Role of mechanosensory stimuli in intraspecific agonistic encounters of the snapping shrimp (*Alpheus heterochaelis*). *The Biological Bulletin* 195, 156–167.

Holthuis, L.B. (1980) FAO species catalogue. Volume 1. Shrimps and prawns of the world. An annotated catalogue of species of interest to fisheries. FAO Fisheries Synopsis No 125, Vol. 1. Food and Agriculture Organization of the United Nations, Rome.

Laokiatsophon, P., Limsuwan, C., Teparhudee, W. and Chuchird, N. (2006) Study on the species composition and abundance of plankton, water quality and stomach contents of Pacific white shrimp, *Litopenaeus vannamei* Boone (1931) reared in low salinity conditions. *Kasetsart University Fisheries Research Bulletin* 29, 14–22.

Leelapiyanart, N. (1992) Taxonomy of Penaeoid shrimps in Thailand. MSc thesis, Chulalongkorn University, Bangkok.

McCann, J.A., Arkin, L.N. and Williams, J.D. (1996) *Non-indigenous Aquatic and Selected Terrestrial Species of Florida*. Center for Aquatic Plants, University of Florida, Gainesville, Florida.

Marte, C.I. (1980) The food and feeding habitats of *Penaeus monodon* Fabricius collected from Makato River, Aklan, Philippines (Dacapoda: Natantia). *Crustaceana* 38, 225–236.

Medina-Reyna, C.E. (2001) Growth and emigration of white shrimp, *Litopenaeus vannamei*, in the Mar Muerto Lagoon, Southern Mexico. Naga, *The ICLARM Quarterly* 24(3/4), 30–34.

Moss, D.R. and Moss, S.M. (2006) Effects of gender and size on feed acquisition in the Pacific white shrimp *Litopenaeus vannamei*. *Journal of the World Aquaculture Society* 37, 161–167.

Panikkar, N.K. (1952) Possibilities of further expansion of fish and prawn cultural practices in India. *Current Science* 21, 29–33.

Pante, M.J.R. (1990) Influence of environmental stress on the heritability of moulting frequency and growth rate of the penaeid shrimp, *Penaeid vannamei*. MSc thesis, University of Houston-Clear Lake, Houston, Texas.

Panutrakul, S., Musika, S. and Mokkongpai, P. (2000) Behavior of heavy metals in the Bangpakong River. Technical report to the National Research Council of Thailand (in Thai). Department of Aquatic Science, Burapha University, Chonburi, Thailand.

Pérez-Castañeda, R. and Defeo, O. (2001) Population variability of four sympatric Penaeid shrimps (*Farfantepenaeus* spp.) in a tropical coastal lagoon of Mexico. *Estuarine, Coastal and Shelf Science* 52, 631–641.

Perez Farfante, I. and Kensley, B. (1997) *Penaeoid and Sergestoid Shrimps and Prawns of The World. Keys and Diagnoses for the Families and Genera*. Memories Du Museum National D'Historie Naturelle, Paris.

Primavera, J.H. (1998) Mangrove as nurseries: shrimp populations in mangrove and non-mangrove habitats. *Estuarine, Coastal and Shelf Science* 46, 457–464.

Saldanha, C.M. and Achuthankutty, C.T. (2000) Growth of hatchery raised banana shrimp *Penaeus merguiensis* (de Man) (Crustacea: Decapoda) juvenile under different salinity. *Indian Journal of Marine Sciences* 29, 179–180.

Senanan, W., Tangkrock-Olan, N., Panutrakul, S., Barnette, P., Wongwiwatanawute, C., Niphonkit, N. and Anderson, D.J. (2007) The presence of the Pacific white shrimp (*Litopenaeus vannamei*, Boone, 1931) in the wild in Thailand. *Journal of Shellfish Research* 26, 1187–1192.

Senanan, W., Tangkrock-Olan, N., Panutrakul, S., Barnette, P., Jaridkun, S. and Wongwiwatanawute, C. (2008) Abundance and sizes of wild-caught Pacific whiteleg shrimp (*Litopenaeus vannamei*) found in the Bangpakong River. In: Panutrakul, S. and Senanan, W. (eds) *Aquaculture Management Strategies for the Pacific Whiteleg Shrimp* (Litopenaeus vannamei) *in the Bangpakong River Basin and the East Coast of Thailand*. Burapha University, Chonburi, Thailand, pp. 36–50.

Spencer, C.N., McClelland, B.R. and Stanford, J.A. (1991) Shrimp stocking, salmon collapse, and eagle displacement. *BioScience* 41, 14–21.

Szuster, B. (2001) *Shrimp Farming In Thailand's Chao Phraya River Delta: Boom, Bust and Echo*. Research Report, Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute (IWMI), Colombo, 57 pp.

Texas Parks and Wildlife Department (1997) Exotic shrimp confirmed in Matagorda Bay. News Release.

Tiensosngrusmee, B. (2000) *Black Tiger Shrimp Farming Technology Beyond the 20th Century*. Department of Aquatic Science, Faculty of Science, Burapha University, Chonburi, Thailand (in Thai).

Tookwinas, S. (1993) *Intensive Marine Shrimp Farming Techniques in Thailand*. Proceedings of the First International Symposium on Aquaculture Technology and Investment Opportunities. Ministry of

Agriculture and King Abdulaziz City for Science and Technology and Riyadh Chamber of Commerce and Industry, Riyadh, pp. 230–240.

Wassenberg, T.G. and Hill, B.J. (1987) Natural diet of the tiger prawns *Penaeus esculentus* and *P. semisulcatus*. *Marine and Freshwater Research* 38,169–182.

Wenner, E.L. and Knott, D.M. (1991) Occurrence of Pacific white shrimp, *Penaeus vannamei*, in coastal waters of South Carolina. In: de Voe, R. (ed.) *Proceedings of the Conference and Workshop, Introduction and Transfers of Marine Species: Achieving a Balance Between Economics and Development and Resources Protection*, 30 October–2 November 1991. South Carolina Sea Grant Consortium, Hilton Head, South Carolina, pp. 173–181.

Wickins, J.F. (1976) The tolerance of warm-water prawn to recirculated water. *Aquaculture* 9, 19–37.

Zarain-Herzberg, M., Campa-Cordova, A.I. and Cavalli, R.O. (2006) Biological viability of producing white shrimp *Litopenaeus vannamei* in seawater floating cages. *Aquaculture* 259, 283–289.

Zhang, P., Zhang, X., Li, J. and Huang, G. (2006) The effects of body weight, temperature, salinity, pH, light intensity and feeding condition on lethal DO levels of white shrimp, *Litopenaeus vannamei* (Boone, 1931). *Aquaculture* 256, 579–587.

7 Improving the Productivity of the Rice–Shrimp System in the South-west Coastal Region of Bangladesh

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Abstract

The production of wet-season rice (mid-August to mid-December) followed by dry-season (mid-December to mid-August) shrimp (*Penaeus monodon*) is a common farming system in the south-western coastal region of Bangladesh. Experiments were conducted in the farmers' fields during the rice- and shrimp-growing seasons of 2004, 2005 and 2006, with the aim of improving the total farm productivity of the rice–shrimp system through technological intervention. During the wet season of 2004, yield responses of different high-yielding (BR23, BRRI dhan 40 and 41, HR1 and 14) and traditional (Horkoz) rice varieties were evaluated for their responses to the prevailing salinity-influenced environment and integrated with: (i) GIFT (genetically improved farmed tilapia) strain of Nile tilapia (*Oreochromis niloticus*) alone; (ii) GIFT and giant freshwater prawn (*Macrobrachium rosenbergii*) at a 1:1 ratio; and (iii) prawn alone at a stocking density of 10,000/ha. In the 2005 rice season, the previous season's best-yielding rice varieties (BR23, BRRI dhan 40 and 41) were cultivated, integrated with a similar aquaculture species combination but at a reduced stocking density of 5000/ha. In the dry seasons of 2005 and 2006, the production of black tiger shrimp (*P. monodon*) was evaluated for three stocking patterns: (i) single stocking (5/m^2); (ii) double stocking (3/m^2 followed by 2/m^2); and (iii) double stocking (2/m^2 followed by 3/m^2). Among the rice varieties, BR23 and BRRI dhan 40 performed best, with similar yields averaging about 5 t/ha. The reduced density of 5000/ha actually gave better fish and prawn yields, resulting in additional average production of 258 kg of GIFT and 71 kg of prawn/ha. The net return from GIFT alone was Tk10,858/ha and that from prawn was marginal or negative. Single and double stocking of shrimp did not show any significant differences in body weight, survival rate and yield, with the values ranging from 20 to 24 g, 26 to 35% and 289 to 380 kg/ha, respectively. There were considerable variations in survival and production within each treatment, particularly because of higher shrimp mortality in the replicate ponds that had comparatively shallower water depth during the culture period. Single stocking resulted in average net returns as high as Tk67,500/ha and was considered more suitable in rotation with rice.

Introduction

The culture of shrimp (particularly black tiger shrimp, *P. monodon*) in Bangladesh started in the 1970s in the low-lying tidal coastal flats within the Bangladesh Water Development Board (BWDB) polders, following the traditional trapping–holding–growing method (Islam, 2003). The increased international demand and lucrative price of shrimp stimulated farmers to focus on shrimp culture as their major farming activity, resulting in an expansion of 0.02 million ha of shrimp farms in 1980 to 0.20 million ha in 2005 (DoF, 2005). About

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75–80% of this area is in the south-western region of the country, where shrimp is cultured during the high saline period of February to mid-August in rotation with rice during the low salinity period of mid-August to December (Islam *et al.*, 2005). In this region, there is a prolonged low-salinity regime, with an average salinity below 1 ppt, during the monsoon (June–September) and post-monsoon (October–November) seasons. The salinity of the river water increases in the winter season (December–February) and reaches a maximum of 13 ppt in the pre-monsoon (March–May) season (Mondal *et al.*, 2006).

The alternate rice–shrimp system is considered to be an ecologically sustainable approach to shrimp farming, with the rice crop providing an ecological buffer between shrimp crops (Brennan *et al.*, 2002). The benefit of rice–aquaculture integration as a low-investment technology for marginal farmers has been demonstrated in inland freshwater areas in Bangladesh (Gupta *et al.*, 1998). Integrated freshwater prawn (*M. rosenbergii*) culture with rice during the rainy season, followed by marine shrimp monoculture in the dry season, increased the incomes of coastal farmers in Vietnam (Hung, 2001). However, the integration of rice–aquaculture in a traditional brackishwater rice–shrimp system is not well developed in the south-west of Bangladesh. Farmers cultivate mainly rice of local varieties, with low yields ranging from 1.0 to 3.0 t/ha (Karim, 2006). Productivity of shrimp monoculture also remains low, ranging between 50 and 250 kg/ha (Islam, 2003), as more than 90% of farmers still practise the traditional extensive method characterized by low stocking density, no feeding and poor water quality management (Islam *et al.*, 2005).

With increasing population pressure, coastal livelihood requirements cannot be met satisfactorily with the existing traditional extensive production systems, but productivity improvements need to take into consideration the existing farming patterns and available coastal resources. With this in mind, experiments were conducted on shrimp production in the dry season and on rice–fish integration in the wet season, with the aim of improving total farm production and the incomes of farmers in the fresh- and saltwater interface areas of south-western Bangladesh.

Materials and Methods

Experimental site and preparation

Experiments during the shrimp and rice seasons in the same calendar year (Fig. 7.1.) were conducted in farmers' rice–shrimp plots (locally termed *gher*) in polder No 16/1 in the Khulna District of Bangladesh. There were nine experimental plots in 2004 and 2005 and 12 in 2006. The area of each experimental plot varied from 910 to 1420 m^2. Attempts were made to weight different-sized plots with different treatments. The fields were connected with the Shibsa River and water exchange occurred with changing tides through sluice gates. All the experimental plots were deepened by excavating the bottom soil to a depth of about 15 cm and the surrounding dykes were raised so that a minimum water depth for shrimp (30–40 cm) and rice–fish (15–20 cm) crops could be maintained. Trenches of 80 cm average depth were constructed along the dykes in each plot. These trenches occupied 8–10% of the plot area. Each experimental plot had a separate water inlet–outlet encircled with nylon fencing.

Rice–fish experiments in the wet season (mid-August to December)

Experimental design

During the rice season (August–December) of 2004 and 2005, the culture of GIFT (genetically

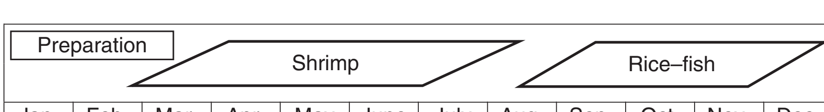

Fig. 7.1. Cropping calendar year for shrimp and rice–fish experiments.

improved farmed tilapia, *O. niloticus*) and giant freshwater prawn (*M. rosenbergii*) integrated with rice cultivation was evaluated. There were three treatment combinations: (i) GIFT alone (T-1); (ii) 1:1 GIFT and prawn (T-2); and (iii) prawn alone (T-3). The total stocking density of cultured species was 10,000/ha in the 2004 rice season, but was reduced to 5000/ha in 2005. Treatment replications were laid out following a completely randomized design. Simultaneously with aquaculture, the performance of six high-yielding varieties (HYVs) of rice (HR1, HR14, BR23, BR23L, BRRI dhan 40, BRRI dhan 41) and a local variety (Horkoz) were evaluated in 2004. HYV rice seeds were collected from the Bangladesh Rice Research Institute (BRRI) seed bank, except for BR23L, which was collected from local farmers. Within each aquaculture treatment plot, the test varieties of rice were planted in randomized subplots, with a minimum of three replications. In 2005, three HYVs, namely BR23, BRRI dhan 40 and BRRI dhan 41, were selected for further testing, based on their superior yield performance in 2004.

Rice crop management

Field preparation activities included ploughing and the application of cow dung, urea and triple super phosphate (TSP) at 2 t/ha, 70 kg/ha and 35 kg/ha, respectively. At the end of August, 1-month-old rice seedlings of the test varieties were transplanted at 23 cm row spacing. A top dressing of urea at 75 and 37.5 kg/ha was applied 24 and 60 days after transplanting, respectively. Nimbicidin (extract of neem seed) was applied at 1.5 l/ha to control the stem borer infestation that had occurred between 20 and 40 days of transplanting in both years. Zinc sulfate was sprayed at a concentration of 3 ml/l in areas affected by leaf blight disease. The rice crop was harvested some time between 100 and 120 days after transplanting.

Aquaculture management

At 8–10 days after transplanting rice, GIFT fry and prawn juveniles, averaging 1.5 g and 3.5 g in body weights, respectively, were stocked in the rice plots according to the experimental layout. After about 120 days of culture, the fish and prawn were harvested and their growth, survival rate and production were estimated. For the entire experiment, no feed was provided either to GIFT or to prawn.

Shrimp production experiments in the dry season (February to mid-August)

Experimental design

Based on observations of local practices of partial stocking and harvesting of shrimp, three stocking patterns of black tiger shrimp (*P. monodon*), namely (i) single stocking at a density of 5/m^2 (T-1), (ii) double stocking at 3/m^2 followed by 2/m^2 (T-2) and (iii) double stocking at 2/m^2 followed by 3/m^2 (T-3), were evaluated during the shrimp-growing season (February–August) following the rice–fish crops in 2005 and 2006. There were three replications for each treatment in the trial of 2005 and four in 2006, based on a completely randomized design layout.

Shrimp crop management

Following the rice harvest, the experimental plots were limed using CaO at 250 kg/ha and filled with tidal river water to a water depth of 60–70 cm at the end of February. Three days later, urea and TSP fertilizers were applied at 2.5 ppm and 3 ppm, respectively. Seven days later, hatchery-reared *P. monodon* postlarvae (averaging 0.007 g in body weight) were stocked in the ponds. The second stocking was done 30–35 days after the first stocking. No regular water exchange was carried out, but any severe water loss as a result of seepage and evaporation was replenished. The ponds were treated with dolomite ($CaMg(CO_3)_2$ at 5–7 ppm) and fertilized with urea (at 1.25 ppm) and TSP (at 1.5 ppm) at 2-week intervals. The shrimps were fed with commercial SABINCO nursery pellet feed (approximate protein content of 35–40%) twice daily at rates of 100, 60, 30 and 10% of the estimated shrimp biomass at the 1st, 2nd, 3rd and 4th weeks of culture, respectively. Thereafter, grow-out feed was supplied at the rate of 2–3% of the estimated standing shrimp biomass. The growth and health condition of the shrimp were monitored periodically using a check tray. Total production and survival rates were estimated at 120–130 days for single stocking and 130–150 days for double stocking, and at final harvest.

Water and soil quality monitoring

During both the rice–fish and shrimp production periods, selected physico-chemical characteristics of the pond water were monitored in the morning between 09.00 and 10.00 at fortnightly intervals. Water depth was measured by a meter gauge set up in each plot. Water transparency, salinity, pH and turbidity were measured using a standard Secchi disc, refractometer, portable pH meter and spectrophotometer, respectively. Dissolved oxygen (DO), alkalinity and hardness were analysed by titrimetric methods, whereas nitrate and phosphate concentrations were estimated by colorimetric methods following Strickland and Parsons (1968) and APHA (1992). Primary productivity was monitored monthly following the standard 'oxygen light and dark bottle' method (APHA, 1992). Collection and quantitative estimation of plankton were carried out following the method of Rahman (1992). Benthos samples from surface sediment were collected monthly by an Ekman grab sampler. The benthic meiofauna were segregated from the sediment by sieving, visually sorted, preserved in buffered formalin and counted. Soil samples from each rice plot were collected, once initially and again at the end of the culture period, and analysed in the laboratory of the Soil Resources Development Institute (SRDI) in Khulna, Bangladesh.

Economic analysis

The gross margin for each crop was calculated based on average market prices and farm production. The cost included all inputs (rice seed, lime and fertilizers, fish fingerlings, prawn juveniles, shrimp postlarvae, shrimp feed, etc.), field preparation, labour, fuel for pumping, and land leasing. Pumping costs and land leasing were allocated to the rice culture during the rainy season crop, which is the main crop for the season. The net return was calculated as the gross margin minus the cost. The benefit cost ratio (BCR) represents the gross margin divided by the cost.

Data analysis

Data were analysed with one-way ANOVA, using Duncan multi-comparison of means and a *t*-test to compare two means, with underlying assumptions of homogeneity of variance and normality of the data. When the data set did not follow normal distribution or if the homogeneity of variance was not assumed, a *K*-sample test was used to compare means. The relationship between water quality parameters and shrimp production was investigated using Pearson's correlation and linear regression methods.

Results and Discussion

Water and soil quality

Mean value ranges of different physico-chemical and biological characteristics of water, monitored during rice and shrimp crop seasons' experiments, are presented in Table 7.1. The differences in values of the water quality parameters were insignificant ($p > 0.05$) for the rice–GIFT/prawn treatments, except for water depth and DO in 2005. Even these variables were not correlated with the primary productivity or aquaculture production. The DO gradually reduced during the rice–fish cropping seasons but remained above the stress threshold value of 2 mg/l for fish and prawn. The water pH was also within the optimum range (7.5–8.1), averting NH_3-N toxicity for prawn (New, 1995).

The treatment differences for the water quality parameters during the shrimp crop seasons in 2005 and 2006 were also not significant (Table 7.1). Variations in water quality during the shrimp culture period were because of management practices, including liming, water exchange and fertilizer

Table 7.1. Ranges of treatment means of physico-chemical and biological water quality parameters during the rice–fish and shrimp crop seasons in 2004, 2005 and 2006.

Water quality parameters	Rice–fish/prawn crop (mid-August to December)		Shrimp crop (March to mid-August)	
	2004	2005	2005	2006
Temperature (°C)	28.31–28.41	26.87–27.24	30.45–30.62	32.08–32.14
Water depth (cm)	15.28–16.59	13.95–19.40	48.50–53.20	33.94–38.39
Salinity (ppt)	0.33–0.33	0.25–0.25	11.95–13.50	15.75–16.41
Transparency (cm)	11.66–12.42	12.49–13.98	21.41–22.63	28.44–30.94
Turbidity (FTU)	128–131	141–182	n/a	40.37–46.56
pH	8.10–8.14	7.72–7.82	8.30–8.34	8.32–8.43
Dissolved oxygen (mg/l)	3.71–3.77	4.36–4.53	5.07–5.12	5.32–5.58
Alkalinity (mg/l)	134–139	140–146	157–159	209–213
NO_3-N (μg-at/l)	n/a	3.84–4.13	n/a	1.96–2.42
PO_4-P (μg-at/l)	n/a	2.61–3.21	n/a	1.19–1.53
Primary productivity (mg-C/l/h)	n/a	0.09–0.17	0.15–0.18	n/a
Phytoplankton (10^3 cell/l)	n/a	33.83–35.16	n/a	20.40–23.69
Zooplankton (10^3 cell/l)	n/a	2.26–2.85	n/a	1.24–1.46
Benthic meiofauna (no./m^2)	2910–3763	2411–3511	1859–2910	1104–2509

application, and also because of rainfall variation. The DO values decreased progressively during the season, but remained above suboptimal levels (> 4 g/l) for shrimp culture (Chanratchakool *et al.*, 1995). Primary production remained generally stable during the culture period.

Variations in soil characteristics during the rice–fish and shrimp farming periods followed a similar pattern to that for water quality and were insignificant for the different treatments (Table 7.2). Variations in values of water and soil quality parameters were within the optimum range for freshwater prawn (New, 1995), tilapia (Boyd and Egna, 1997) and shrimp (Chakraborti *et al.*, 1985; Chanratchakool *et al.*, 1995; Hariati *et al.*, 1996) grow-out operation. The soil quality data were more or less similar for both rice–fish and shrimp crop seasons (Table 7.2), suggesting that the different cropping patterns did not modify the soil properties substantially. However, some residual salinity in the soil (2.3–3.5 ppt), even when the water salinity during the rice cropping period is almost zero (Table 7.1), indicates the need for some minimal salinity-tolerant rice varieties to be grown in this coastal area that are characterized with seasonality in salinity variations (Islam *et al.*, 2005).

Aquaculture production in rice–fish/prawn systems

Production results of Nile tilapia (GIFT) and giant freshwater prawn integrated with the wet-season rice crop are presented in Table 7.3. In 2004, at a total stocking density of 10,000/ha, the freshwater prawn showed significant differences in survival rates ($t(4) = 5.22$; $p < 0.05$) and yield ($t(4) = 6.14$; $p < 0.05$) between treatments T-2 and T-3, but not in average body weight, whereas GIFT showed significant differences between treatments T-1 and T-2 both for survival ($t(4) = 4.29$; $p < 0.05$) and average body weight ($t(4) = 10.55$; $p < 0.05$). The highest survival and average body weights for both GIFT and prawn were found at a 1:1 combination, suggesting that a stocking density of 5000/ha for each may suit the environmental requirements and cultural practices for higher yields of both species.

With a lower stocking density of 5000/ha in the 2005 experiment, the survival rate of GIFT was significantly higher ($t(4) = 2.85$; $p < 0.05$) in mixed culture with prawn than in monoculture, but the yield difference was not significant, even though the stocking density was 50% lower in the mixed culture. However, yield rates of GIFT in monoculture at 5000/ha stocking density were higher than those at 10,000/ha.

Table 7.2. Ranges of treatment means of soil-quality parameters during the rice–fish and shrimp crop seasons.

	Rice–fish/prawn crop (mid-August to December)		Shrimp crop (March to mid-August)	
Soil-quality parameters	2004	2005	2005	2006
pH	7.99–8.08	7.85–7.88	7.85–7.90	7.78–7.86
Salinity (ppt)	2.76–2.83	3.21–3.34	4.75–5.29	5.09–5.66
Organic matter (%)	1.47–1.50	1.35–1.95	1.73–1.99	1.57–1.79
Total nitrogen (%)	0.07–0.08	0.09–0.11	0.10–0.11	0.09–0.11
Phosphorus (μg/g)	9.95–12.38	10.23–13.87	9.22–9.85	9.84–11.54
Iron (μg/g)	63.23–66.20	59.20–60.03	33.99–41.93	52.60–66.59
Zinc (μg/g)	2.34–3.65	0.53–0.62	0.45–0.59	0.66–0.76
Potassium (me/100g)	0.86–0.92	0.99–1.00	1.02–1.10	1.16–1.32

Table 7.3. Production of (mean ± Sd) tilapia (GIFT) and prawn (*M. rosenbergii*) cultured with rice for the period of August–December in 2004 and 2005.

Aquaculture production treatment					
Notation	Species combination	Stocking density (/ha)	Final individual body weight (g)	Survival rate (%)	Yield (kg/ha)
2004					
T-1	GIFT	10,000	78.50 ± 0.36	17.66 ± 1.41	141.30 ± 4.20
T-2	GIFT	5,000	86.30 ± 1.23	22.00 ± 1.42	94.93 ± 1.53
	Prawn	5,000	22.10 ± 1.49	37.00 ± 2.39	40.88 ± 1.98
T-3	Prawn	10,000	22.30 ± 0.91	26.54 ± 2.51	57.87 ± 4.36
2005					
T-1	GIFT	5,000	125.5 ± 42.27	42.15 ± 4.56	258.08 ± 65.39
T-2	GIFT	2,500	164.16 ± 1.89	51.67 ± 3.54	211.98 ± 12.74
	Prawn	2,500	27.17 ± 9.29	42.43 ± 2.36	28.83 ± 10.36
T-3	Prawn	5,000	30.27 ± 8.74	47.91 ± 7.60	70.91 ± 16.47

Production levels of GIFT over the 2 years (2004 and 2005) suggest stability of its production in an integrated rice–fish system in the coastal semi-saline environment. The production level ranging from 141 to 258 kg/ha is also consistent with 125–239 kg/ha for a freshwater rice–fish system (Gupta *et al*., 1998, 2002). The survival rates of fish and prawn in these experiments seem low, but are not unlikely in the rice–fish system (Haroon *et al*., 1992; Kohinoor *et al*., 1995), given its predation and habitat conditions (Haroon and Pittman, 1997).

Prawn in monoculture demonstrated better performance than in mixed culture with GIFT, particularly in 2005 when yields were significantly higher ($t(4) = 3.74$; $p < 0.05$); and survival rates and body weights were apparently higher. As in the case of GIFT, prawn in monoculture has higher yields at the lower stocking density of 5000/ha. Even so, the average prawn yields at the stocking density of 10,000/ha (equivalent to $1/m^2$) obtained in this study (58 kg/ha in 2004 and 71 kg/ha in 2005) are higher than the 30 kg/ha yield at a stocking density of $1.2/m^2$, reported in a rice–shrimp system in Vietnam (Hung, 2001). In our study, the fish and prawn were reared for about 120 days only, integrated with the *aman* (monsoon/wet)-season rice, without supplemental feeding. Considering these conditions, and based on the results of a study of two seasons, it could be concluded that a total stocking density of 5000/ha is feasible for the expected production, survival and growth rates of both GIFT and prawn (*M. rosenbergii*) in a coastal rice–shrimp environment such as in south-western Bangladesh.

Rice production

Among the seven rice varieties cultivated along with GIFT and prawn in the 2004 wet season, the HYVs (BR23, BRRI dhan 40 and BRRI dhan 41) gave significantly higher yields exceeding 4 t/ha (Fig. 7.2.). These are similar to those of various non-aromatic HYVs grown in the wet season (Mondal *et al*., 2006). The variety BR23 gave the highest average yield of 5.1 t/ha, but the yield from using locally collected seed of the same variety (BR23L) was significantly lower, averaging 4.1 t/ha, possibly as a result of its loss of purity and vigour with time in the farmers' fields. HR1 and HR14 varieties produced lower yields, but the duration of cultivation was shorter (95 days) than the 105–120 days for the other varieties.

Rice yields for the three selected HYVs in 2005 were comparatively lower than in 2004 (Fig. 7.2.), mainly because of waterlogging in the fields caused by unusually heavy and prolonged rainfall. The recorded rainfall in 2005 during the study period was 3003 mm, which was about 1000 mm higher than the long-term average for that locality (Department of Agriculture, personal communication). Despite this, the rice yields obtained were higher than the usually harvested amount of 2.0–2.5 t/ha in the coastal area (Mondal *et al*., 2006).

Increased salinity in the topsoil, because of the expansion of shrimp culture in the coastal areas, has been blamed for the decline in rice production of 1.5 t/ha (Karim, 2006). Figure 7.3 shows that whereas water salinity during the rice season varies from 0.0 to 1.5 ppt, in the experimental *ghers* the soil salinity varies from 2.3 to 3.5 ppt. With this soil salinity, all tested HYVs yielded between 3 and 5 t/ha, suggesting that salinity tolerance was not an absolute requirement for rice grown during the wet season with soil salinity of about 3 ppt (Mondal *et al*., 2006).

Shrimp production

Results of shrimp culture under three stocking patterns, tested in the dry season of 2005

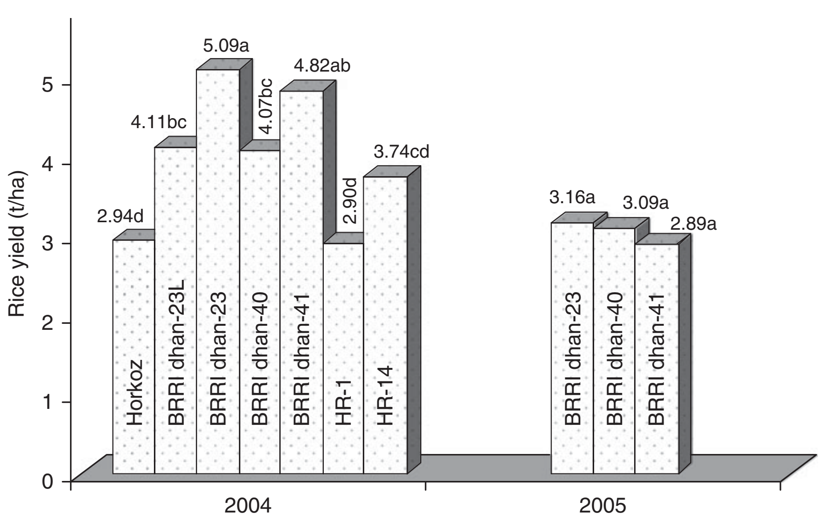

Fig. 7.2. Mean yield of different rice varieties integrated with aquaculture in a rice–shrimp system in the coastal environment. a,b,c and d indicate significant differences ($p < 0.05$).

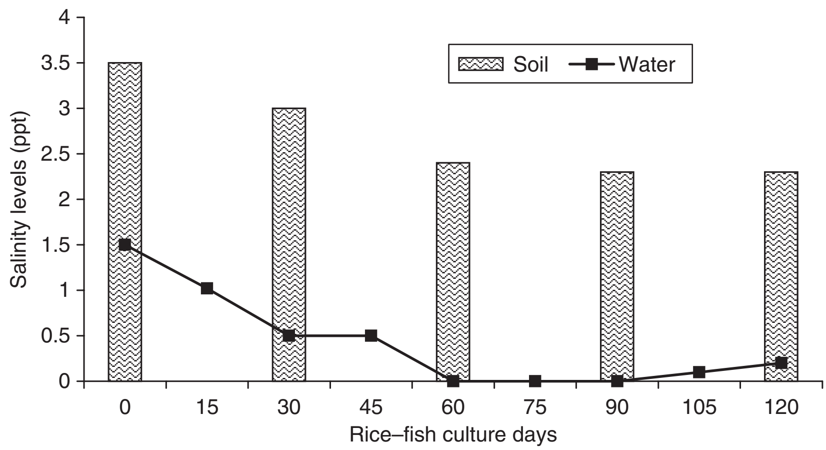

Fig. 7.3. Soil and water salinity variations during rice–fish culture periods (August–December) in rice season experiments.

and 2006, are presented in Table 7.4. There were no significant differences ($F = 1.59$; $p > 0.05$) in performance among the different stocking patterns in terms of growth, survival and yield, although single stocking ponds (T-1) resulted in higher average yields. The average shrimp yields (289–380 kg/ha) obtained in the present study were much higher than those reported by other authors for shrimp farms located in the same region. Nuruzzaman *et al.* (2001) reported yield levels of 74–221 kg/ha for the shrimp farms ranging from extensive to improved extensive scales in the south-west districts of Khulna and Bagerhat. Islam *et al.* (2005) reported similar average yields of 83–204 kg/ha from shrimp farms of different sizes (< 5 and > 10 ha) practising partial stocking at densities of 2–3/m^2 and an extended culture period of 180–200 days. The shrimp yields obtained in this study are also closer to the average production of 343 kg/ha/crop that has been reported at a stocking rate of 5/m^2 in monoculture with supplemental feed and improved water management (Apud *et al.*, 1984).

Attainment of shrimp production levels in the present study (Table 7.4) is attributable to proper management of water depth, pH and primary productivity (Table 7.1). Although the intention was to maintain a minimal water depth of 50 cm in all the experimental *ghers*, it was not possible because of differences in water retention capacity and the soil substrate, and uncontrollable field conditions. Shrimp yield was found to be correlated positively with a water depth ($r = 0.855$; $p < 0.001$) that ranged from 27 to 65 cm. The highest yield range of 521–583 kg/ha, with a corresponding survival rate of 42–58%, was attained in *ghers* with deeper water (47–65 cm depth). Higher mortality and lower growth rates were observed following heavy and prolonged rain in both years, causing a sharp drop in water salinity (Fig. 7.4) and temperature (Fig. 7.5), particularly in the shallower *ghers*.

These sudden changes might have caused physiological stress in shrimp, resulting in disease and/or mortality. Apud *et al.* (1984) reported a mean survival rate of 70.4% in shrimp ponds of 70–100 cm depth, compared to that of 37.5% in ponds of 40–70 cm depth. Truchot (1983) reported that the acid–base balance of crustaceans was affected directly by salinity, whereas New and Singholka (1985) found that an abrupt temperature change of even 1°C might cause mortality in prawns.

Economic analysis

A simple cost–benefit analysis showed that at a total stocking density of 5000/ha, an average

Table 7.4. Shrimp production (mean ± Sd) with different stocking patterns in two seasons' shrimp crop in the coastal rice–shrimp system during March–August 2005 and 2006.

Treatment	Final weight (g/ind)	Survival rate (%)	Yield (kg/ha)
1st trial in 2005 shrimp season			
T-1: single stocking (5/m^2)	20.16 ± 2.34[a]	34.54 ± 22.3[a]	343 ± 212[a]
T-2: double stocking (3 > 2/m^2)	20.75 ± 2.66[a]	27.00 ± 13.0[a]	297 ± 181[a]
T-3: double stocking (2 > 3m^2)	20.56 ± 2.87[a]	26.94 ± 16.1[a]	289 ± 206[a]
2nd trial in 2006 shrimp season			
T-1: single stocking (5/m^2)	23.88 ± 1.3[a]	31.35 ± 11.2[a]	380 ± 161[a]
T-2: double stocking (3 > 2/m^2)	22.99 ± 1.2[a]	27.77 ± 6.1[a]	322 ± 90[a]
T-3: double stocking (2 > 3m^2)	23.06 ± 0.6[a]	26.07 ± 6.9[a]	302 ± 112[a]
Average of 1st and 2nd trials			
T-1: single stocking (5/m^2)	22.28 ± 2.58[a]	32.72 ±15.2[a]	364 ± 168[a]
T-2: double stocking (3 > 2/m^2)	22.03 ± 2.12[a]	27.68 ± 8.8[a]	311 ± 123[a]
T-3: double stocking (2 > 3m^2)	21.99 ± 2.18[a]	26.44 ± 10.0[a]	296 ± 135[a]

[a]Indicates significant difference, $p < 0.05$.

net return of Tk24,640.00 (US$1 = Tk68.00) for integration of rice with GIFT alone was significantly higher ($p < 0.05$) than that of Tk13,290 for rice with prawn alone (Fig. 7.6.).

The estimated BCR of 1.96 for rice–tilapia monoculture was also significantly higher ($F(2; 8) = 22.11$; $p < 0.05$) than for the other treatments. However, the difference in net return between rice–GIFT and rice–GIFT–prawn was insignificant. Monoculture of prawn integrated with rice incurred significantly higher cost than the other treatments ($F(2; 8) = 763.9$; $p < 0.001$), accounting for 50% of the total production cost (mainly because of the high cost of juvenile prawn), but only 36% of the gross and 0% of the net return.

In terms of aquaculture contribution to the integrated rice–fish system output, the 2005 results showed that the treatment T-1 (GIFT in monoculture, RG) gave the highest net return of Tk10,858/ha (43% of total net return from rice–fish) with a BCR of 3.09, compared with Tk8521/ha (37%) and Tk494/ha (0%) for T-2 (RGP) and T-3 (RP), respectively, with corresponding BCR of 1.65 and 0.97.

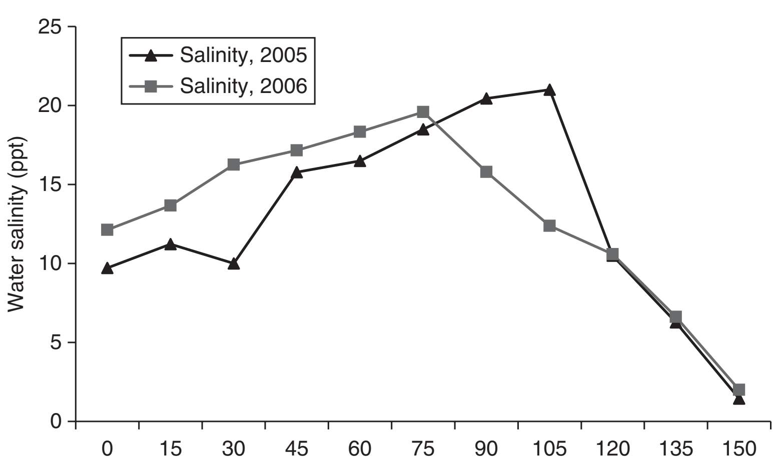

Fig. 7.4. Variations in average water salinity during the shrimp culture period of 2005 and 2006.

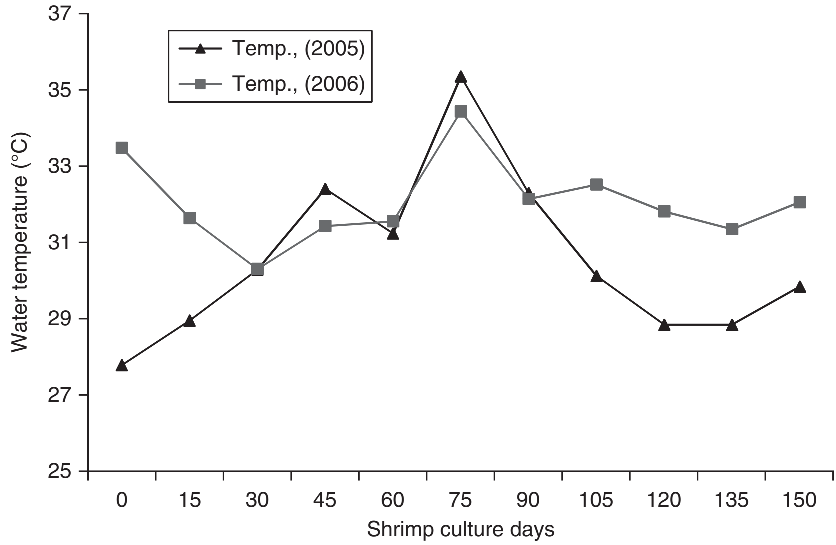

Fig. 7.5. Variations in average water temperature during the shrimp culture period of 2005 and 2006.

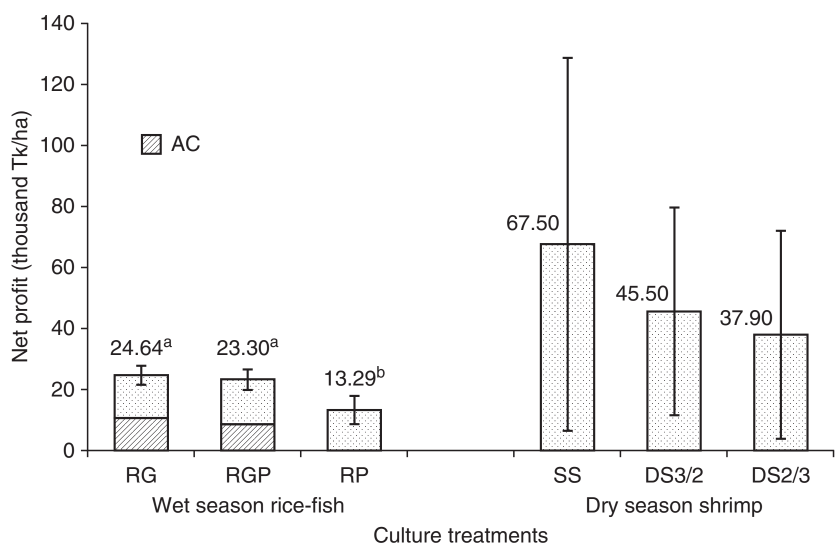

Fig. 7.6. Net economic profit (NP) from different culture treatments for rice–fish (RG, rice–GIFT; RGP, rice–GIFT–prawn; RP, rice–prawn) and shrimp (SS, single stocking at 5/m^2; DS3/2, double stocking at 3 followed by 2/m^2; DS2/3, double stocking at 2 followed by 3/m^2) production in 2005. [a] and [b] indicate significant differences ($p < 0.05$). AC represents aquaculture contribution in rice–fish/prawn system.

Figure 7.6 also shows that the average net return from single stocking (SS) is higher, although not significantly so, than that from double stocking (DS). The lower market price of the smaller-sized shrimp from the second stocking resulted in lower returns from double stocking. The higher the later stocking rate, the lower the returns. Net profits vary across treatments from a low of Tk11,000/ha to a high of Tk121,000/ha, with corresponding BCR of 1.14–2.58. This variation was particularly a result of low survival rates of shrimp in certain replicate ponds in each treatment. The net benefits from the shrimp culture reported here are generally comparable with, or significantly higher than, those reported elsewhere on shrimp yields under extensive production in south-western Bangladesh – net returns of Tk21,617/ha to Tk57,997/ha have been reported by Islam *et al*. (2005); Tk35,500/ha by Ling *et al*. (2001); and Tk40,200/ha by Rahman *et al*. (2002).

Economic analysis of the entire rice–shrimp production system suggests that average net incomes as high as Tk62,000–92,000/ha could be achieved through practising the integration of rice and GIFT followed by shrimp with either single or double stocking. This represents a 130–190% increase of net farm income compared with existing farming systems in the same agroecological area (Joffre *et al*., unpublished).

Conclusions and Recommendations

This study demonstrates that cultivating HYVs of rice (preferably BR23, BRRI dhan 40 and BRRI dhan 41) along with short-duration fish (preferably GIFT strain of tilapia) and/or prawn during the low-salinity period (August–December), followed by shrimp (*P. monodon*) during the high-salinity period (February–August), with proper water and feed management, would not only reduce the risk of crop loss but also increase total farm productivity and net income. Although the rice crop performance could benefit from the integrated culture of fish and crustacea (Halwart and Gupta, 2004), water management for both rice and fish remains crucial for the rice–shrimp system.

The recommended stocking density of aquaculture species, farmed together with rice, is $0.5/m^2$. The short rice-growing period necessitates stocking of larger prawn juveniles (of 4–5 g individual body weight) that are more costly (Tk5.00–6.00/piece), consequently resulting in marginal gross profit and even negative net profit. A more profitable alternative would be to nurse less costly prawn postlarvae for 45–60 days using a hapa nursery (Alam *et al*., 1997) prior to stocking in the rice field.

Management of water productivity and feeding played key roles in increasing shrimp production compared with the existing practice of multiple stocking and harvesting. Despite not obtaining statistically significant results, our study suggests that single stocking of shrimp at the rate of $5/m^2$, with improved farm management, may be more suitable for the production system involving rice with fish and/or prawn followed by shrimp culture in south-western Bangladesh. It has been thought that partial stocking would be advantageous because of the phasing of expenditures on input and spreading of the financial risk in the event of crop failure. On the other hand, partial stocking has the risk of introducing a second stock of any pathogen-affected postlarvae that might infect the earlier crop. The main disadvantage of multiple stocking is the requirement for longer culture duration at the expense of delaying the start of the next rice crop.

The positive correlation between shrimp yield and water depth suggests the importance of maintaining a sufficient water depth in the shrimp *ghers*. However, deepening the *gher* may affect the yield of the subsequent rice crop through waterlogging, particularly as a result of prolonged monsoon rain. Therefore, a proper physical infrastructure for well-controlled water intake and discharge needs to be in place to enable managing of optimal water depths for both shrimp and rice–fish farming.

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References

Alam, M.J., Hoq, M.E., Zahan, D.A. and Mazid, M.A. (1997) Nursery rearing of *Macrobrachium rosenbergii* (de Man) using hapa-nets: effects of stocking density. *Bangladesh Journal of Fisheries Research* 1(1), 9–16.

APHA (American Public Health Association) (1992) *Standard Methods for the Examination of Water and Wastewater*, 18th edn. APHA, Washington, DC.

Apud, F.D., Gonzales, K. and Deatras, N. (1984) Survival, growth and production of *Penaeus monodon* fabricus at different stocking densities in earthen ponds with flow-through systems and supplemental feeding. *Fisheries Research Journal of the Philippines* 6(2), 1–9.

Boyd, C.E. and Egna, H.S. (eds) (1997) *Dynamics of Pond Aquaculture*. CRC Press LLC, Boca Raton, Florida.

Brennan, D., Preston, N., Clayton, H. and Be, T.T. (2002) An evaluation of rice–shrimp farming systems in the Mekong Delta. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Published by the Consortium, Bangkok.

Chakraborti, R.K., Ravichandran, P., Halder, D.D., Mandal, S.K. and Sanfui, D. (1985) Some physico-chemical characteristics of Kakdwip brackishwater ponds and their influence on survival, growth and production of *Penaeus monodon* (Fabricius). *Indian Journal of Fisheries* 32(2), 224–235.

Chanratchakool, P., Turnbull, J.F., Funge-Smith, S. and Limsuwan, C. (1995) *Health Management in Shrimp Ponds*, 2nd edn. Aquatic Animal Health Institute, Thailand.

DoF (Department of Fisheries) (2005) *Fish Week Compendium*. Department of Fisheries, Ministry of Fisheries and Livestock, Dhaka, Bangladesh.

Gupta, M.V., Sollows, J.D., Mazid, M.A., Rahman, A., Hussain, M.G. and Dey, M.M. (1998) Integrating aquaculture with rice farming in Bangladesh: feasibility and economic viability, its adoption and impact. ICLARM Technical Report 55. ICLARM, Metro Manila, 90 pp.

Gupta, M.V., Sollows, J.D., Mazid, M.A., Rahman, A., Hussain, M.G. and Dey, M.M. (2002) Economics and adoption patterns of integrated rice–fish farming in Bangladesh. In: Edward, P., Little, D.C. and Demaine, H. (eds) *Rural Aquaculture*. CAB International, Wallingford, UK.

Halwart, M. and Gupta, M.V. (eds) (2004) *Culture of Fish in Rice Fields*. FAO and WorldFish Center, Kuala Lumpur, Malaysia.

Hariati, A.M., Wiadnya, D.G.R., Tanck, M.W.T., Boon, J.H. and Verdegem, M.C.J. (1996) *Penaeus monodon* (Fabricius) production related to water quality in East Java, Indonesia. *Aquaculture Research* 27, 255–260.

Haroon, A.K.Y. and Pittman, K.A. (1997) Rice–fish culture: feeding, growth and yield of two size classes of *Puntius gonionotus* Bleeker and *Oreochromis* spp. in Bangladesh. *Aquaculture* 154, 261–281.

Haroon, A.K.Y., Dewan, S. and Karim, S.M.R. (1992) Rice–fish production systems in Bangladesh. In: de la Cruz, C.R., Lightfoot, C., Costa-Pierce, B.A., Charangal, V.R. and Bimbao, M.P. (eds) *Rice–Fish Research and Development in Asia*. ICLARM Conference Proceedings 24. ICLARM, Metro Manila, pp. 165–171.

Hung, L.T. (2001) Rice–prawn and rice–shrimp culture in coastal areas of Vietnam, integrated agriculture–aquaculture: a primer. FAO/ICLARM/IIRR Fisheries Technical Paper No 407. FAO, Rome.

Islam, M.S. (2003) Perspectives of the coastal and marine fisheries of the Bay of Bengal, Bangladesh. *Ocean and Coastal Management* 46, 763–796.

Islam, M.S., Milstein, A., Wahab, M.A., Kamal, A.H.M. and Dewan, S. (2005) Production and economic return of shrimp aquaculture in coastal ponds of different sizes and with different management regimes. *Aquaculture International* 13, 489–500.

Karim, M.R. (2006) Brackish-water shrimp cultivation threatens permanent damage to coastal agriculture in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 61–71.

Kohinoor, A.H.M., Saha, S.B., Akhteruzzaman, M. and Gupta, M.V. (1995) Suitability of short cycle species *Puntius gonionotus* (Bleeker) for culture in rice fields. *Journal of the Inland Fisheries Society of India* 27(1), 60–64.

Ling, B.H., Leung, P. and Shang, Y.C. (2001) *Comparing Asian Shrimp Farming: The Domestic Resource Cost (DRC) Approach. Economics and Management of Shrimp and Carp Farming in Asia*. NACA, Bangkok, Thailand, pp. 1–19.

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudury, M.H.K., Chasi, A.M., Majumder, P.K., Islam, M.M. and Adhikary, S.K. (2006) Coastal water resource use for higher productivity: participatory research for increasing cropping intensity in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment* *and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 72–85.

New, M.B. (1995) Status of freshwater prawn farming: a review. *Aquaculture Research* 26, 1–54.

New, M.B. and Singholka, S. (1985) Freshwater prawn farming. FAO Technical Paper No 225, Rev. 1, Rome.

Nuruzzaman, M., Anwari, B., Shahjahan, M. and Moniruzzaman, M. (2001) The dynamics and diversity of the shrimp farming in Bangladesh. Final Report, Fourth Fisheries Project, Shrimp and Coastal Aquaculture Component, Department of Fisheries, Bangladesh.

Rahman, M.S. (1992) *Water Quality Management in Aquaculture*. BRAC Publishing, Dhaka, Bangladesh.

Rahman, M., Siriwardena, P.P.G.S.N. and Shah, W. (2002) Case studies on shrimp aquaculture management in Bangladesh. Report prepared under the World Bank, NACA, WWF and FAO Consortium Programme on Shrimp Farming and Environment. Published by the Consortium, Bangkok.

Strickland, J.D.H. and Parsons, T.R. (1968) A practical handbook of seawater analysis. *Bulletin of Fisheries Research Board of Canada* 167. Fisheries Research Board of Canada, Ottawa.

Truchot, J.P. (1983) Regulation of acid–base balance. In: Mantel, L.H. (ed.) *The Biology of Crustacea*, Vol. 5. Academic Press, New York, pp. 431–457

8 Zooplankton Dynamics and Appropriate Management Approach for Blue Swimming Crab in Kung Krabaen Bay, Thailand

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Abstract
Zooplankton dynamics were assessed, including the relationships between crab larvae, other zooplankton and ecological factors, and an appropriate approach to the management of blue swimming crab in Kung Krabaen Bay, Chanthaburi Province was explored. Sixteen stations were selected for bimonthly sample collection during 2004 and 2005 and these revealed 40 groups of zooplankton from 15 phyla. Among these, four economically important groups were recorded, including shrimp larvae, fish larvae, bivalve larvae and brachyuran larvae (crab larvae). The distribution and density of these four groups were different in relation to the influence of the monsoon season and the specific habitat in the bay where they were found. In particular, brachyuran larvae density was highest (1.4×10^5 to 3.8×10^3 ind/100 m^3) during the south-west monsoon (May–October), which had a negative correlation with fish larvae and a positive correlation with *Acetes* spp. The study results indicated that the highest distribution and density of brachyuran larvae were found at the seagrass habitat and the bay mouth. The density and distribution of brachyuran larvae also corresponded to the study of the gonad somatic index, which found two peaks of the spawning of berried female blue swimming crab in September and January. Spawning of female crab showed a relationship with the peak density of brachyuran larvae in November. Both crab larvae and young blue swimming crab use the seagrass bed as a refugium and nursery habitat. With regards to the specific characteristics of this bay, the blue swimming crab is a dominant economic species, which has supported the livelihood of local fishing communities. Blue swimming crab production has declined from 120 t in 2002 to 80 t in 2004 and 62 t in 2005, which is clearly related to over-crabbing in this bay using small mesh size (3.50 cm) collapsible crab traps. Average catching size has also reduced from 11.22 cm in 1999 to 7.31 ± 0.42 cm in 2005, with pre-reproductive females representing 70% of the catch. An appropriate management approach for the blue swimming crab fishery that enhances survival would include: (i) conserving seagrass beds by prohibiting crabbing during the north-east monsoon when berried female blue swimming crab and brachyuran larvae are at their highest density; (ii) enlarging the mesh size of collapsible crab traps to not less than 6.50 cm to avoid catching young crab; (iii) banning the capture of berried females; (iv) promoting crab restocking and culture; and (v) educating and publicizing sustainable crabbing to fisher communities, as well as other stakeholders.

Introduction

Blue swimming crab *Portunus pelagicus* has a wide geographical distribution throughout the Indo-Pacific region (Kailola *et al*., 1993). It is usually found in large numbers in shallow bays with a sandy bottom (Dai and Yang, 1991) and is a very important commercial species in many countries such as Australia, Japan and the South-east Asian countries, including Thailand. The Thailand commercial fishery currently harvests blue swimming crab at a rate of more than 25,000 t/year (Department of Fishery Thailand, 2007), but total production has decreased in many areas of the country because of overharvesting, catching ovigerous female crab in the spawning season and using fishing gear with a mesh size smaller than that recommended. Strategies to resolve these problems have not succeeded and population declines have resulted because of the insufficient recruitment of larvae. Zooplankton communities are also important in supporting blue swimming crab production in coastal ecosystems, especially in Kung Krabaen Bay, Thailand. Zooplankton links producers and consumers through the higher trophic levels and understanding their distribution and production could help to identify areas of potential production of fishery resources (Paphavasit *et al.*, 2003). This chapter reports on a study carried out to assess zooplankton dynamics and search for the relationship between crab larvae, other zooplankton and ecological factors so as to help conserve the blue swimming crab population. The study also explored appropriate management strategies for blue swimming crab in Kung Krabaen Bay.

Fig. 8.1. Location of Kung Krabaen Bay.

Study Area

Kung Krabaen Bay is located between latitude 12°34' to 12'N and longitude 101°53' to 101°55'E. It is a small, semi-enclosed estuarine system on the west coast of Chanthaburi Province in the eastern region of Thailand (Fig. 8.1).

The bay's morphological profile is as follows: its size is 2.5 × 4.0 km; has an average depth of 2.5 m; an approximate area of 10 km^2; and a total volume of 2.5 × 10^7 m^3. The bay is connected to the Gulf of Thailand by a channel 700 m wide on the south-eastern corner (KKBRDSC, 2003). A fringing mangrove forest covers approximately 2.58 km^2 along the north-eastern shore and parts of the north-western and south-western shores and is an appropriate feeding and nursing ground (Chatananthawej *et al.*, 2002).

Methods

To study zooplankton dynamics in Kung Krabaen Bay, zooplankton diversity, density, distribution and the relationships between zooplankton density, especially branchyuran larvae, other zooplankton and ecological factors were assessed. A sampling programme was designed and included 16 stations in the bay with a set of four stations covering four different habitat types (Fig. 8.2) including: a reforested mangrove area near the mouth of the discharge canal (I); seagrass bed (II); open water in the middle of the bay (III); and the bay mouth (IV). Zooplankton were sampled bimonthly in May, July and September, which represented the south-west monsoon season. Sampling during November, January and March represented the north-east monsoon season. Zooplankton were collected using net mesh size 103 μm for 2 min of horizontal hauling by boat, travelling at low speed. Samples were fixed in 7% neutralized formalin. Zooplankton were counted and identified to higher taxonomic groups and density was

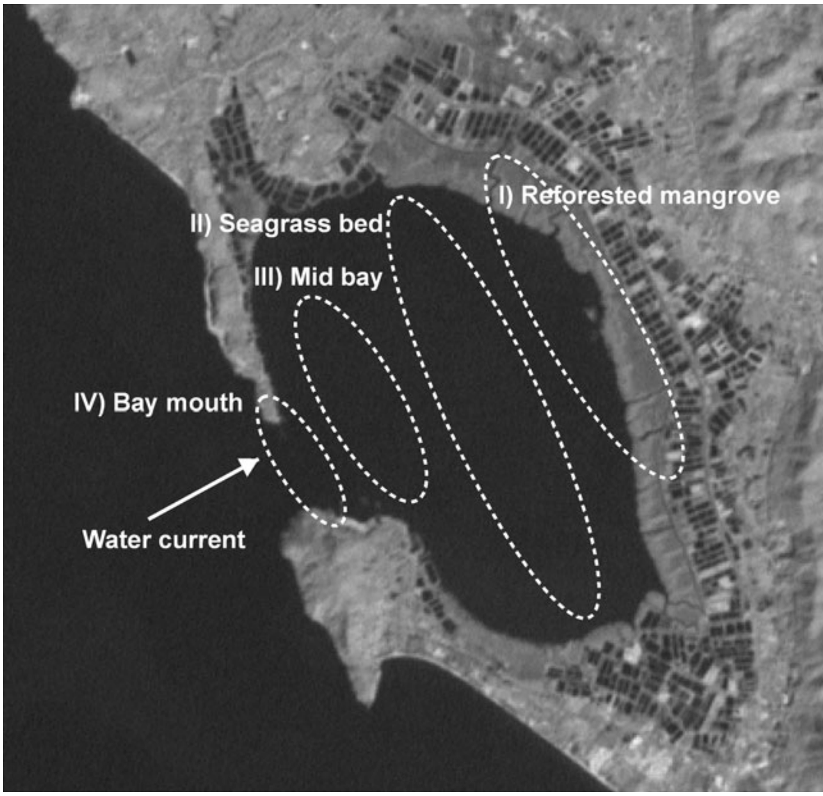

Fig. 8.2. Study area at Kung Krabaen Bay (Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) satellite image courtesy of the US Geological Survey; http://www.usgs.gov).

calculated as the number of individuals per 100 cubic metres (ind/100 m^3). Ecological factors were also measured, including: temperature, pH, dissolved oxygen (DO), salinity, transparency depth, depth and chlorophyll *a* based on standard methods (Parsons *et al.*, 1985), and the relationships between zooplankton density and ecological factors were analysed. To study population dynamics, blue swimming crab in Kung Krabaen Bay were sampled monthly from January to December 2005, and this programme also considered the south-west (May–October) and north-east (November–April) monsoon seasons. A system of 25 sampling stations was designed and covered the previously discussed habitat types corresponding to zooplankton sampling stations (Fig. 8.2). Blue swimming crabs were trapped by a collapsible crab trap with mesh size 3.50 cm, with three traps set up per sampling station. Collected data included sex, carapace width, carapace length, wet weight, stomach content (Williams, 1981) and the gonad somatic index of females (Zar, 1984). Data analysis focused on: (i) blue swimming crab harvesting rate; (ii) density and distribution pattern; (iii) gonad somatic index; and (iv) stomach content of young and adult blue swimming crab.

Results and Discussion

Distribution and density of zooplankton

This study found zooplankton from 40 groups in 15 phyla divided into two categories: (i) Holozooplankton – 22 groups from eight phyla; and (ii) Merozooplankton – 18 groups from eight phyla (Table 8.1). The copepod population (calanoid copepod, cyclopoid copepod

Table 8.1. Zooplankton diversity, density and distribution in Kung Krabaen Bay, Chanthaburi province, Thailand.

Phyla	Taxa	Reforested mangrove	Seagrass bed	Middle sea	Bay mouth
Protozoa	Foraminifera	R	O	R	R
	Radioraria	R	R	R	R
	Tintinnid	R	R	R	R
Cnidaria	Hydromedusae	R	R	R	R
	Siphomedusae	R	R	R	R
Ctenophora	Ctenophore	NF	R	NF	NF
Nemertea	Pilidium larvae*	NF	R	NF	NF
Platyhelminthes	Turbellaria larvae*	NF	NF	R	NF
Nematoda	Nematode	R	R	R	NF
Rotifera	Rotifer	R	NF	R	R
Annelida	Polychaete larvae*	R	R	R	R
Chaetognatha	Arrow worm	R	R	R	R
Bryozoa	Cyphonautes larvae*	R	R	R	R
Mollusca	Gastropoda larvae*	O	R	R	R
	Bivalvia larvae*	R	R	R	R
Arthopoda	Cladocera	NF	R	R	R
	Ostracoda	R	R	R	R
	Cirrepedia larvae*	R	R	R	R
	Calanoid copepod	R	O	O	O
	Cyclopoid copepod	R	O	O	O
	Harpacticoid copepod	R	R	R	R
	Amphipod	R	R	R	NF
	Lucifer sp.	R	R	R	O
	Acetes sp.	NF	R	R	NF
	Pagurid larvae*	R	R	R	R
	Cypris	R	R	R	R
	Shrimp larvae*	R	R	R	R
	Brachyuran larvae*	R	R	R	R
	Anomura larvae*	R	R	R	NF
	Alima larvae*	R	NF	NF	NF
	Sea mite	R	NF	NF	NF
	Crustacean nauplii	O	R	R	R
Echinodermata	Echinopluteus larvae*	NF	R	R	R
	Ophiopluteus larvae*	NF	R	R	R
	Bipinnaria larvae*	NF	R	NF	R
	Auricularia larvae*	NF	R	R	R
Urochordata	Larvacean	R	R	R	R
	Thaliacean	NF	NF	NF	R
Chordata	Fish larvae*	R	R	R	R
	Fish eggs*	R	NF	R	R

O, occasional, 20–39%; R, rare, 1–19%; and NF, not found. *Merozooplankton.

and harpacticoid copepod) dominated at all stations throughout the year and comprised 44.32–65.37% of total zooplankton density. This corresponded with the reports of Marumo *et al*. (1985), Satapoomin (1999) and Aiemsomboon (2000), who identified that copepods were dominant, with approximately 71.63, 88.40 and 40.00% of total zooplankton density, respectively. The co-dominant zooplankton group was crustacean nauplii, mollusc larvae, polychaete larvae, larvacean and tintinnid, comprising 7.19–23.69%, 3.61–21.64%, 0.80–11.80%, 1.69–5.22% and 0.02–4.36%, respectively. This group was ranked based on density that indicated occasional (O) and rare (R) situations (Table 8.1). Opportunistic zooplankton groups were identified during the south-west monsoon (rainy season), whereas the Cladocera and Rotifer groups were identified in the reforested mangrove area because of its sensitivity to salinity. This also corresponded with the studies of Piumsomboom *et al.* (1999), which found Cladocera and Rotifer in October 1997 during the south-west monsoon and that salinity was a limiting factor of these groups. Moreover, this study found four economically important groups, including shrimp larvae, fish larvae, bivalve larvae and brachyuran larvae (crab larvae).

In terms of zooplankton distribution (Fig. 8.3), we found that bivalve larvae, shrimp larvae, fish larvae and brachyuran larvae density and distribution were highest in the mid-bay zone, in the seagrass area and the bay mouth area during the south-west monsoon season (range of 6.72×10^5–8.04×10^5; 237–284; 294–353 and 408–489 ind/100 m^3, respectively. During the north-east monsoon season, only shrimp larvae were found in high density near the bay mouth and the seagrass area, ranging from 705 to 1411 ind/100 m^3. Nateekarnjanalarp (1990) studied fish at Samui Island, Thailand, and found some fish living in seagrass beds and that some species, such as Lutjanidae, used seagrass beds for mating and nursing in the breeding season. Zieman (1982) reported that *Argopecten irradians* larvae (bivalve larvae) lived in seagrass beds and depended on seagrass leaf. Furthermore, Williams (1981), Chande and Mgaya (2004), Patel *et al.* (1971) and Cannicci *et al.* (1996) studied the stomach content of blue swimming crab and found crustacean, mollusc and fish as the major food sources of young and adult blue swimming crab.

Relationship between brachyuran larvae, ecological and biological factors

Analysis of the relationships between brachyuran larvae and ecological and biological factors such as depth, transparency depth, salinity, temperature, DO, pH and chlorophyll *a* showed no significant differences. On the other hand, brachyuran larvae had a negative correlation with fish larvae ($p < 0.05$) and had a positive correlation with *Acetes* spp. ($p < 0.05$). Other zooplankton (Hydromedusae, Chaetognatha, *Lucifer* sp. and shrimp larvae) indicated their role as predators, which was not correlated with brachyuran larvae (Table 8.2). Lestang *et al.* (2003) and Queiroga *et al.* (2006) reported that the brachyuran larvae, first crab stage and young crab migrated from the sea to the estuarine area near the coastal zone. In the case of Kung Krabaen Bay, the water current and tidal cycle influence zooplankton distribution because of the topographic characteristics with shallow water in the bay. Brachyuran larvae are densely distributed in the seagrass bed toward the north-west part of the bay where the water current flows into the bay ends. The water volume exchange rate in Kung Krabaen Bay depends on seawater from the open sea flowing through the bay mouth, and the volume of inflow from the open sea is more than 40 times the water flow of the brackishwater discharge flowing in from shrimp farms (Sangrungrueang *et al.*, 1999).

Blue swimming crab situation

The blue swimming crab (*P. pelagicus*) situation in 2005 indicated that production was 62 t/year, which was far lower than in 2002 (120 t/year). Furthermore, the average catching size was also reduced from 11.22 cm in 1999 to 7.31 ± 0.42 cm in 2005. As a result, the ratio of male and female crabs was 1:1.23 from a total of 4046 crabs (Table 8.3). This differs from the sex ratio of blue swimming crab in Chumporn and Songkhla Provinces in the Gulf of Thailand, where Tantikul (1984) found a ratio of 1:1.4. In terms of size distribution, approximately 70% of the crabs caught in Kung Krabaen Bay were pre-reproductive females (≤ 7.31 cm). This suggests overharvesting as a result of using small mesh size collapsible traps (3.50 cm), which catch more female than male crabs. Fishermen also double the number of traps during the spawning season because the ovigerous female has a higher market demand (Kunsook, 2006). Our study also found 2816 young blue swimming

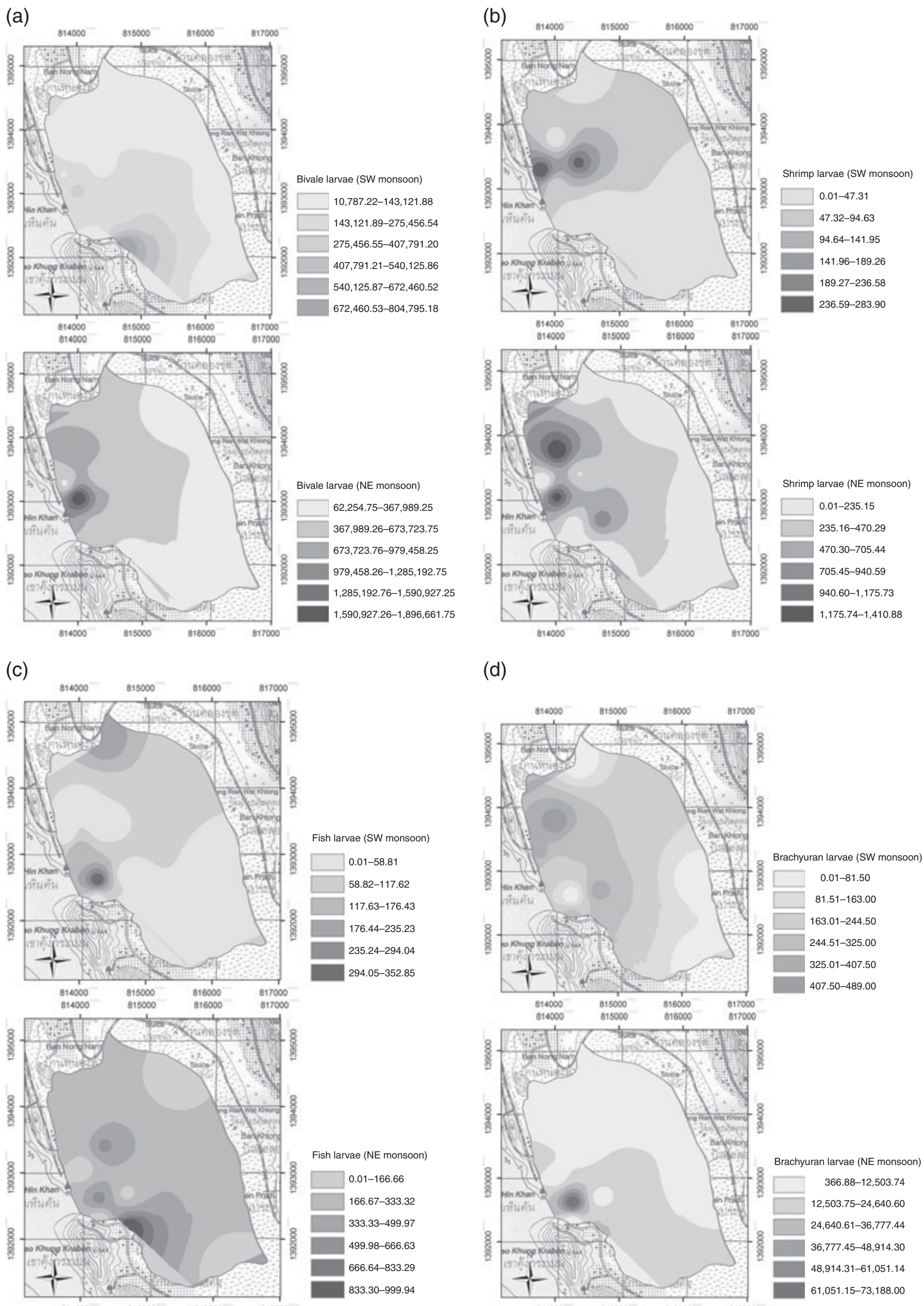

Fig. 8.3. Density and distribution pattern of: (a) bivalve larvae; (b) shrimp larvae; (c) fish larvae; and (d) brachyuran larvae.

Table 8.2. Correlation coefficient between brachyuran larvae density, ecological and biological factors ($P < 0.05$).

Factors	South-west monsoon	North-east monsoon
Depth	–0.068	–0.093
T-depth	–0.043	–0.129
Salinity	0.451	0.271
Temperature	–0.310	0.205
Dissolved oxygen	0.032	0.224
pH	0.019	0.132
Chlorophyll *a*	–0.200	–0.026
Hydromedusae	0.054	0.237
Chaetognathas	0.107	–0.168
Lucifer sp.	0.375	–0.162
Acetes spp.	0.603*	–
Shrimp larvae	0.287	–0.338
Fish larvae	–0.583*	0.376

crabs and 1230 adult blue swimming crabs (Table 8.3), which corresponded with a report by Jindalikit *et al*. (2002), who found that coastal zones were more suitable for young blue swimming crab, whereas adults preferred to live in the open sea. This combination of factors led us to conclude that an urgent change in existing crabbing practices in Kung Krabaen Bay was required to protect the blue swimming crab population. Sustainable management practices are needed, not only to conserve the crab population but also to support the local economy, which will suffer without a viable crab fishery.

Density and distribution of brachyuran larvae and blue swimming crab

Brachyuran larvae (megalopa stage) were highly abundant in the north-east monsoon season in the bay mouth and seagrass bed (Fig. 8.4), especially in November, when we found approximately $1.42 \times 10^5 \pm 3820$ ind/100 m^3. A lower density of brachyuran larvae was found throughout the bay during the south-west monsoon season. Salinity is a major factor for brachyuran larvae development to the first crab stage and the optimal salinity is in the range of 30–33 ppt (Tantikul, 1984). A similar report by Pillay and Nair (1972) found a high density of brachyuran larvae during February–March (the north-east monsoon season) in the coastal zone of the Indian Ocean, and Kuptawatin (2000) reported that seagrass beds provided good shelter and nursing ground for brachyuran larvae. Moreover, the gonad somatic index of blue swimming crab in Kung Krabaen Bay indicates two spawning periods: January–March and August–September, which corresponds to the highest observed density of brachyuran larvae during November 2004–March 2005 (Fig. 8.5). Blue swimming crab population density in the south-west monsoon season is higher than in the north-east monsoon season (Fig. 8.4b).

Table 8.3. Ratio between young and adult blue swimming crab.

	Male	Female	Total
Young crab	1251	1565	2816
Adult crab	564	666	1230
Total	1815	2231	4046

Stomach content of young blue swimming crab

Stomach content analysis of blue swimming crab from 140 samples by frequency of occurrence found eight groups including crustacean, fish, mollusc, squid, algae, seagrass, organic matter and sand (83.57, 69.29, 58.57, 27.14, 23.57, 22.14, 18.57 and 10.00, respectively) (Fig. 8.6). This corresponds with other reports

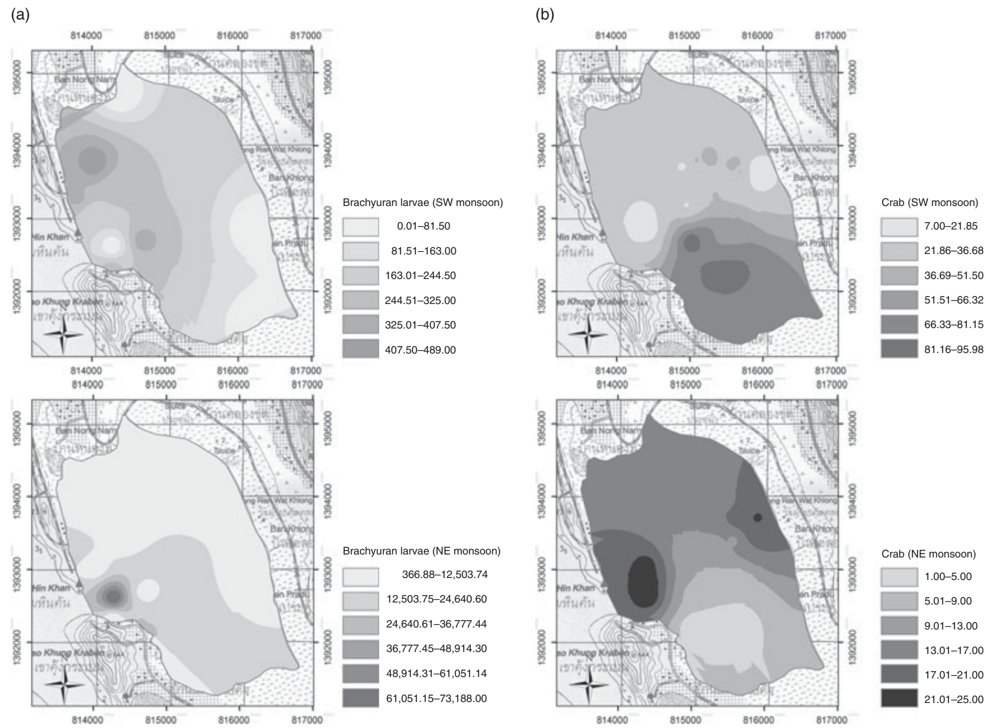

Fig. 8.4. Density and distribution pattern of (a) brachyuran larvae and (b) blue swimming crab in Kung Krabaen Bay.

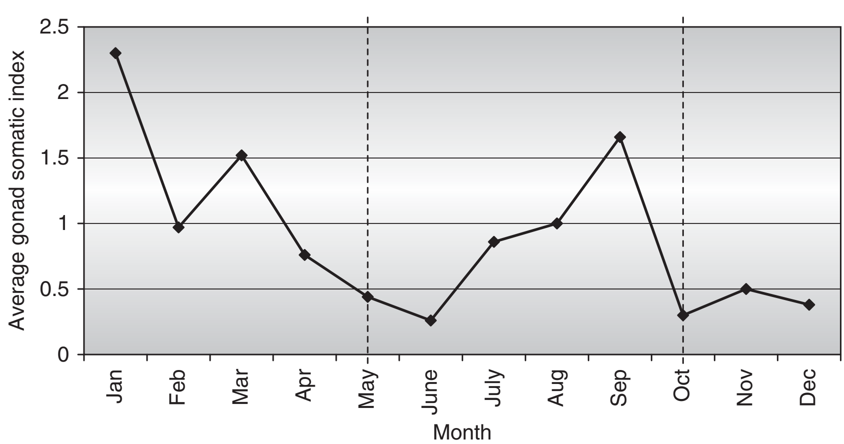

Fig. 8.5. Gonad somatic index of female blue swimming crab (*P. pelagicus*).

from Patel *et al*. (1971), Williams (1981) and Chande and Mgaya (2004). This study also found that crustaceans (which are a major calcium source for the development of crab carapace) represented 45–75% of the stomach contents in young and adult blue swimming crab. Analysis of the stomach content of young blue swimming crab (carapace < 7.0 cm) found mollusc, fish, crustacean and sand, whereas fish, crustacean, mollusc and organic matter

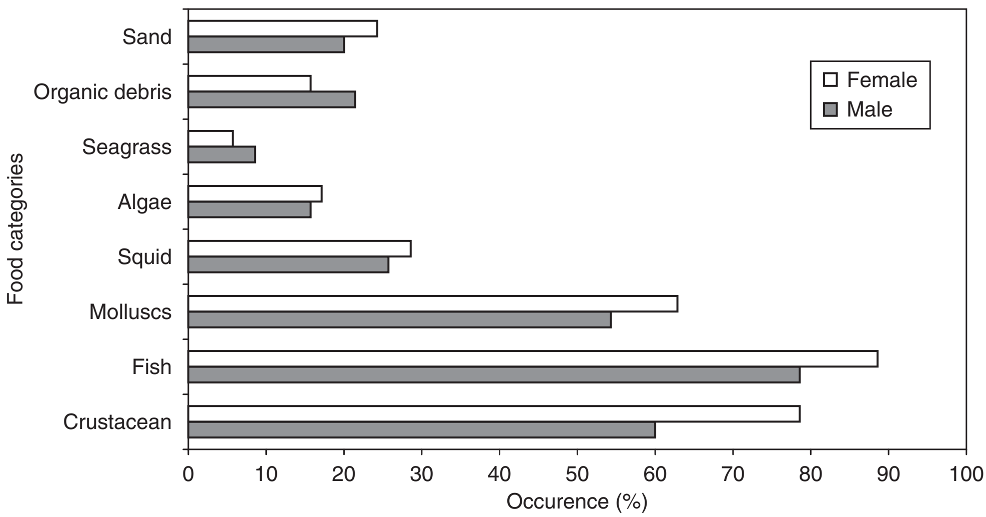

Fig. 8.6. Frequency of stomach content in male and female blue swimming crab by frequency of occurrence method.

were found in adult blue swimming crab (carapace > 7.0 cm). A comparison of food quantity consumed by male and female crab found that females ate more food because of their additional energy requirements for ovogenesis (Cannicci *et al.*, 1996).

Conclusions

Zooplankton dynamics in Kung Krabaen Bay revealed 40 groups from 15 phyla, including four economically important groups, namely shrimp larvae, fish larvae, bivalve larvae and brachyuran larvae (crab larvae). Copepod was a dominant group and could be found all year round. Zooplankton density was higher in the north-east monsoon season than in the south-west monsoon season. The distribution pattern of brachyuran larvae showed higher densities in the seagrass bed and bay mouth than in the reforested mangrove area. The blue swimming crab population in Kung Krabaen Bay clearly declined from 120 t in 2002 to 62 t in this study in 2005, and we also found the proportion of the population of young to adult blue swimming crab was 2.3:1. The young crabs live mostly in seagrass beds, whereas adult crabs prefer the open sea. The spawning period of blue swimming crab as identified by the gonad somatic index showed two periods: January–March and August–September. This implies a relationship between spawning blue swimming crab and brachyuran larvae, as brachyuran larvae density is highest during the north-east monsoon (November–March), which overlaps both spawning periods. Analysis of the stomach content of blue swimming crab revealed that both young and adult blue swimming crabs foraged mainly on crustaceans, followed by molluscs, squid, algae and organic matter. These results could help in the development of appropriate feeding and crab culture.

The blue swimming crab population and production in Kung Krabaen Bay urgently requires an improved management approach. This is especially true with respect to the young blue swimming crab and should focus on: (i) enhancing the survival of crab larvae through the active conservation of seagrass bed areas; (ii) requiring the use of larger mesh sizes in collapsible crab traps; (iii) immediately banning the capture of berried females; (iv) promoting crab restocking and crab culture; and (v) educating local fishermen and other stakeholders about sustainable crabbing practices. Appropriate areas should be selected for the release of crab larvae to promote the survival of crabs in different stages, and further study is recommended to understand blue swimming crab migration through techniques such as tagging. Future studies should also assess the survival rate of cultured crab and of crab released into natural habitats, and the participation of stakeholders should also be encouraged to achieve sustainable management.

References

Aiemsomboon, N. (2000) Abundance of shrimp, crab and fish larvae in Tha-Chin estuary, Samut Sakhon Province. MSc thesis, Chulalongkorn University, Bangkok.

Cannicci, S., Guebas, F.D., Anyona, D. and Vannini, M. (1996) Natural diet and feeding habits of *Thalamita crenata* (Decapod: Portunidae). *Journal of Crustacean Biology* 16(4), 678–683.

Chande, A.I. and Mgaya, Y.D. (2004) Food habits of the blue swimming crabs *Portunus pelagicus* along the coast of Dar es Saalam, Tanzania. *Western Indian Ocean Journal of Marine Science* 3(1), 37–42.

Chatananthawej, B., Piumsomboon, A. and Paphavasit, N. (2002) Budget models of phosphorus and nitrogen in Kung Krabaen Bay, Chanthaburi Province. *Journal of Science Research* 1, 93–108.

Dai, A. and Yang, S. (1991) *Crab of the China Seas*. China Ocean Press, Beijing.

Department of Fishery (2007) Statistics of total production of blue swimming crab in Thailand. Bangkok.

Jindalikit, J., Panwichian, S. and Praput, P. (2002) Distribution of *Portunus pelagicus* (Linnaeus, 1758), Chanthaburi Province. Printed material No 16, Department of Fishery, Bangkok.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. and Grieve, C. (1993) *Australian Fisheries Resources*. Bureau of Resource Sciences, Department of Primary Industries and Energy, and the Fisheries Research and Development Corporation, Canberra.

KKBRDSC (The Kung Krabaen Bay Royal Development Study Center) (2003) *Mangrove Forest in Kung Krabaen Bay*. Department of Fishery, Bangkok.

Kunsook, C. (2006) Population dynamics of blue swimming crab *Portunus pelagicus* (Linnaeus, 1758) at Kung Krabaen Bay, Chanthaburi Province. MSc thesis, Chulalongkorn University, Thailand.

Kuptawatin, W. (2000) Cultivation and nursery of young blue swimming crab for increasing its population by releasing into natural habitat. Printed material No 1, Department of Fishery, Bangkok.

Lestang, S., Hall, N. and Potter, I.C. (2003) Reproductive biology of the blue swimming crab (*Portunus pelagicus*, Decapoda: Portunidae) in five bodies of water on the west coast of Australia. *Fishery Bulletin* 101, 745–757.

Marumo, R., Laoprasert, S. and Karnjanagesorn, C. (1985) Plankton and near-bottom communities of the mangrove regions in Ao Kung Krabaen and the Chanthaburi River, Thailand. In: Thai-Japanese cooperative research project on mangrove productivity and development 1983–1984. Japanese Ministry of Education, Science and Culture, pp. 55–75.

Nateekanjanalarp, S. (1990) Seagrass communites at Koh Samui, Surat Thani Province. MSc thesis, Chulalongkorn University, Thailand.

Paphavasit, N., Aksornkoae, S., Suwannodom, S., Termwitchakorn, A., Tangjaitrong, S., Siriboon, S., Piumsomboon, A., Tongnunui, P. and Promtong, I. (2003) *Rapid Assessment Methodology as a Tool for Coastal Zone Management in Thailand: Mangrove Ecosystem*. Chulalongkorn University Press, Bangkok.

Parsons, T.R., Naita, Y. and Lalli, C.M. (1985) *Manual of Chemical and Biological Methods for Seawater Analysis*. Pergamon Press, New York.

Patel, N.M., Chaya, N.D. and Bhaskaran, M. (1971) Stomach content of *Portunus pelagicus* (Linn.) from AD net catches. *Indian Journal of Marine Science* 8, 48–49.

Pillay, K.K. and Nair, J.B. (1972) Observations on the incidence and seasonal fluctuations of certain crustacean larvae in the plankton of the south-west coast of India. *Hydrobiologia* 43, 443–461.

Piumsomboon, A., Paphavasit, N. and Phomthong, I. (1999) Zooplankton communities in replanting mangrove swamp of Samut Songkhram, Thailand. The 15th International Conference of Estuarine Research Federation, 25–30 September 1999, New Orleans, Louisiana (poster).

Quieroga, H., Almeida, M.J., Alpium, T., Flores, A.A.V., Francisco, S., Gonzalez-Gordillo, I., Miranda, A.I., Silva, I. and Paula, J. (2006) Tide and wind control of megalopal supply to estuarine crab populations on the Portuguese west coast. *Marine Ecology Progress Series* 307, 21–36.

Sangrungrueang, C., Sakares, W., Anongpornyoskun, M. and Damrak, B. (1999) The environmental impact of shrimp culture on physical characteristics, soil qualities and seawater qualities of Kung Krabaen Bay before seawater irrigation construction, Chanthaburi Province, Thailand. Department of Fishery, Ministry of Agricultural and Cooperatives, Bangkok.

Satapoomin, S. (1999) Zooplankton community in Kapur mangrove canal, Ranong Province. Phuket Marine Biology Research Center, Thailand. *Research Bulletin* 62, 33–56.

Tantikul, S. (1984) Biology of blue swimming crab fishery in Gulf of Thailand. In: *Annual Report 1984*. Department of Fishery, Bangkok.

Williams, M.J. (1981) Methods for analysis of natural diets in portunid crabs (Crustacea: Decapoda: Portunidae). *Journal of Experimental Marine Biology and Ecology* 52, 103–113.

Zar, J.H. (1984) *Biostatistical Analysis*, 2nd edn. Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Zieman, J.C. (1982) The ecology of the seagrasses of south Florida: a community profile. US Fish and Wildlife Service, Office of Biological Services, USFWS/OBS-85/25.

9 Rebuilding Resilient Shrimp Aquaculture in South-east Asia: Disease Management, Coastal Ecology and Decision Making

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Abstract

We contend there are currently two competing scenarios for the sustainable development of shrimp aquaculture in coastal areas of South-east Asia. First, a landscape approach where farming techniques for small-scale producers are integrated into intertidal areas in a way that the ecological functions of mangroves are maintained and disease controlled. Second, a closed-system approach where problems of disease and effluent are eliminated in closed recirculation ponds behind the intertidal zone controlled by industrial-scale producers. Moving towards either scenario requires a better understanding of the scaled interaction between the ecological, social and political dynamics underlying processes of change and possible threats to the resilience of mangrove forested coastal ecosystems. We discuss how the analytical concepts of resilience, uncertainty, risk and scale can contribute to a social–ecological system understanding of decision making related to shrimp production by exploring their use in the empirical research areas of coastal ecology, shrimp health management and epidemiology, livelihoods and governance in response to the two scenarios. The challenge for the science–policy divide is to ensure that the complexity of social and ecological change in coastal areas, as understood from these empirical areas, is simplified but not made so simple that management becomes ineffective in steering production to rebuild resilience and maintain social and ecological stability. The discussion leads to a transdisciplinary research agenda that can contribute to sustainable shrimp aquaculture in coastal areas.

Introduction

The production of Penaeid shrimps (*Litopenaeus vannamei* and *Penaeus monodon*), which comprise about 80% of total shrimp production, increased from just over 1600 t in 1950 to close to 3.7 million t at a value of over US$14 billion in 2004 (FAO, 2006). In some countries of South-east Asia, this has contributed to between 50 and 80% of the total loss of mangrove area compared to 50 years ago, and mangroves continue to disappear at a rate of 1–2%/year (Valiela *et al*., 2001; Alongi, 2002). Ecosystem changes resulting from shrimp production are now increasingly recognized as key drivers of biodiversity loss, decreasing pond productivity and, subsequently, the increased vulnerability of coastal livelihoods (Primavera, 1997; Manson *et al*., 2005; Vaiphasa *et al*., 2007).

The relationship between ecological and social change is complicated further by uncertainties associated with changing international market conditions, such as food safety and quality standards, and ecological feedback mechanisms, such as disease incidences and epidemics (Kautsky *et al*., 2000; Barbier and Cox, 2004; Oosterveer, 2006). The resilience of shrimp culture systems – or the capacity to maintain their integrity when responding to external changes and feedbacks in their wider coastal social–ecological systems (Holling, 2001; Folke, 2006) – is therefore co-determined by a multitude of decisions made by producers and fishers in relation to scaled economic, political and ecological conditions. How producers make decisions related to livelihoods and production is dependent on an interrelated set of local to global institutions, as well as by their ability to adapt to changes in the natural resource base of the aquatic production systems.

As the demand for shrimp in international markets is unlikely to abate in the short to medium term, the challenge is to formulate management systems that can engender sustainable production practices. Decision makers at all levels of government, industry and society – collectively termed governance – are faced with the challenge of steering a highly lucrative industry away from the now well-established problems of unequal social welfare and environmental destruction caused by the extensification of shrimp aquaculture. To ascertain what core set of production regulations or standards can ensure a 'minimum' level of social, economic and ecological sustainability, a certain degree of simplification is required. The challenge for the science–policy divide is to ensure that the complexity of social and ecological change in coastal areas is simplified, but not made so simple that management is unable to maintain social and ecological stability.

Based on ongoing debates between NGOs, state and industry, we contend that there are essentially two opposing scenarios emerging over how best to manage shrimp production in order to ensure both social and ecological resilience in coastal areas. The first is that shrimp aquaculture is integrated into intertidal landscapes so that the ecological functions of coastal mangroves are maintained, diseases controlled and production kept in the hands of poorer small-scale producers who make up the majority of production (Fitzgerald, 2002; Primavera, 2006). The second scenario entails closing the aquaculture system to the surrounding environment, thereby eliminating the flow of effluent and spread of disease, as well as locating production behind the intertidal zone, thereby avoiding alteration of wetland or mangrove habitats (FAO *et al*., 2006; Phillips, 2006). A consequence of this is that, given the (generally) high investment needed for such systems, small-scale producers would be unable to participate.

Moving towards either scenario requires a better understanding of the scaled interaction between the ecological, social and political dynamics that pose possible threats to the resilience of mangrove forested coastal ecosystems. In this chapter, we develop an analytical approach to clarify the linkages between: (i) mangrove ecosystems and estuarine fisheries; (ii) shrimp disease and pond management; (iii) local livelihood decision making; and (iv) local to global governance processes of shrimp aquaculture in Southeast Asia. These are four key areas of research under the Rebuilding Resilience of Coastal Populations and Aquatic Resources (RESCOPAR) programme. To investigate these research themes in the context of complex interactions between ecological and societal processes, and the importance of their contribution in decisions over the realization of either the landscape-integrated or closed-system scenario, we require integrative concepts to understand the decision-making pathways that are underlying human agency. We have identified the key concepts of resilience, uncertainty and risk, as well as organizing heuristics of scale and networks to allow interdisciplinary exchange between these areas of empirical research. Exploring how these concepts can contribute to our understanding of sustainable use and management of coastal resources is the central objective of the chapter.

The chapter is divided into four sections. The first section presents the two scenarios for development dominating the current international discourse on the future for shrimp aquaculture in coastal areas. This is followed by a discussion of the concept of resilience of social–ecological systems, exploring possible responses in each of the four RESCOPAR research areas – coastal ecology, epidemiology, livelihoods and governance. The third section then discusses how each of these research areas contributes to research in response to the two propositions. The final section discusses how transdisciplinary research can contribute to sustainable shrimp aquaculture in coastal areas.

Coastal Aquaculture Scenarios

Landscape-integrated systems

Small-scale shrimp aquaculture systems are an important source of nutrition and income for coastal communities. A way of ensuring their sustainability is to integrate them into the mangrove and estuarine habitats. Silvofisheries – a form of low-input aquaculture that integrates mangrove tree culture with brackishwater aquaculture – offers such a scenario. Two basic models of silvofisheries exist – with mangroves either within or outside the pond system at specific pond–mangrove area ratios – with a variety of designs in different South-east Asian countries (Fitzgerald, 2002). All systems attempt to balance conservation issues with optimizing economic profitability (Primavera, 2000, 2006). Hatchery-reared seed is often supplemented with low-input farming techniques such as allowing natural recruitment of wild juveniles through tidal flushing. Expected benefits of landscape-integrated systems include minimization of contamination by pond effluents of the coastal ecosystem, provision of higher quality supply of water for shrimp farming and the enhancement of coastal fisheries.

In integrated forestry–fisheries–aquaculture systems, mangroves function as a biofilter for pond effluents (Vaiphasa *et al.*, 2007). Farm density is important so as not to exceed the capacity of the environment to assimilate waste flushed from the ponds during low tide. Mangroves adjacent to intensive ponds can be used to process nutrients from pond effluents. Mangroves inside ponds can play a similar role but, in addition, provide food and shading. Diseases may be controlled by optimizing seasonal environmental conditions such as temperature and salinity, as well as hygiene, nutrition and feeding. Little is known about the relation between disease outbreaks and pond management, but evidence suggests that the longer duration of submergence of mangroves in ponds compared to adjacent mangrove areas deteriorates the pond soils and lowers the capacity of ponds to support the cultured shrimps. As mangroves play an important role as a nursery area for coastal fishes (Mumby *et al.*, 2003; Manson *et al.*, 2005), the integration of ponds with mangroves in intertidal zones is seen as a means of maintaining the productive capacity of nearby coastal fisheries without compromising the productivity of shrimp aquaculture.

These 'ecologically integrated' mangrove-friendly aquaculture technologies are amenable to small-scale, family-based operations and are also accessible to poorer members of coastal communities who have only limited access to finance and are largely dependent on open-access resources (Luttrell, 2006). In addition, employment is maintained in dispersed trade and processing industries that absorb a large number of poor rural producers, especially women. By leaving these producers to operate within the mangroves, their already vulnerable livelihoods are supplemented with potentially appropriate aquaculture technologies that can contribute to the sustainable development of coastal areas. Landscape-integrated systems may therefore have the potential to support coastal ecosystem conservation while maintaining the high-income potential shrimp aquaculture for coastal communities (Binh *et al.*, 1997; Macintosh, 1998).

The complex nature of these production systems means that both state regulation and private certification are required, as well as the development of methodologies for monitoring and evaluating their ongoing performance. Some efforts have been undertaken to formulate codes of conduct and private standards governing: (i) the area of mangroves inside and outside ponds; (ii) health and safety requirements; and (iii) the levels of chemical pesticide use for sustainable use of mangroves and adjacent coastal areas (e.g. Bagarinao and Primavera, 2005; EUREPGAP, 2007). For these initiatives to be successful, it is increasingly recognized that state and private institutions need to supplement existing customary arrangements with microfinance and new technical capacities and technologies. Furthermore, the success of such initiatives is dependent on coastal communities being rewarded through either improved market access or price premiums for niche organic, fair trade or environmental products.

Closed systems

One way to minimize the negative impacts of shrimp aquaculture on coastal mangroves and wetlands is to invest in (super)-intensive closed recirculation systems and move ponds out of the intertidal zone. Production in these systems ranges from less than 8000 kg/ha to more than 20,000 kg/ha per crop. Such high production per unit area without water exchange presents several advantages over conventional shrimp aquaculture, including greater potential for mechanization, fewer logistical problems in pond operations and less effluent. Closed systems also enable better control of disease in broodstock and more efficient use of water through effective wastewater treatment. Because these intensive systems are not located in mangrove or wetland areas, coastal environments are maintained and the productivity of coastal fisheries is no longer directly influenced by shrimp farm activities.

Only very recently have intensive shrimp-culture recirculation systems become commercially viable (Otoshi *et al*., 2006). Basic elements that appear to be crucial to the success of these systems include small lined ponds, aeration and disease-resistant strains of omnivorous shrimp species. Some intensive systems operated in various South-east Asian countries also have limited water exchange and attempts have been made to close them to the surrounding environment (Kongkeo, 1997). Although closed recirculation systems are, with few exceptions, operated as pilot operations, their higher efficiencies have led Boyd and Clay (2002) to suggest that if they are 'suitable for general adoption by shrimp producers around the world, [they] could provide a more environmentally responsible method of shrimp production' (p. iv).

Because of the high cost of investment required, small-scale shrimp producers are less likely to be able to participate, thereby reducing significantly the proliferation of shrimp ponds built on marginal land in intertidal mangrove forests. Producers that are able to adopt these intensive practices could benefit from more stable production output as a result of improved disease, feed and broodstock management. At a societal level, the disruption to existing coastal livelihoods would be offset by the improved reliability of intensive shrimp production, which would increase global competitiveness and provide a source of foreign export exchange (FIAS, 2006). New employment opportunities would also arise in these farms, as well as in processing companies, whereas other employment could be generated through coastal restoration programmes. Given the continued growth of the sector, these intensive systems could possibly lead to the improved well-being of coastal communities, by decreasing the destructive development of extensive pond culture in coastal areas.

By promoting closed-system production, governments would need to reallocate agricultural land for shrimp production and, with the assistance of companies and NGOs, facilitate the transfer of required aquaculture technologies and techniques. A significant burden would be placed on governments to relocate coastal shrimp farmers who are moved out of shrimp production and establish alternative livelihood programmes outside of mangrove areas. Because of the large venture capital needed and the tendency for vertical integration in largely transnational companies, the state's role would be to facilitate investment (Neiland *et al*., 2001). Certification would play an increasingly important role in restructuring the shrimp industry, rewarding more streamlined and higher quality shrimp production with access to lucrative European and North American markets.

Analysing Social–Ecological Systems

Reducing the uncertainty and risk of resource users and rebuilding the resilience of social–ecological systems have emerged as key normative objectives for 'responsible' management of coastal areas in South-east Asia and further afield (see, for example, Nicholls and Branson, 1998; Adger *et al*., 2001). This section discusses resilience and the associated concepts of uncertainty, risk and complexity, focusing on the analytical power they hold for understanding the potential of landscape-integrated and closed systems for ecosystems and livelihoods in coastal areas. Scale is introduced as an organizing concept for elaborating the complexity of coastal areas and the multiple 'resiliences' that can be described when zooming in from landscapes to single units such as fishers and producers, ponds, mangrove forests and estuaries.

Resilience has emerged from the ecological concepts of complexity, coevolution and multiple equilibria (see Odum, 1975; Norgaard, 1994; Holling, 2001; Costanza, 2003), to provide an integrative theory for understanding combined social–ecological systems. The theory emerged through recognition that more than one steady state or equilibrium can exist in a specified system and has led to the study of the shifts and responses to internal and external drivers of system change (Holling, 1973). The resilience perspective has led researchers to focus on the magnitude of external disturbances to a system that can be absorbed or buffered without leading to fundamental changes of its functional – human and non-human – characteristics (Berkes *et al*., 2003). The theory is now being used to understand the capacity of social–ecological systems to absorb recurrent disturbances by examining how interactions, processes and feedbacks inhibit or facilitate change from one system state to another (Adger *et al*., 2005; Folke, 2006).

The concept of resilience has evolved from the technical and ecological sciences to engage and incorporate social systems. Technical or 'engineering' resilience focuses on the efficiency of a system to return to a stable state. Ecologists have focused largely on the robustness of systems to 'buffer' themselves from shock and disturbance, or adaptively realign themselves into different states (Folke, 2006). Social resilience has been described as the capacity of humans – either individual or communities – to withstand external shocks from wider economic, political or cultural perturbations (Adger, 2000). Berkes and Folke (1998) demonstrate, through an analysis of natural resource management practices, that the social and the ecological mutually constitute each other through processes of interaction. Change is an inherent property of this interaction from which new patterns emerge. This two-way interaction requires a breakdown of the distinction between the two domains. In doing so, the concept of resilience not only highlights the impact of human activities on ecosystems, and vice versa, but also the memory, learning and purposive adaptation of social–ecological systems that are necessary for transformation and innovation (Walker *et al*., 2004).

Central to understanding the resilience of a complex social–ecological system is the identification of the components that enable self-organization and adaptation in response to external forces driving changes in the stability or integrity of both social and ecological systems (Folke *et al*., 2002; Adger *et al*., 2005). Self-organization is comprised of: (i) aggregation into localized functional groups through endogenous formation; (ii) historically evolved development pathways, with new rules for organization emerging in correspondence with the system; and (iii) the maintenance of diversity as a means of enhancing opportunity for adaptation (Levin, 1998). Resilient systems are not only those which have the capacity to maintain their functional interactions, but rather those that have the ability to adapt to external change and evolve through learning and self-organization. Conversely, systems with low levels of self-organization may have very little capacity to respond to external pressure and maintain their functional interactions.

The resilience of a system is closely related to the temporal and spatial scale at which it is defined. Although socially constructed and relational – i.e. dependent on human observation (Howitt, 1998) – the choice of scale provides observers a framework with which to order the temporal and spatial characteristics of a system, including its self-organizational and adaptive capacities. Furthermore, the scales of organization within a system define the relationships between the parts that constitute and distinguish the whole (Cash and Moser, 2001). For example, to distinguish between various interacting processes, observational units for the transmission of White Spot Syndrome Virus (WSSV) are defined between shrimp in ponds, between shrimp ponds in a coastal area and as an epidemic across regions such as South-east Asia. Each scale has its own constituent level of resilience against infection. Observations at one scale find their explanation in processes at smaller scales, yet are contained in and constrained by processes at higher levels within coastal social–ecological landscapes. Recognizing the possibility of multiple 'resiliences' at a range of temporal and spatial scales enables us to distinguish sets of internal and external social and ecological factors influencing shrimp aquaculture development in coastal environments.

Understanding self-organization and adaptation to pressures emanating from interdependent scales is a useful framework for understanding complex social–ecological systems, but only provides a partial view when analysing processes of change. Human agency means that change is not a deterministic process of self-organization and adaptation but instead is directed by social, economic, cultural and political practices. Understanding ecosystem change in its wider spatial and temporal context therefore requires understanding how individual and collective decisions are made in response to uncertainty and risk. Single events of change can then be understood with reference to the level from which they originate and the scale at which they operate. In order to understand and predict local changes in coastal fish or shrimp communities, it is therefore necessary to understand the source of these risks, how they are communicated through social, economic, cultural and political networks, how they influence decision making and, finally, what influence they have over the resilience of social–ecological systems.

Shrimp Aquaculture as a Complex Social–Ecological System

The rest of the chapter now turns to a discussion of closed and landscape-integrated systems of shrimp aquaculture as complex social–ecological systems. Resilience, uncertainty and risk are used to understand the two scenarios described earlier with respect to the interaction between coastal landscapes and shrimp farming, the management of shrimp disease and the social processes of decision making in the context of coastal livelihoods and governance – the four themes of the RESCOPAR programme (Fig. 9.1).

Shrimp farming as a landscape-forming practice

At least four observations are often reiterated and illustrated in the general and scientific literature on the use of mangrove ecosystems by shrimp aquaculture: (i) pond systems remove mangrove forests and thus impact populations of marine and estuarine organisms; (ii) water pollution from ponds impacts adjacent mangrove ecosystems negatively; (iii) shrimp farming depends on wild stocks of gravid females; and (iv) the establishment of the WSSV has led to the abandonment and extension of ponds in new mangrove areas. However, we lack a clear understanding of whether and at what scale shrimp farming can be integrated successfully in mangrove forest landscapes so that ecological functions are maintained. Detailed knowledge of ecological processes is available for some parts of the mangrove ecosystem, in particular the benthic habitats of the forests. Ecological patterns of linkages between mangroves and coastal benthic and pelagic systems have been observed through correlations over large scales. But the strength and spatial scale of the linkages between mangrove and coastal ecosystems are largely unresolved: our ability to scale up processes or scale down patterns obtained through these ecological studies to the scale of landscapes is tenuous at best. This is problematic, as it is at the landscape scale that decisions are to be made on the integration of shrimp farming in coastal ecosystems.

Tides, waves and currents, as well as the spatial and temporal scale of disturbance, all play a role in the extent to which estuarine areas can be rehabilitated. Undisturbed estuaries have large areas with oxidized sediments, whereas ponds in the same areas always have reduced sediments, with considerably altered benthic communities. The combination of these changes means that abandoned ponds are rarely taken back into production, regardless of farming strategies such as fallowing, as used, for example, in forests and savanna ecosystems. Although there is evidence that within 12 years after rehabilitation with a single mangrove tree species, benthic communities are able to return to states indistinguishable from natural forest reserves (Macintosh *et al.*, 2002), there has been limited experience with soil rehabilitation over larger scales and shorter time periods. A range of questions remain about the relationship between shrimp aquaculture, tidal flows, benthic communities

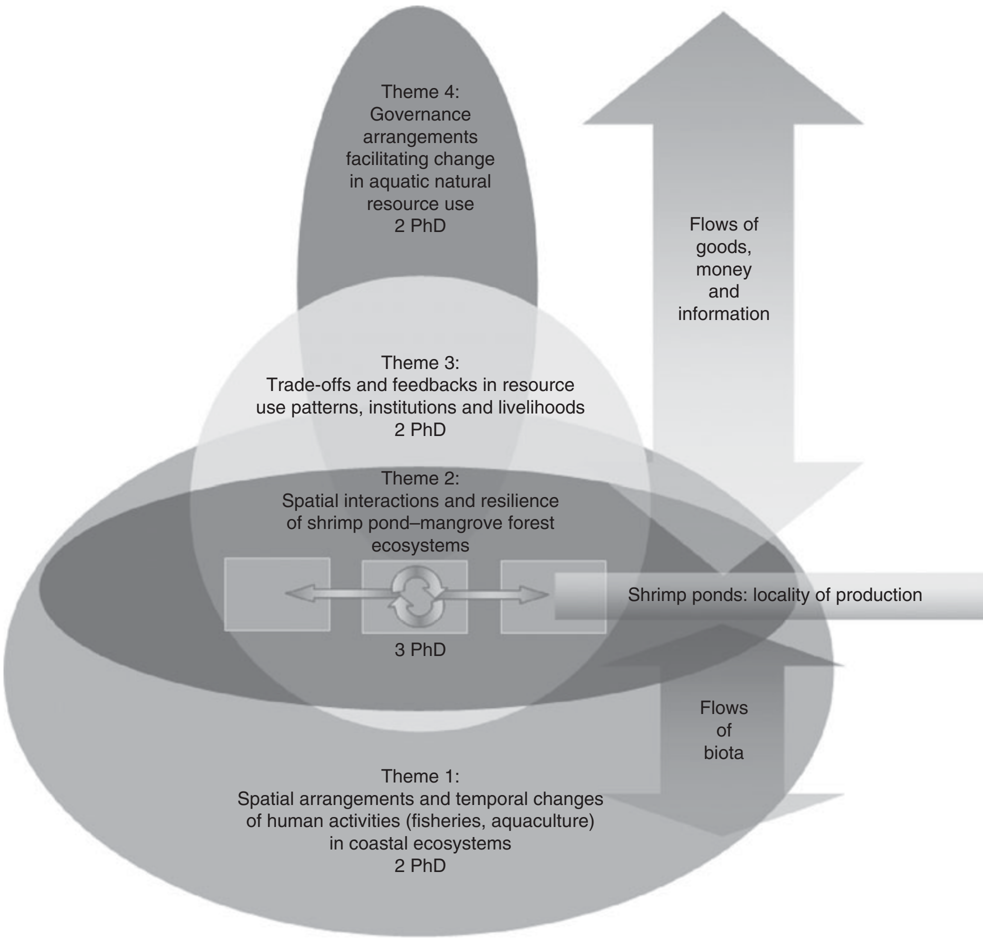

Fig. 9.1. The relationship between the four research themes of the RESCOPAR programme. Each theme is carried out by PhD students in Ca Mau and Bac Lieu Provinces in Vietnam (5) and East Kalimantan in Indonesia (4).

and the resilience of soils to regenerate, including: the effect on benthic communities of closing off an estuarine soil from tides and waves for shrimp culture; the impacts of farm management on the structure and development of benthic communities both within and outside ponds; the feedbacks from the benthic community to the estuarine soil and forests through burrowing, recycling and filtering; and understanding of the temporal and spatial scale of the reversibility of impacts.

Mangrove conversion for shrimp culture represents a trade-off with coastal fisheries production. At large spatial scales (> 100–1000 km), linkages between mangrove extent and coastal fisheries production for penaeid prawns have been detected through correlative approaches (Manson *et al*., 2005). Based on such studies, mangrove forests are considered critical for coastal fisheries by providing nursery habitats for the juvenile stages of commercially important species of fish and invertebrates. However, there is little reliable empirical evidence that lower coastal fisheries production results from the reduced function of mangrove forests, and reliable predictions of the implications of habitat loss or degradation on animal populations and fisheries production at smaller spatial scales (< 100 km – estuarine catchments) is not possible because of the current lack of understanding of habitat connectivity within coastal landscapes (van Zwieten *et al*., 2006). As fish use multiple habitats in the coastal zone, the loss or degradation of one type of habitat is likely to influence the value of the others. Therefore, size, location and connectivity of habitats that support fish resources are important to support production and recruitment to fisheries.

Mangrove ecosystems can fulfil their key role in shrimp farming and as coastal nurseries for fisheries even when large parts of the forest have disappeared. For instance, Loneragan *et al*. (2005) described stable landings of shrimp in areas of Malaysia where mangrove had been maintained and increases in landings in adjacent areas of rapidly degraded mangroves, perhaps because of the migration of prawns from adjacent areas. Thus, at a larger scale, the mangrove ecosystem can be viewed as being built up from subsystems or areas that 'switch' between alternative states of degraded soils with no trees to forested land with stable ecosystem functions. At a lower spatial scale, these components are merely adjacent to each other. At the higher scale, the spatial arrangements of the components within the system become important. Indeed, the spatial arrangement and the total area covered by shrimp ponds affect the key role mangroves have in supporting the shrimp industries and the local fisheries. In fact, low levels of fragmentation might even increase fish catches (Hindell and Jenkins, 2005), indicating that a spatially explicit analysis is required before predictions can be made (Pittman *et al*., 2004). The spatial configuration and the extent of the different components of the ecosystem are thus important attributes in analysing the ecological resilience at various scales in a landscape-integrated mangrove forest–shrimp farming system.

In the closed system scenario, the mangrove ecosystem gets taken out of the equation. Linkages between shrimp farming and coastal ecology will still exist, but at a distance from the actual production system: the fisheries for gravid females; the possibilities for crustacean diseases to enter the culture system from the wild; and the fishmeal required for shrimp feed. But, when the reproductive cycle of shrimp gets closed and genetically modified, disease-resistant strains of shrimp also are developed, the first two linkages will disappear.

Disease management of shrimp production systems

The resilience of a production system is dependent on the ability of a producer to reduce a system's exposure to disease vectors and to manage environmental factors so that the capacity of the shrimp to coexist with the pathogen is maximized. Broader environmental conditions – temperature, dissolved oxygen, salinity, soil condition – influence vulnerability to diseases, both as stress factors for shrimp, reducing its defence mechanisms, and as determinants of virulence and transmission of pathogens (Lightner *et al*., 1998). Evidence indicates that populations of wild organisms such as crustaceans, insect larvae, copepods and polychaetes in tropical coastal areas act as a reservoir for infectious diseases (Flegel, 2006). Given the high motility of these wild populations, they may also act as an effective vector of the disease between ponds and also between unconnected coastal areas. The resilience of production systems can therefore be analysed by: (i) the isolation of a system from a disease; (ii) its internal resistance once it has been infected; and (iii) secondary risks associated with management measures to decrease their vulnerability.

The total exclusion of pathogens is technically difficult and expensive, and though closure reduces the risk of infection, it does not mean the system has a higher resilience to catastrophic change should a pathogen enter. As known from a range of intensive systems, including pigs and poultry, the internal capacity or 'self-organization' to respond to diseases is small and infection with a pathogen can lead to catastrophic mortality. Conversely, open production systems in which shrimp are exposed continuously to a diversity of organisms will have a higher capacity to adapt to the stress from diseases, reducing the probability of complete stock loss. However, in dense cultivation areas, this tolerance is offset by the higher risk of direct transmission through wild populations of macroinvertebrates, soil or water exchange.

Soil structure in ponds is an important environmental factor affecting shrimp health, as shrimp live in sediments during a large part of their life cycle. As in agriculture, pond soils can be managed partially through water exchange, mixed cropping, fallowing, harrowing, drying and sediment removal. However, over time, all aquaculture ponds accumulate sediments in the form of a flocculent layer of varying thickness that can be considered as a microbiological laboratory with an oxygen gradient that is more or less fully oxidized at the top and highly reduced at the bottom. Shrimp health and resistance to pathogens seems highly dependent on changes in this flocculent layer. This is particularly true for the main cultured species, *Macrobrachium rosenbergii*, *L. vannamei* and *P. monodon*, as each of these species exhibits specific behaviour and tolerance to adverse water quality in relation to the flocculent layer. Although difficult to standardize measurements to assess impacts on shrimp health and productivity, it appears that shrimp avoid low oxygen areas (Meijer and Avnimelech, 1999) and that disease risks can be reduced by appropriate soil management measures (Yu *et al.*, 2006).

Risk management relates to both the producers' knowledge about aspects of a production system that are likely to increase the exposure to infection and the cost and benefits of management in order to prevent a disease outbreak. Maintaining soils, choosing temperature to stock and harvest and understanding the seasonal nature of the incidence of pathogens in the wild populations of mobile organisms such as crabs, macroinvertebrates and wild shrimp are some of the management aspects. Closed systems may be less vulnerable to infection, but the probability of infection has to be weighed against the cost of isolation. In comparison, open systems are comparatively low cost and the relative availability of land in mangrove areas gives more opportunity to producers simply to extend the area of production once their ponds are infected. However, the result has been the exponential increase of pathogens in the surrounding waters and wild crustacean populations, leading to extensive clearing of mangroves to maintain production.

Decisions over disease management also lead to considerable economic risk, as evidenced by the US$4–6 billion loss of *P. monodon* throughout Asian countries between 1992 and 2001 (Lightner, 2005). International pressure for food quality and safety, coupled with poor management decisions, increased the risks associated with shrimp farming. To combat the increased prevalence of disease, producers increased their use of antibiotics. Poor application of these chemicals has led to the higher resistance of pathogens, as well as higher concentrations of residual chemicals in exported shrimp. As many of these chemicals are restricted substances in the EU and USA, producers have found themselves excluded from lucrative global markets (Bush and Oosterveer, 2007). The scale and locality of risk in shrimp farming is therefore linked from local to global scales. The application of chemical substances may reduce the risks associated with diseases but, if unmanaged, may also increase a producer's vulnerability to market regulation.

Decision making under uncertainty

The resilience of a household – its ability to maintain a viable livelihood – is comprised of a complex portfolio of assets and income streams, the continuation of which is subject to the capacity to make decisions under uncertainties associated with the risk of disease, changing weather patterns, political change and market prices. At the same time, the resilience of the mangrove areas, on which the household depends, may be characterized by complex interactions within and between mangrove forests, estuaries and coastal zones which face considerable uncertainty from natural fluctuations and events. Within such social–ecological systems, decision making is an iterative process in which producers (and other actors) constantly adjust their livelihoods to changing conditions based on assessment and reassessment of the stocks of assets at their disposal, given environmental conditions. Before understanding the effectiveness of governance mechanisms to steer towards open or closed production systems, livelihoods need to be understood in the context of how decisions deal with risk under conditions of uncertainty.

Analysing these iterative decision-making processes under conditions of uncertainty moves beyond linear livelihood diversification models to focus on 'pathways' of decision making. Rather than measuring the success or failure of a livelihood relative to a predefined goal, these pathways comprise a series of iterative decision events based on external influences and environmental context (De Bruijn and Van Dijk, 2004). Livelihoods are therefore understood in the context of external driving forces that determine the risk associated with acquiring adequate access and control over assets and capabilities. These external events may be environmental, such as local flood events or disease outbreaks, or social, such as changing dynamics with local credit and kinship relations or global market fluctuations. Normative strategies, such as diversification, of course remain, but should be understood in terms of the wider context in which they can be fulfilled. Whether a producer can develop a successful closed or landscape-integrated aquaculture system is therefore dependent on the wider context within which capacities and assets are operationalized.

In open landscape-integrated systems, the uncertainties of producers are based largely on daily, seasonal and longer-term environmental variability and local and domestic market fluctuations. To adapt to these external risks, producers make iterative decisions on how to use and adapt their capabilities and assets to change their aquaculture practices, diversify to other off-farm activities or exit production completely. In doing so, producers are able to offset the risks associated with shrimp production with gains in alternative activities. Shrimp producers across South-east Asia who are successful with as few as one in eight shrimp crops, because of disease and market fluctuations, often avoid bankruptcy by offsetting these losses with income streams from alternative on- and off-farm sources (Luttrell, 2006; Hue and Scott, 2008). The challenge is to identify the external social and environmental factors that enable or constrain producers and, given their endowment of assets and capabilities, understand how they avoid the risk of failure by making either pre-emptive or reactive decisions related to production.

If producers are unable to develop a pre-emptive strategy, they are less able to resist unfavourable change, mould events to minimize their exposure to change or innovate *ex post* to take advantage of changed circumstances. Open landscape-integrated farms, assuming they are small scale and local in origin, may adapt under these circumstances through a range of coping strategies including communal mechanisms of insurance through social and familial support networks to mitigate risk and loss. A more extreme response may be the decision to exit from farming and/or migrate for labour opportunities. If the catastrophic change in shrimp farming is caused by disease outbreaks or acidified soils, then producers may decide to access new mangrove areas, so beginning the cyclical process of social–ecological destruction associated so strongly with shrimp aquaculture in South-east Asia. In comparison, closed-system farmers, assuming their farms are larger in scale and that they are unable to extend to new areas because of cost, may decide to close down their operations and shift their capital into new industries. Alternatively, assuming they are larger and wealthier, they may decide on a strategy of innovation to provide a pre-emptive and purposeful transformation to more secure production, or more desirable market advantages with higher returns.

As the level of production increases and producers' access to national, regional and global markets improves, they have considerable incentive to intensify. However, in doing so, they must consolidate their time, effort and financial resources, thereby reducing the diversity of their livelihood portfolios. Shrimp producers in Thailand who followed this path in the 1990s benefited with incomes up to 15–16 times higher than those obtained from their former diversified rice-based livelihoods (Flaherty *et al*., 1999, 2000). These systems may be less vulnerable to disease and environmental perturbation than landscape-integrated systems if they can be isolated successfully. But, the higher investment required for closed systems, their increased dependence on external inputs through international markets and the vagaries of intensification expose them to new risks. Recent examples include the billions of dollars lost from WSSV in the past decade and the volatility of reorienting export markets as a result of the recent downturn in Japanese consumption of shrimp (Lightner, 2005; Loc, 2006). Governing shrimp production in order to steer producers towards either closed or open systems therefore requires an understanding of the external driving forces, both environmental and social, that set producers on specific decision-making pathways and the implications these pathways have for the broader resilience of coastal social–ecological systems.

Steering towards resilience

Effective governance arrangements face the challenge of promoting resilient forms of shrimp production by steering producers to both timely and adaptive responses that enable them to respond to external drivers of change. As state policy and legislation is less able to adapt to changing demand from global markets, shrimp production practice has expanded beyond the rate at which coastal ecosystems can maintain either social or ecological resilience (Armitage and Johnson, 2006). Likewise, local natural resource management institutions, which have evolved through the long-term engagement of coastal communities, have also been eroded, largely by rapid market integration or captured by political elites (Stonich and Bailey, 2000; Hall, 2004). Taking into consideration the uncertainty of decision making at the producer level, attention has now turned to alternative governance arrangements that provide timely and effective mechanisms and that are inclusive of actors at a range of scales from local producers, private sector investors and international consumers. It is yet to be seen how effective these mechanisms are in simplifying complex social–ecological systems and steering towards either closed or landscape-integrated systems.

Market-based certification has emerged as a novel form of governance which harnesses global material, financial and informational flows to steer towards improved environmental performance and socially equitable production. There currently are more than 50 certification schemes for fisheries, of which at least 30 are aimed at aquaculture, including shrimp, in Asia and the Pacific region (Corsin *et al.*, 2007). Certification represents a globally networked governance system, which operates within global flows of goods and information that transcend the traditional jurisdiction of the nation state (Oosterveer, 2007). Food quality and safety certification systems such as Hazard Analysis and Critical Control Points (HACCP) and International Organization for Standardization (ISO) have been amended to include environmental and social production practices. Standards are set by a range of private organizations, including NGOs, retailers and state organizations. The independence of standards is maintained through the internal and external boards and review panels, and accreditation through third-party auditors.

The majority of certification schemes have been successful in developed countries with traceable, information-rich production systems. However, less success has been met in developing countries where producers have poorer capacity for compliance and the cost of certification is prohibitive (Klooster, 2005). Across South-east Asia, the system of provision for shrimp is already changing in response to the decision by Walmart in the USA and GlobalGAP retailers in the EU to sell only environmentally certified seafood in their shops by 2012 (Jacquet and Pauly, 2007). To reduce transaction costs of certification and maintain competitive advantages, commodity chains appear to be integrating vertically, with more control going to large producers – which may include high investment closed-system producers – and exporters. Under these conditions, small landscape-integrated producers will be left with the choice of complying and gaining access to lucrative global markets or diverting their attention to lower-value and more variable domestic markets.

As environmental and social standards are adopted industry-wide, a range of new capabilities will be required by producers to maintain market access. However, given the experiences obtained in other sectors such as forestry (e.g. Klooster, 2005; Taylor, 2005), it is unlikely that small-scale producers will be able to meet these requirements without more participatory implementation, monitoring and evaluation. In landscape-integrated systems, area-based certification methodologies may prove more effective to reduce the cost and account more adequately for the ecological interactions with surrounding coastal habitats. Managing the risk of these aquaculture systems requires new methodologies for including the uncertainty of environmental monitoring evaluation (Power, 2007). To increase compliance, these methodologies may seek better interaction with existing communal resource management arrangements that govern access to coastal resources such as water, tidal flows and wild seed (Vandergeest, 2007). In closed systems, environmental standards are likely to be more effective, given their internally controlled and monitored production. Existing social standards based on United Nations (UN) and International Labour Organization (ILO) conventions would remain adequate enough to cover the conditions of employees. However, more attention is needed to determine whether and how standards could help in the evaluation of grievances between surrounding communities over issues such as access to coastal resources.

In order to develop governance arrangements that can steer producers effectively to either closed or open systems, we need to understand how producers, as well as market and state actors, respond to the external drivers of change. Compared to the territorial and somewhat fossilized nature of state regulation, certification has the potential to provide a timely response to rapidly expanding international markets and decisions of producers as they adapt to changing social, environmental and economic circumstances. However, it is yet to be seen whether certification developed through lengthy deliberations with stakeholders – as seen currently with the World Wildlife Fund (WWF) aquaculture dialogues (see Boyd *et al.*, 2005) – will be adaptive and inclusive enough over time. To steer producers effectively towards either closed or landscape-integrated systems, we need to understand better the interaction between state, market and community-based governance mechanisms – from local to global scales – to determine what combinations foster the resilience of coastal social–ecological systems best.

Conclusion: an Emerging Transdisciplinary Research Agenda

The closed and landscape-integrated scenarios provide a polar dichotomy that represent competing visions of rebuilding resilient coastal environments in South-east Asia. There are no definitive answers to whether either of them is ‘better’, nor can it be outlined clearly in general which scenario is more achievable or what the steps are towards achieving transitions to more resilient farming and use of coastal resources. There is likely to be a range of systems along a spectrum between these two poles that are more sustainable than current systems. The chapter has elaborated the complexity of shrimp production systems and requirements of rebuilding social–ecological resilience in coastal areas. The first challenge is to understand the complexities and uncertainties of these systems in order to coordinate decision making at farm, community and regional scales to mitigate existing and potential impacts. Decision makers at all levels of governance – producers, fishers, governments and certifiers – therefore need to consider what simplifications can and should be made. The second challenge is to ensure that these simplifications are effective enough to steer production so as to rebuild the resilience of ponds, coastal ecosystems and the communities that exploit them.

In order to address these challenges, we need to debate what implications the two scenarios hold for various disciplinary approaches and determine what the key questions are for ongoing research. In short, we ask how research in ecology, epidemiology and shrimp farm management, livelihoods and global markets can contribute to our understanding of how to rebuild coastal shrimp aquaculture as a resilient social–ecological system in the context of decision making at all levels of governance.

Ecosystem health and fishery productivity in coastal waters are dependent on functioning coastal mangrove forests. Based on our current understanding, it is not clear whether open landscape-integrated shrimp farming can have a positive or neutral effect on biodiversity and the productive functions of the coastal zone. Failure to detect and respond to impacts may be a result of either or both a lack of capacity to engage with and understand the perceptions of stakeholders or the inherent difficulties in detecting impacts on and attributing changes to coastal fish communities to potentially multiple causes (van Zwieten *et al*., 2006). A central question is at what scale and to what extent can shrimp farming be integrated successfully in mangrove ecosystems without affecting the production function of ponds and the surrounding biodiversity? What indicators can be developed for this? From a biodiversity perspective, a negative effect may be tolerated if impacts do not change the adaptive capacity of the mangrove ecosystems to maintain the resilience of coastal environments and their associated productive capacity. Alternatively, the most effective means of ensuring the ecological functions of mangrove areas is to develop closed systems outside mangrove areas.

The diversity of open landscape-integrated systems, although not mitigating uncertainty, may be more likely to advance both the social and ecological capacity for self-organization and increased disease resilience, though it is unlikely that WSSV will be contained within these approaches to aquaculture development. Fostering internal self-organization in these systems, however, requires often drastic changes in production practices. This may come at a cost to short-term income, and therefore stay out of reach of a large proportion of producers. Still, the question remains why the practice of silvofisheries – landscape-integrated shrimp farming – is not widespread in South-east Asia and mangroves continue to be lost (Tong *et al*., 2004). Alternatively, questions also remain as to whether closed systems offer a possible avenue for disease-resilient shrimp production. These systems may be better protected from pathogens, but also highly engineered systems are never fail-safe and lead to an ever-increasing need for external intervention (e.g. screening of seeds, certification of hatcheries) that increases complexity and vulnerability. Investing in this form of production may force further investment in engineered solutions and complex maintenance systems to keep up the security and resilience of the system.

The resilience of producer's livelihoods is dependent on the capacity to make decisions in response to external forces. Coastal areas inhabited by shrimp ponds are in flux, based on the compounded factors of disease, changes in ecological function and fluctuation in trade. Given this, the question remains as to whether producers are able to meet the increasingly complex demands set out for integrated sustainable shrimp production after the mangrove areas have deteriorated as a result of their production system. What are the internal and external factors that would drive producers to: (i) develop alternative aquaculture systems that are ecologically, financially and socially sound; (ii) diversify production into new areas; or (iii) seek employment in intensive farms located outside of mangrove areas?

The international nature of the shrimp trade and the failure of governments to deal adequately with the negative social and environmental impacts of shrimp production have meant that new forms of governance are necessary. How effective these forms of governance are depends on the degree to which standards can steer producers to new forms of production. Research should thus focus on finding new arrangements, both state and non-state, to govern coastal shrimp production. If certification is set to guide much of the industry's development, then new methodologies for auditing shrimp aquaculture as complex social–ecological systems, whether closed or landscape-integrated, are needed. Given the rise of market-driven forms of governance, to what degree can the state maintain control and influence over aquaculture and coastal regulation (e.g. zoning)? What capacity do farmers have to comply with new and changing standards, regulations, rules and norms? As governance shifts from local to global and from state to market, it is increasingly important to develop governance arrangements that can deal adequately with the drivers of change in complex systems and promote environmentally and socially desirable outcomes.

References

Adger, W.N. (2000) Social and ecological resilience: are they related? *Progress in Human Geography* 24, 347–364.

Adger, W.N., Kelly, P.M. and Ninh, N.H. (eds) (2001) *Living with Environmental Change: Social Vulnerability, Adaptation and Resilience in Vietnam*. Routledge, London.

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S. and Rockstrom, J. (2005) Social–ecological resilience to coastal disasters. *Science* 309, 1036–1039.

Alongi, D.M. (2002) Present state and future of the world's mangroves. *Environmental Conservation* 29, 331–349.

Armitage, D. and Johnson, D. (2006) Can resilience be reconciled with globalization and the increasingly complex conditions of resource degradation in Asia coastal regions? *Ecology and Society* 11, 2 (http://www.ecologyandsociety.org/vol11/iss1/art2/, accessed 22 June 2009).

Bagarinao, T.U. and Primavera, J.H. (2005) *Code of Practice for Sustainable Use of Mangrove Ecosystems for Aquaculture in Southeast Asia*. SEAFDEC Aquaculture Department, Tigbauan, Iloilo, Philippines.

Barbier, E.B. and Cox, M. (2004) An economic analysis of shrimp farm expansion and mangrove conversion in Thailand. *Land Economics* 80, 389–407.

Berkes, F. and Folke, C. (eds) (1998) *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press, Cambridge, UK.

Berkes, F., Colding, J. and Folke, C. (eds) (2003) *Navigating Social–Ecological Systems: Building Resilience for Complexity and Change*. Cambridge University Press, Cambridge, UK.

Binh, C.T., Phillips, M.J. and Demaine, H. (1997) Integrated shrimp–mangrove farming systems in the Mekong Delta of Vietnam. *Aquaculture Research* 28, 599–610.

Boyd, C., McNevin, A., Clay, J. and Johnson, H. (2005) Certification issues for some common aquaculture species. *Reviews in Fisheries Science* 13, 231–279.

Boyd, C.E. and Clay, J.W. (2002) Evaluation of Belize Aquaculture, Ltd: a super-intensive shrimp aquaculture system. Report prepared for the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment.

Bush, S.R. and Oosterveer, P. (2007) The missing link: intersecting governance and trade in the space of place and the space of flows. *Sociologia Ruralis* 47, 384–400.

Cash, D.W. and Moser, S.C. (2001) Linking global and local scales: designing dynamic assessment and management processes. *Global Environmental Change* 10, 109–120.

Corsin, F., Funge-Smith, S.J. and Clausen, J. (2007) *A Qualitative Assessment of Standards and Certification Schemes Applicable to Aquaculture in the Asia-Pacific Region*. FAO Regional Office for Asia and the Pacific, Bangkok.

Costanza, R. (2003) A vision of the future of science: reintegrating the study of humans and the rest of nature. *Futures* 35, 651–671.

De Bruijn, M. and Van Dijk, H. (2004) The importance of socio-cultural differences and of pathway analysis for understanding local actors' responses. In: Dietz, A.J., Ruben, R. and Verhagen, A. (eds) *The Impact of Climate Change on Drylands With a Focus on West Africa*. Springer, Dordrecht, pp. 342–362.

EUREPGAP (2007) Control points and compliance criteria integrated farm assurance. Interim Final V.3.0. EUREPGAP, Cologne.

FAO (2006) *Fisheries Global Information System (FIGIS)*. Food and Agriculture Organization of the United Nations, Rome.

FAO, NACA, UNEP, WB and WWF (2006) *International Principles for Responsible Shrimp Farming*. Food and Agriculture Organization of the United Nations (FAO), the Network of Aquaculture Centres in Asia-Pacific (NACA), United Nations Environment Programme (UNEP), the World Bank Group (WB), and the World Wildlife Fund (WWF), Bangkok.

FIAS (2006) *Improving Indonesia's Competitiveness: Case Study of Textile and Farmed Shrimp Industries, Volume 1*. Foreign Investment Advisory Service (FIAS), Jakarta.

Fitzgerald, W.J. (2002) Silvofisheries: Integrated mangrove forest aquaculture systems. In: Costa-Pierce, B.A. (ed.) *Ecological Aquaculture: The Evolution of the Blue Revolution*. Blackwell Science Ltd, Oxford, UK, pp. 161–262.

Flaherty, M., Vandergeest, P. and Miller, P. (1999) Rice paddy or shrimp pond: tough decisions in rural Thailand. *World Development* 27, 2045–2060.

Flaherty, M., Szuster, B. and Miller, P. (2000) Low salinity inland shrimp farming in Thailand. *Ambio* 29, 174–179.

Flegel, T.W. (2006) Detection of major penaeid shrimp viruses in Asia, a historical perspective with emphasis on Thailand. *Aquaculture* 258, 1–33.
Folke, C. (2006) Resilience: the emergence of a perspective for social–ecological systems analysis. *Global Environmental Change* 16, 253–267.
Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S. and Walker, B. (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* 31, 437–440.
Hall, D. (2004) Explaining the diversity of Southeast Asian shrimp aquaculture. *Journal of Agrarian Change* 4, 315–335.
Hindell, J.S. and Jenkins, G.P. (2005) Assessing patterns of fish zonation in temperate mangroves, with emphasis on evaluating sampling artefacts. *Marine Ecology Progress Series* 290, 193–205.
Holling, C.S. (1973) Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4, 1–23.
Holling, C.S. (2001) Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4, 390–405.
Howitt, R. (1998) Scale as relation: musical metaphors of geographical scale. *Area* 30, 49–58.
Hue, L.T.V. and Scott, S. (2008) Coastal livelihood transitions: socio-economic consequences of changing mangrove forest management and land allocation in a commune of central Vietnam. *Geographical Research* 46, 62–73.
Jacquet, J.L. and Pauly, D. (2007) The rise of seafood awareness campaigns in an era of collapsing fisheries. *Marine Policy* 31, 308–313.
Kautsky, N., Ronnback, P., Tedengren, M. and Troell, M. (2000) Ecosystem perspectives on management of disease in shrimp pond farming. *Aquaculture* 191, 145–161.
Klooster, D. (2005) Environmental certification of forests: the evolution of environmental governance in a commodity network. *Journal of Rural Studies* 21, 403–417.
Kongkeo, H. (1997) Comparison of intensive shrimp farming systems in Indonesia, Philippines, Taiwan and Thailand. *Aquaculture Research* 28, 789–796.
Levin, S.A. (1998) Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1, 431–436.
Lightner, D.V. (2005) Biosecurity in shrimp farming: pathogen exclusion through use of SPF stock and routine surveillance. *Journal of the World Aquaculture Society* 36, 229–248.
Lightner, D.V., Hasson, K.W., White, B.L. and Redman, R.M. (1998) Experimental infection of western hemisphere Penaeid shrimp with Asian White Spot Syndrome Virus and Asian Yellow Head Virus. *Journal of Aquatic Animal Health* 10, 271–281.
Loc, V.T.T. (2006) *Seafood Supply Chain Quality Management: The Shrimp Supply Chain Quality Improvement Perspective of Seafood Companies in the Mekong Delta, Vietnam*. University of Groningen, Groningen, Netherlands.
Loneragan, N.R., Ahmad Adnan, N., Connolly, R.M. and Manson, F.J. (2005) Prawn landings and their relationship with the extent of mangrove and shallow waters in western peninsular Malaysia. *Estuarine Coastal and Shelf Science* 63, 187–200.
Luttrell, C. (2006) Adapting to aquaculture in Vietnam: securing livelihoods in a context of change in two coastal communities. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 17–29.
Macintosh, D.J. (1998) Mangroves and coastal aquaculture sustainability. In: *Aquaculture Sustainability and the Environment. Report on a Regional Study and Workshop*. ADB/NACA, Bangkok, pp. 242–251.
Macintosh, D.J., Ashton, E.C. and Havanon, S. (2002) Mangrove rehabilitation and intertidal biodiversity: a study in the Ranong mangrove ecosystem, Thailand. *Estuarine Coastal and Shelf Science* 55, 331–345.
Manson, F.J., Loneragan, N.R., Skilleter, G.A. and Phinn, S.R. (2005) An evaluation of the evidence for linkages between mangroves and fisheries: a synthesis of the literature and identification of research directions. *Oceanography and Marine Biology – An Annual Review* 43, 483–513.
Meijer, L.E. and Avnimelech, Y. (1999) On the use of micro-electrodes in fish pond sediments. *Aquacultural Engineering* 21, 71–83.
Mumby, P.J., Edwards, A.J., Arias Gonzales, J.E., Lindeman, K.C., Blackwell, P.G., Gall, A., Gorczynska, M.I., Harborne, A.R., Pescod, C.L., Renken, H., Wabnitz, C.C.C. and Llewellyn, G. (2003) Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* 427, 533–536.
Neiland, A.E., Soley, N., Varley, J.B. and Whitmarsh, D.J. (2001) Shrimp aquaculture: economic perspectives for policy development. *Marine Policy* 25, 265–279.

Nicholls, R.J. and Branson, J. (1998) Coastal resilience and planning for an uncertain future: an introduction. *The Geographical Journal* 164, 255–258.

Norgaard, R.B. (1994) *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*. Routledge, New York.

Odum, E.P. (1975) *Ecology: The Link Between the Natural and Social Sciences*. Rinehart and Winston, Holt, London.

Oosterveer, P. (2006) Globalization and sustainable consumption of shrimp: consumers and governance in the global space of flows. *International Journal of Consumer Studies* 30, 465–476.

Oosterveer, P. (2007) *Global Governance of Food Production and Consumption: Issues and Challenges*. Edward Elgar, Cheltenham, UK.

Otoshi, C.A., Holl, C.M., Moss, D.R., Arce, S.M. and Moss, S.M. (2006) Super-intensive RAS trial yields encouraging shrimp harvest at Oceanic Institute. *Global Aquaculture Advocate* 9, 64–65.

Phillips, M.J. (2006) Regional study on economic opportunities in shrimp farming in West Africa: an initial review. Technical Working Paper 3: Environmental Aspects and Sustainable Development. Prepared for the Sahel and West Africa Club, OECD. Network of Aquaculture Centres in Asia-Pacific (NACA), Department of Fisheries, Kasetsart University Campus, Bangkok.

Pittman, S.J., McAlpine, C.A. and Pittman, K.M. (2004) Linking fish and prawns to their environment: a hierarchical landscape approach. *Marine Ecology Progress Series* 283, 233–254.

Power, M. (2007) *Organized Uncertainty: Designing a World of Risk Management*. Oxford University Press, Oxford.

Primavera, J.H. (1997) Socio-economic impacts of shrimp culture. *Aquaculture Research* 28, 815–827.

Primavera, J.H. (2000) Integrated mangrove–aquaculture systems in Asia. *Integrated Coastal Zone Management, Autumn*, 121–128.

Primavera, J.H. (2006) Overcoming the impacts of aquaculture on the coastal zone. *Ocean and Coastal Management* 49, 531–545.

Stonich, S.C. and Bailey, C. (2000) Resisting the blue revolution: contending coalitions surrounding industrial shrimp farming. *Human Organization* 59, 23–36.

Taylor, P.L. (2005) In the market by not of it: Fair Trade coffee and Forest Stewardship Council certification as market-based social change. *World Development* 33, 129–147.

Tong, P.H.S., Auda, Y., Populus, J., Aizpuru, M., Al Habshi, A. and Blasco, F. (2004) Assessment from space of mangroves evolution in the Mekong Delta in relation to extensive shrimp farming. *International Journal of Remote Sensing* 25, 4795–4812.

Vaiphasa, C., de Boer, W.F., Skidmore, A.K., Panitchart, S., Vaiphasa, T., Bamrongrugsa, N. and Santitamnont, P. (2007) Impacts of solid shrimp pond waste materials on mangrove growth and mortality: a case study from Pak Phanang, Thailand. *Hydrobiologia* 591, 47–57.

Valiela, I., Bowen, J.L. and York, J.K. (2001) Mangrove forests: one of the world's threatened major tropical environments. *BioScience* 51, 807–815.

van Zwieten, P.A.M., Sidik, A.S., Noryadi, Suyatna, I. and Abdunnur (2006) Aquatic food production in the coastal zone: data-based perceptions on the trade-off between mariculture and fisheries production of the Mahakam Delta and Estuary, East Kalimantan, Indonesia. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 219–236.

Vandergeest, P. (2007) Certification and communities: alternatives for regulating the environmental and social impacts of shrimp farming. *World Development* 35, 1152–1171.

Walker, B.H., Holling, C.S., Carpenter, S.R. and Kinzig, A. (2004) Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society* 9(2), 5 (http://www.ecologyandsociety.org/vol9/iss2/art5/, accessed 22 June 2009).

Yu, R., Leung, P. and Bienfang, P. (2006) Optimal production schedule in commercial shrimp culture. *Aquaculture* 254, 426–441.

10 Integrated Management of Aquatic Resources: a Bayesian Approach to Water Control and Trade-offs in Southern Vietnam

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Abstract
The BayFish–Bac Lieu model presented in this chapter is a Bayesian model that aims to identify optimal water control regimes and trade-offs between water uses in order to improve management of water-dependent resources in the inland coastal area of Bac Lieu Province, Mekong Delta, Vietnam. The model was developed between 2004 and 2007 and integrated local databases, outputs from the Vietnam River Systems and Plains (VRSAP) model and stakeholder consultations. The model facilitates analyses of the consequences of different water management scenarios (quantitative and qualitative) on rice, fish, crab and shrimp production in the province. However, beyond production, trade-offs between household income, food security or environmental protection were also identified during the model development process. Subsequently, the BayFish–Bac Lieu model allows detailing of: (i) annual production probabilities in the case of a baseline scenario; (ii) outcomes of four different sluice gate operation modes; and (iii) trade-offs between household income, food security and environment outcomes for each scenario. The model shows that through improved shrimp farming and fish production, total household income benefits directly from open sluice gates allowing saline intrusion. However, this has the opposite effect on rice production, and on food security. Results suggest that a suitable compromise involving at least one sluice gate open at all times should be adopted for optimized outcomes.

Introduction

The management of coastal zone development is challenging, not only because of the dynamic nature of coastal systems, but also because of competition and conflict between stakeholders involved in different economic activities. Understanding trade-offs inherent in the management of the system is, therefore, essential. This was particularly the case in Bac Lieu Province, Mekong Delta, Vietnam (Fig. 10.1), where multiple sluice gates were constructed by the government along the main coastal road to prevent the incursion of salt water, thus favouring the extension of rice farming in a freshwater environment. As a result, between 1994 and 2000, the area under rice cultivation in Bac Lieu increased (Hossain *et al*., 2006). However, at the same time, market forces prompted other farmers to invest in shrimp farming, which is dependent on salt water. Conflicts of interest grew and peaked in February 2001 when shrimp farmers breached the dyke system in Lang Tram to let salt water

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

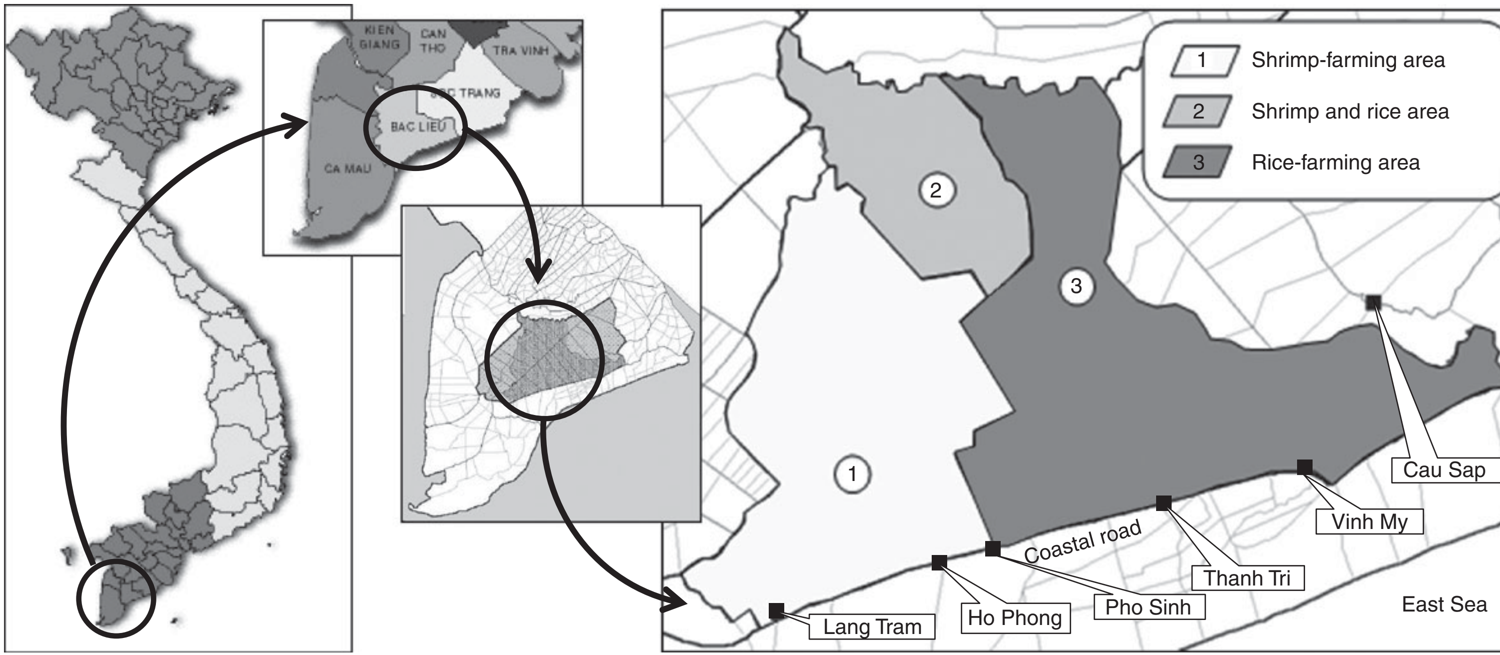

Fig. 10.1. Study area in Bac Lieu Province (black squares mark sluice gates).

into the protected area. Subsequently, a compromise operation mode for the sluice gates was adopted, thereby allowing the influx of salt water by opening certain gates at times or preventing its influx by not opening them. Now, the study area can be divided roughly into three zones (Fig. 10.1): zone 1, where water is quite brackish and dominated by shrimp farming; zone 2, brackish in the dry season, where shrimp and rice farming are combined; and zone 3, where water is mainly fresh (this is the predominantly rice growing area).

In addition to rice and shrimp farming, water management options have a significant impact on aquatic resources, fish being another significant commodity for the local population. Combined, agriculture, aquaculture and fisheries contribute 52.6% of GDP in the province. In this context, the need for a methodology assessing interactions and trade-offs among the various food commodities has been highlighted (Gowing *et al.*, 2006a).

BayFish–Bac Lieu, a Bayesian probabilistic model, has been developed to make explicit the cause–effect links in these production systems, to understand inherent trade-offs and, ultimately, to assist water management in the province. The objectives of the model are (from the most specific to the broadest):

1. To help optimize the operation of the sluice gates.
2. To assist decision making about water management options, through the modelling of different scenarios.
3. To identify stakeholders and inform them about the production trade-offs inherent in water management.
4. To involve stakeholders in the management process.

This chapter is a follow-up of a previous publication (Baran *et al.*, 2006), which presented the first steps in the model development process, i.e. the theoretical background of Bayesian modelling, the approach in BayFish–Bac Lieu, the stakeholder consultation process and the overall model structure. Since then, databases and results from other surveys and studies have been integrated into the model and scenarios have been produced and analysed. Data used, model development, parametrization and outcomes are detailed in Jantunen *et al.* (2007). In this chapter, we present a summary of the entire model development cycle, followed by a detailed discussion of the model outputs, with a particular emphasis on scenarios and trade-offs.

Model Development, Testing and Validation

Bayesian networks – also called Bayes' nets or Bayesian Belief Networks (BBN) – consist of a set of variables linked by probabilistic interactions (Charniak, 1991; Jensen, 1996; Cain, 2001). These variables can be quantitative or qualitative and a small number of classes are defined for each of them (e.g. 'rice farming area', <1000 ha or >1000 ha). Then probabilities, originating from data analysis or from consultation with experts, are attached to each class of each variable. When variables are linked (e.g. 'rice farming area' and 'rice productivity' being combined into 'rice production'), the resulting probabilities are calculated throughout the network using the Bayes' formula. For computation, we use Norsys' 'Netica' software since it is widely recognized, user-friendly and freely available on the Internet (www.norsys.com) for users to run the models developed.

In the case of the BayFish–Bac Lieu model, the structure is based entirely on stakeholder consultations held at the commune and provincial level. During the process, stakeholders identified the dominant factors (model variables) determining food production in the province and their cause–effect relationships (model linkages). Stakeholders also gave respective weights to factors at each level (probability elicitation). The model structure is shown in Fig. 10.2.

During the development process, it became clear that the initial objective – to propose an optimal sluice gate operation schedule that would maximize the production of all water-dependent commodities – was based on the improper assumption that harvest maximization (in terms of biomass) was the only expected outcome, regardless of economic or environmental considerations. Hence, the two latter variables were integrated as management outputs. On the input side, the sluice gate scenarios and corresponding hydrological data were

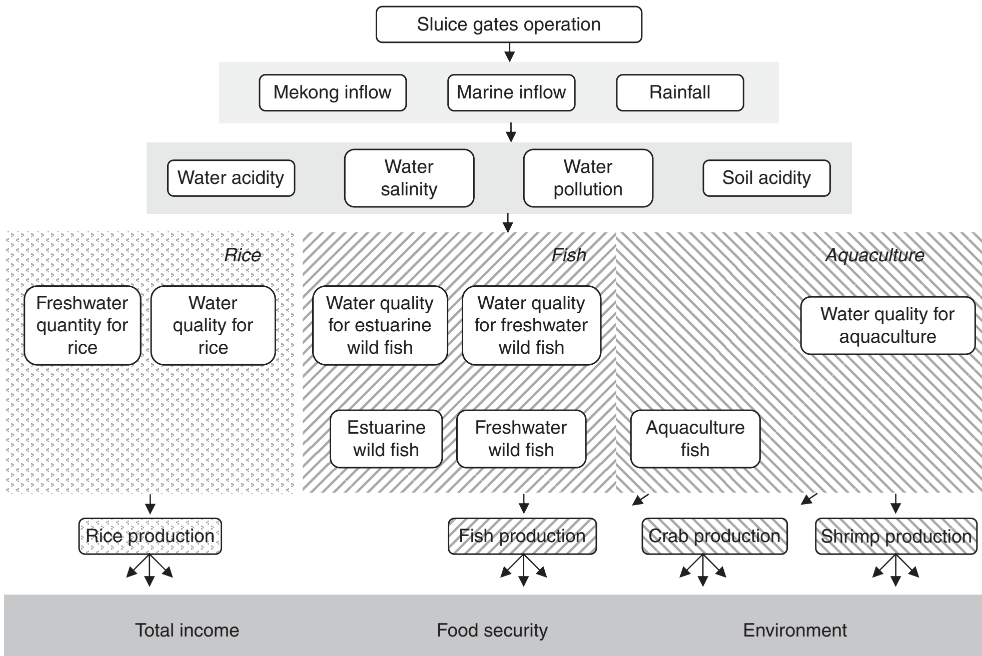

Fig. 10.2. Main variables and structure of the BayFish–Bac Lieu model.

derived from the VRSAP model (Hoanh, 1996). Five sluice gate managemement scenarios were considered (Jantunen *et al*., 2007):

1. *Baseline*: current complex operation schedule for 2001, 2003 and 2004 in which Lang Tram and Ho Phong sluices, and some smaller sluices, are opened or closed depending on salinity at three upstream benchmarks.
2. *All open*: all sluice gates open at all times (saltwater scenario).
3. *LT open*: only southern Lang Tram sluice gate is opened.
4. *LT and HP open*: Lang Tram and Ho Phong sluice gates are opened.
5. *All closed*: all sluice gates are closed at all times (the freshwater scenario), but in practice gates are opened briefly at certain times to let excess freshwater out.

Model fine-tuning (in particular thresholding) was carried out in collaboration with the Southern Institute for Water Resources Planning and local experts (details are given in Jantunen *et al*., 2007). Calibration was undertaken with a baseline scenario by relating provincial food production statistics with model output probability units. The resulting model is presented in Fig. 10.3.

Because the BayFish–Bac Lieu model focuses on water management options at the province level but does not integrate management options at the farm level (such as stocking density or use of fertilizers), the notion of ‘production’ could not refer to a number of tonnes only. Therefore, the land area used to produce a certain commodity was used as a proxy of production.

Figure 10.4 shows the relationships between model outputs (in probabilistic units) and land area used for agriculture and aquaculture; the model prediction for each production appears good.

In order to be readable, the model outputs, expressed in probabilistic terms, have been related to actual data for the years available, in particular for agriculture area and production and household income. These relationships are detailed below:

- Relationship between model units (x) and agriculture production (y, tonnes): $y = 7307.4x - 39{,}587$.

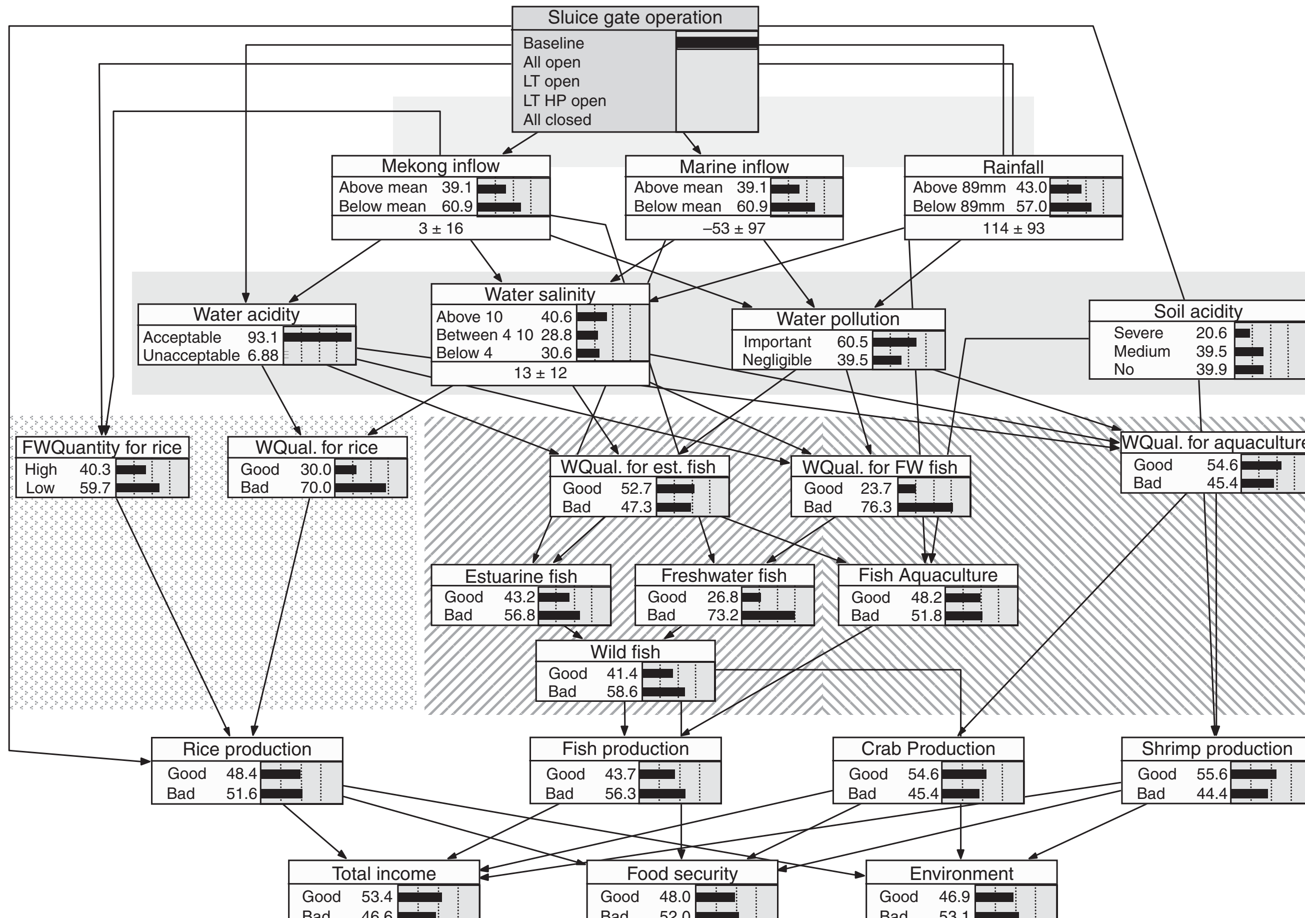

Fig. 10.3. Overview of the BayFish–Bac Lieu model. Values in boxes are probability units varying between 0 and 100%.

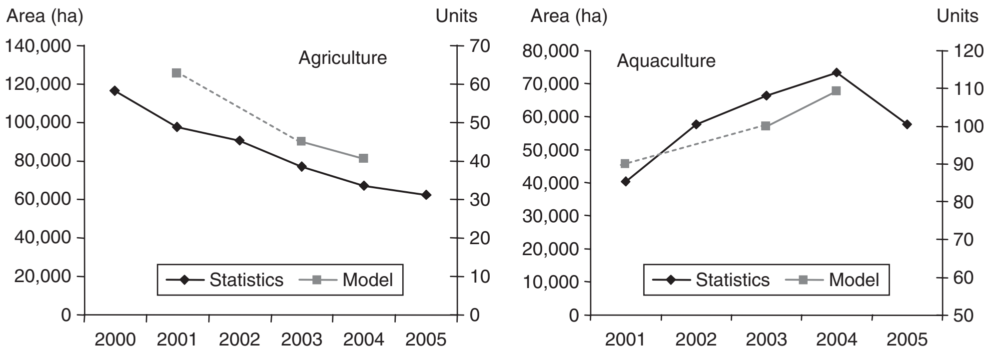

Fig. 10.4. Baseline scenario prediction (squares) compared to production area (lozenges) for agriculture and aquaculture.

- Relationship between model units (x) and agriculture area (y, ha): $y = 1916.4x - 18{,}009$.
- Relationship between model units (x) and aquaculture production (y, tonnes): $y = 1119.5x - 79{,}368$.
- Relationship between model units (x) and aquaculture area (y, ha): $y = 1977.9x - 13{,}7674$.
- Relationship between model units (x) and household income (y, US$): $y = 133.87x - 5306.9$.

Results

Water quantity and quality

The model was used to analyse the consequences of different sluice gate operation scenarios on water quality (Table 10.1). *Soil acidity* and *Rainfall* are not considered here as they are static nodes, i.e. scenarios do not affect their probabilities. The response of the model reflects closely the functioning of the environment. For all physical and chemical variables (except *Water pollution*), the *All gates open* and *All gates closed* scenarios provide the opposite extreme in response. When the *Baseline* scenario is compared to the *Lang Tram open* and the *Lang Tram and Ho Phong open* scenarios, the latter has much higher *Marine inflow*, but *Lang Tram and Ho Phong open* results in lower *Mekong inflow* probabilities. This means that having one main sluice gate (Lang Tram) open draws in more fresh water from the Mekong than enters in the *Baseline* scenario.

Water salinity levels do not increase much from the *Baseline* to the *Lang Tram open* scenario, whereas the *Lang Tram and Ho Phong open* scenario increases salinity significantly, especially above 10 ppt. *Water acidity* also behaves in opposition to salinity: the more *Marine inflow* is allowed, the less acidity is a problem in the province. *Water acidity* problems are also local, but they can be significant. The significance of acidity problems depends on soil type and excavation of new shrimp ponds; Gowing *et al*. (2006b) note that under

Table 10.1. Water quality depending on sluice gate operation scenarios. Results in probability units varying between 0 and 100%.

Variable	State	Baseline	All open	LT open	LT and HP open	All closed
Mekong inflow	Above 10 m^3/s	39.1	8.7	47.8	30.4	52.2
Marine inflow	Above 10 m^3/s	39.1	69.6	65.2	69.6	4.4
Water salinity	Above 10 ppt	40.6	59.9	43.3	51.2	27.3
	Between 4 and 10 ppt	28.8	24.0	30.1	27.4	27.8
	Below 4 ppt	30.6	16.1	26.7	21.3	44.9
Water acidity	Acceptable	93.1	96.5	92.2	94.1	91.7
Water pollution	Important	60.5	45.3	40.5	40.9	82.2

present circumstances, the release of acidity has a more significant impact on water quality than organic pollution.

Scenarios confirm that when sluice gates are all closed, there is no flushing of pollutants to the sea, which causes a high probability of pollution. Conversely, the *All gates open* scenario is not the best scenario for pollution either, since it corresponds to high-intensity shrimp farming (many authors argue that intensive shrimp farming is not sustainable, e.g. Gowing *et al.*, 2006a; Hossain *et al.*, 2006; Luttrell, 2006; Dung *et al.*, 2009). In fact, the best scenarios pollution-wise are the *Lang Tram open* and *Lang Tram and Ho Phong open* scenarios. This is because these scenarios allow a fairly high inflow of both Mekong and marine water, thereby diluting the pollutants.

Scenarios and consequences

Results for each of the scenarios in the BayFish–Bac Lieu model are presented in Table 10.2. Probability units (ranging from 0 to 100% probability) are those attached to the variable state defined as ‘Good’. *Total aquaculture* is the sum of *Shrimp production* and *Fish production* variables (statistics were not available for *Crab production*). Linear equations detailed above were used to compute indicative yield and area for each scenario.

All gates open

The *All gates open* scenario represents the system as it would be without any sluice gates. In this scenario, marine inflow is characteristically high, with minute *Mekong inflow*. This causes the province to have very high salinity concentrations. As a consequence, aquaculture production is very high (between 28,000 and 90,000 t/year for the 2001–2004 period, i.e. *Baseline* +100%), whereas *Rice production* decreases significantly to 210,000–280,000 t/year (i.e. *Baseline* −30%). Given the high price of shrimps, *Household income* is likely to rise to US$3000/household/year (+70%). This comes at the cost of reducing *Food security* significantly for the poorest of the province by limiting possibilities for rice cultivation, which is counterweighted to a degree by increased possibilities for *Fish production* through better access to open resources.

Table 10.2. Food production according to the different scenarios. Results in probability units (varying between 0 and 100%; focus on state ‘Good’ of each variable).

Variable	Baseline	All open	LT open	LT and HP open	All closed
Model output probabilities					
Fish production	43.7	59	56.7	58.9	26.4
Crab production	54.6	71.2	59.1	65.2	40.1
Shrimp production	55.6	68.9	59.2	64.1	44
Total aquaculture	99.3	127.9	115.9	123	70.4
Rice production	48.4	35.6	50.8	44	55
Total household income	53.4	63.2	57.7	60.7	43.7
Food security	48	41.5	52.6	47.8	49.3
Environment	46.9	47.2	45.9	46.4	47.8
Indicative production					
Aquaculture (ha)	58,731	115,299	91,565	105,608	1,570
Aquaculture (t)	31,798	63,816	50,382	58,331	–555
Agriculture (ha)	74,745	50,215	79,344	66,313	87,393
Agriculture (t)	314,091	220,556	331,629	281,939	362,320
Household income (US$)	1,842	3,154	2,417	2,819	543
Change from Baseline					
Aquaculture (ha)	0	96.3	55.9	79.8	−97.3
Aquaculture (t)	0	100.7	58.4	83.4	−101.7
Rice (ha)	0	−32.8	6.2	−11.3	16.9
Rice (t)	0	−29.8	5.6	−10.2	15.4
Income (US$)	0	71.2	31.3	53.1	−70.5

Lang Tram open

In this scenario, the *Marine inflow* is much higher than in the *Baseline* scenario, but less than in the *All gates open* or in the *Lang Tram and Ho Phong open* scenarios. *Water salinity* is a bit higher than in the *Baseline* scenario, resulting in an aquaculture production of 22,000–72,000 t/year for the 2001–2004 period (*Baseline* +55–60%). Surprisingly, rice production increases to 310,000–420,000 t/year (*Baseline* +5%), mainly because of higher *Mekong inflow*. It seems that opening this southern sluice gate does not allow salt water to penetrate far into the freshwater zone. This, however, allows more water exchange, which reduces *Water pollution* and *Water acidity*. *Household income* increases from *Baseline* level (US$1800/household/year) to US$2400/household/year (+30%) and *Food security* also increases in the province. However, this increased production pattern results in slightly more damage to the *Environment* than in the *Baseline* scenario.

Lang Tram and Ho Phong open

In this scenario, *Marine inflow* is as high as in the *All gates open* scenario. However, *Mekong inflow* is considerably higher than in the *All gates open* scenario, which results in a much lower *Water salinity*. Subsequently, aquaculture production reaches between 25,000 and 81,000 t/year for the 2001–2004 period (*Baseline* +80%). Because of higher *Marine inflow* and *Water salinity* levels, rice production decreases by 10% to 270,000–360,000 t/year. *Household income* increases from US$1800/household/year to US$2800/household/year (*Baseline* +50%), while almost holding *Food security* and *Environment* in the province at the same level as the *Baseline* scenario.

All gates closed

When all sluice gates are closed, *Marine inflow* is very low, whereas *Mekong inflow* is high. This holds *Water salinity* very low, but at the same time causes problems with increased *Water acidity* and *Water pollution*. The lack of *Marine inflow* results in aquaculture production sinking by 100% to 7000–23,000 t/year for the 2001–2004 period. At the same time, rice production increases by only 15% to 350,000–460,000 t/year, reflecting problems caused by extensive acidity. In this scenario, the low production intensities cause the least damage to the environment, but *Household income* decreases significantly to US$500/household/year, which is not even balanced by a significant increase in *Food security*. Omission of open-access fish catches in provincial statistics, i.e. self-consumed fish production, is demonstrated by a −555 t result in terms of aquaculture production. This also illustrates that yield probabilities are indicative rather than definite.

Shrimp versus rice versus fish

The government agenda of creating a regional ‘rice bowl’ by closing all sluice gates to suppress saline intrusion and favour rice production is impractical and does not benefit production, the people or the environment, as demonstrated by the *All gates closed* scenario. On the other hand, shrimp production is risky as it is susceptible to sudden failure because of shrimp diseases (Luttrell, 2006; Dung *et al*., 2009). In addition, intensive shrimp cultivation is detrimental to the environment, similar to intensive rice cultivation. Overall, it is clear that the shift from extensive to intensive systems brings trade-offs between economic benefit and environmental and social impacts (Gowing *et al*., 2006a). Hossain *et al*. (2006) point out that shrimp provides more postharvest employment opportunities than rice, which can contribute to poverty reduction and increased income at the provincial level. Fluctuating market prices of shrimp, however, introduce uncertainty in postharvest employment and the market price of shrimp is more volatile than that of rice (Hossain *et al*., 2006). However, 2008 saw a sharp increase in rice prices over a short period, which was not reflected in this model as it was designed and calibrated earlier on. Actually, economic sustainability can be improved by adopting a combined shrimp–rice cultivation system, which is possible under a *Lang Tram gate open* scenario. Indeed, ‘even if the relative price of shrimp had declined by 50% from

Table 10.3. Predictions of the model for the fish component. Results in probability units varying between 0 and 100%.

Model output	State	Baseline	All open	LT open	LT and HP open	All closed
Water quality for estuarine fish	Good	52.7	66	60.6	63.8	39.6
Water quality for freshwater fish	Good	23.7	13.8	21.4	17.6	33.4
Estuarine fish	Good	43.2	68.5	63.8	67.8	14.9
Freshwater fish	Good	26.8	12.8	26.6	20.1	37.1
Wild fish	Good	41.4	62.3	59.7	62.5	26.4
Fish aquaculture	Good	48.2	52.6	50.8	51.9	43.8
Fish production	Good	43.7	59	56.7	58.9	26.4

the level of 2001, the rice–shrimp system would remain more profitable than the intensive rice production system' (Hossain *et al.*, 2006, p. 42).

From an aquatic resources viewpoint, 'Fish have always been abundant and are considered a commodity, like water and air, that will always be there, but there is evidence that changes within the protected area have had an impact on fishery resources' (Gowing *et al.*, 2006b, p. 59). It is clear from the *All gates closed* scenario (Table 10.3) that the sluice gates have a significant impact on fish production in the province. Direct impacts include acting as a barrier to fish movements and indirect impacts such as altering *Mekong inflow* and *Marine inflow* and subsequently affecting salinity levels. Fish production is currently dominated by larger and more abundant estuarine fish species (Baran *et al.*, 2007) and the *All gates closed* scenario practically eradicates them from the canals. Fish production in estuarine systems is always higher than in freshwater systems because of the incursion of marine species and of the high productivity of robust permanent estuarine species, as opposed to the lower overall productivity of temporary freshwater species (Baran, 2000); thus, the water management option of closing gates to estuarine species results in a substantial overall loss of aquatic productivity. Fish make an important contribution to food security since they are an open-access resource. Open-access resources are essential in providing income and sustenance for the poor for whom aquaculture is not an accessible livelihood option (Gowing *et al.*, 2006b; Hossain *et al.*, 2006; Luttrell, 2006). The *All gates open* scenario results in the highest fish production, but there is actually little difference with *Lang Tram open* and *Lang Tram and Ho Phong open* scenarios because of trade-offs between fish aquaculture production and estuarine fish input. In terms of fisheries production, and thus in terms of food security, these two latter scenarios are quite acceptable.

Conclusion

Analysis of the scenario results clearly shows that neither *All gates open* nor *All gates closed* are a desirable operation mode (Fig. 10.5). The *All gates closed* scenario devastates aquaculture production, while not providing added benefits (in particular no significant increase in rice production), and it also decreases overall water quality. On the other hand, the *All gates open* scenario affects *Food security* seriously through reduced rice production, while encouraging unsustainable and environmentally damaging intensive shrimp aquaculture. Even though the *All gates open* scenario seems to provide the best household income, it causes increased reliance on monoculture.

Of the four scenarios tested here, *Lang Tram open* and *Lang Tram and Ho Phong open* seem to offer the best potential for the province, with significant improvements from the *Baseline* scenario in terms of aquaculture production and household income. In addition, *Lang Tram open* increases *Food security* and *Environment* outputs, whereas the *Lang Tram and Ho Phong open* scenario shows a marginal decrease in both compared to the *Baseline* scenario. Overall, *Lang Tram open* provides a more balanced approach, with a moderate increase in household income and aquaculture, yet providing a small increase in rice production

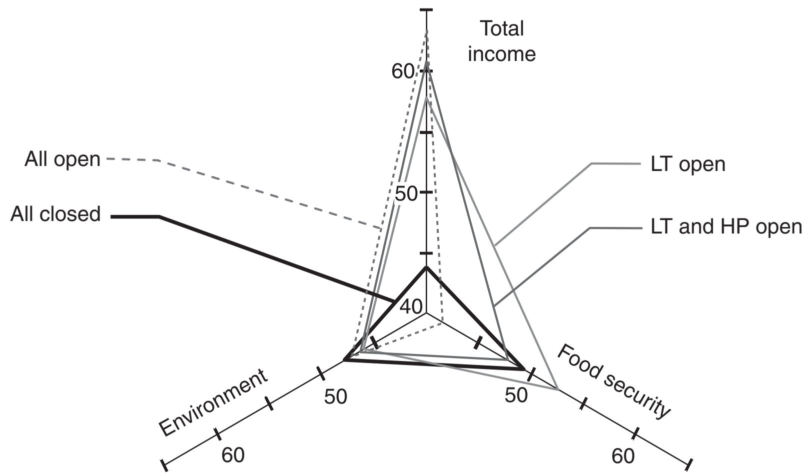

Fig. 10.5. Star graph comparing the outcomes of four sluice gate management scenarios in terms of income, food security and environment. Results in probability units varying between 0 and 100%.

as well. Moreover, it allows both freshwater and estuarine fish to prosper in the canals, when *Lang Tram and Ho Phong open* causes a decrease in freshwater fish production.

Based on the results of this study, the opening of *Lang Tram* sluice gate is seen as the optimum choice in the current circumstances. This confirms that the change in sluice gate operation mode that took place from 2001 to 2004 has been positive. However, given the dynamics of change in Bac Lieu Province, it is recommended that planning is not undertaken more than 3 years in advance.

As a tool allowing the integration of expert knowledge, databases and model output data, BayFish–Bac Lieu has proved to be a useful platform, illustrating the usefulness of a Bayesian approach in planning and managing natural resources. The qualities and shortcomings of this approach have been detailed in Baran *et al.* (2006). From a local management perspective, the current model is constrained by its broad scope and could be refined by: (i) a division into smaller unit models to reflect the characteristics of each area better; (ii) using daily and/or weekly input data instead of the current monthly input data, in particular for water quality; and (iii) analysing temporal issues on the basis of a lunar calendar to reflect tidal influence better, which is crucial in this region.

Another major improvement would be the development of detailed scenarios focusing on the opening and closure schedule of Lam Than and Ho Phong sluice gates. However, Bayesian networks do not accommodate iterations and thus should not be expected to model dynamic processes at small temporal scales. Nevertheless, unlike dynamic environmental models, Bayesian networks allow the analysis of the consequences of sluice gate management to encompass income, food security or environmental dimensions. In conclusion, the modelling approach presented also highlights trade-offs between management outcomes, highlighting the need for clear identification of the political choices driving environmental management.

References

Baran, E. (2000) Biodiversity of estuarine fish faunas in West Africa. *NAGA* 23(4), 4–9.

Baran, E., Jantunen, T. and Chheng, P. (2006) Developing a consultative Bayesian model for integrated management of aquatic resources: an inland coastal zone case study. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Baran, E., Chheng, P., Warry, F., Vo, T.T., Ha, P.H. and Hoanh, C.T. (2007) Aquatic resources and environmental variability in Bac Lieu Province (Southern Vietnam). Final report of the Coastal Lands Challenge Program Project No 10 Managing Water and Land Resources for Sustainable Livelihoods at the Freshwater/Saline Interface in Vietnam and Bangladesh. WorldFish Center, Phnom Penh.

Cain, J. (2001) *Planning Improvements in Natural Resources Management. Guidelines for Using Bayesian Networks to Support the Planning and Management of Development Programmes in the Water Sector and Beyond*. Centre for Ecology and Hydrology (CEH), Wallingford, UK.

Charniak, E. (1991) Bayesian networks without tears. *Artificial Intelligence* 12(4), 50–63 (http://www-psych.stanford.edu/~jbt/224/Charniak_91.pdf, accessed 31 August 2009).

Dung, L.C., Hoanh, C.T., Le Page, C., Bousquet, F. and Gajaseni, N. (2009) Facilitating dialogue between aquaculture and agriculture: lessons from role-playing games with farmers in the Mekong Delta, Vietnam. Water Policy, Special Issues on Trade-off and Synergies in Water Management Across Scales. *Water Policy* 11(S1), 80–93.

Gowing, J.W., Tuong, T.P. and Hoanh, C.T. (2006a) Land and water management in coastal zone: dealing with agriculture–aquacultre–fishery conflicts. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006b) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Hoanh, C.T. (1996) Development of a computerized aid to integrated land use planning (CAILUP) at regional level in irrigated areas. A case study for the Quan Lo Phung Hiep region, Mekong Delta, Vietnam. PhD thesis, Wageningen Agricultural University and International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, the Netherlands.

Hossain, M., Ut, T.T. and Bose, M.L. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

Jantunen, T., Baran, E., Chheng, P., Warry, F., Hoanh, C.T. and Binh, N.T. (2007) Sluice gate operation, outcomes and trade-offs: BayFish–Bac Lieu, a model for integrated management of inland coastal resources in southern Vietnam. Final report. CGIAR Water and Food Challenge Program Project PN 10 Managing Water and Land Resources for Sustainable Livelihoods at the Interface Between Fresh and Saline Water Environments in Vietnam and Bangladesh. WorldFish Center, Phnom Penh.

Jensen, F.V. (1996) *An Introduction to Bayesian Networks*. UCL Press, London.

Luttrell, C. (2006) Adapting to aquaculture in Vietnam: securing livelihoods in a context of change in two coastal communites. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones*. CAB International, Wallingford, UK.

11 Soil Characteristics of Saline and Non-saline Deltas of Bangladesh

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Abstract
The delta soils of Bangladesh occur in the coastal region of the Ganges tidal flood plain, the young Meghna estuarine flood plain, the old Meghna estuarine flood plain and the Chittagong coastal plains. Although delta soils constitute some of the most productive lands of the country, their characterization has received little attention, often because of limited accessibility. However, this information is necessary to maximize their use for agriculture to enhance national food security. Soil characteristics of farmers' fields from saline and non-saline delta zones were evaluated to understand their soil fertility status, salt content and distribution in these soils and their potential for the cultivation of modern rice varieties. Electrical conductivity in the saturation extract of the topsoil in the saline zone varied from 1 to 20 dS/m, whereas it ranged from 0.7 to 1.6 dS/m in the non-saline zone. The pH of these coastal soils ranged from moderately acidic to mildly alkaline (5.8–7.8) and soil organic matter varied between 1.2 and 3.6%. The tested soils had a wide range of available phosphorus (2–59 mg/kg) and exchangeable potassium varied from 0.2 cmol/kg to as high as 2.5 cmol/kg soil. Across the soils, potassium saturation was always higher than 2% of the base saturation. Soil analysis indicated widespread zinc deficiency (less than 2 ppm available Zn) in coastal delta soils. Wet-season rice is grown in most of the saline and non-saline areas and, given the moderate percolation rate of these soils and availability of good-quality river water in most of these coastal areas, the land is suitable for rice cultivation. Recently developed salt-tolerant rice varieties (BRRI dhan 40 and BRRI dhan 41 for the wet season; BRRI dhan 47 for the dry season) should be evaluated in these delta areas to replace the currently grown landraces with low productivity, and packages of proper crop and nutrient management options for these modern rice varieties need to be established.

Introduction

Deltas are depositional bodies that form at the point where a river empties into a lake or the sea. The combined actions of river and marine processes determine whether a depositional body can form at the mouth of a river and what kind of body will form. If the rate of sediment input from the river exceeds marine sediment redistribution, the depositional sequence will progress seaward to form a delta. The delta of the Ganges–Brahmaputra river system in Bangladesh is a tide-dominated delta plain. In Bangladesh, about 30% of the net cultivable area (9.5 million ha) lies in the coastal zone. Coastal soils are in a state of disequilibrium with the physical environment because of the destructive, transportive and constructive activities of waves, tides, currents, rivers and winds acting throughout the year. Many of the coastal lands are subjected to detrimental river erosion, while others experience continuous sedimentation.

The coastal lands of Bangladesh are categorized into highlands (≤0.5 m flood depth), medium highlands (≤0.9 m flood depth), medium lowlands (0.9–1.8 m flood depth) and lowlands (1.8–3.0 m flood depth). Highlands cover about 0.25 million ha, medium highlands cover about 1.16 million ha, medium lowlands cover 0.16 million ha and lowlands cover about 5700 ha (Islam *et al*., 1993). Out of 2.85 million ha of coastal and offshore land, 0.83 million ha are affected by varying degrees of salinity. The salinity on about 0.287 million ha of coastal soils is 2–4 dS/m, 0.426 million ha have a salinity of 4–8 dS/m and 0.12 million ha of coastal land have a salinity of more than 8 dS/m. Salinity is usually below 4 dS/m during the monsoon season, starts to increase during December and is at its maximum during March–April. The differences in characteristics between saline and non-saline soils may be noticeable only in potassium fertility. Saline soils may contain more potassium than non-saline soils, but potassium saturation of the former would be lower than that of the latter.

In Bangladesh, three rice-cropping seasons are distinguished. 'T. aman' rice (T = transplanted) is grown during the monsoon season from July to January, irrigated 'boro' rice is grown from December to May, and 'T. aus' rice is grown from April to August. The most common cropping pattern in the coastal deltas of Bangladesh is T. aman–fallow–fallow, followed by the less common T. aman–pulses–T. aus and T. aman–boro–fallow sequences. Rice is the principal crop in coastal soils because of its wide adaptation and farmers' preference. In recent years, high-yielding rice varieties (HYV) have become increasingly popular in coastal regions and today, about 90% of boro, 49% of T. aus and 29% of T. aman rice areas are occupied by HYV in these coastal areas. However, boro coverage in the coastal area is only 14% of the total rice area (824,000 ha), which is much less than in other parts of the country. The yield of HYV rice in the coastal region varies from 4.70 to 5.71 t/ha in the boro season, from 3.18 to 4.00 t/ha in T. aus and from 3.87 to 4.40 t/ha in the T. aman season. However, there are reports of up to 9.0 t/ha of grain yield during the boro season in some coastal non-saline soils. Average fertilizer use in coastal areas is relatively low, estimated at 48 kg N, 5 kg P, 3 kg K, 1 kg S and 0.3 kg Zn per hectare in the boro season and at 29 kg N, 3 kg P, 4 kg K, 1 kg S and 0.2 kg Zn per hectare in the T. aus and T. aman seasons. Only a few farmers apply S and about 30% of the farmers apply Zn.

Sedimentation, associated with tidal flooding, is an important source of nitrogen (N), phosphorus (P) and potassium (K) for many delta soils. In these sediments, N is deposited mostly as a component of organic matter (OM), whereas P is associated primarily with the fine-grained clay minerals (Odum, 1988). Local hydrological factors (e.g. velocity and duration of flooding), as well as local geomorphology, can influence the spatial patterns of sediment deposition and, hence, soil nutrient availability (Darke and Megonigal, 2003). Seasonal variations in estuarine processes that affect nutrient fluxes may also be important (Barko *et al*., 1991). High rates of local deposition (particularly of fine clays) occur near the estuarine turbidity maximum (ETM) – the upstream end of saltwater intrusion – which migrates upstream during summer as freshwater discharge decreases (Lin and Kuo, 2001).

Given this scenario of the importance of rice cropping on delta soils, current rice yields and common fertilizer practices, coastal delta soils need to be characterized better as a first step to develop fertilizer recommendations for increased rice yields, as well as more efficient cropping patterns. The present investigation seeks to describe some features of coastal delta soils in Bangladesh and to explore options for improved fertilizer management for rice in these regions.

Materials and Methods

Soil samples were collected from farmers' fields in two districts representing non-saline delta regions – Patuakhali and Barisal – and in two districts representing saline delta regions of Bangladesh – Borguna and Satkhira (Table 11.1; Fig. 11.1). Sampling sites were located within 5–120 km from the sea, but all of them were influenced by tidal movements and were flooded seasonally. Dominant cropping patterns at the sampling sites were either rice–rice–fallow or rice–fallow–fallow.

At each site, nine soil samples were collected and composited from the rice root zone (0–15 cm depth) and from 5 to 20 farmers' fields representing each site. Soil samples were dried, crushed and sieved through a 2 mm sieve.

Table 11.1. Sampling site locations, dominant cropping patterns and occurrence of salinity.

Location	Distance from the sea (km)	Dominant cropping pattern	Salinity occurrence
Bauphol, Patuakhali	50	Aus[a]–aman[b]–fallow	Non-saline
Ujirpur, Barisal	110	Boro[c]–fallow–fallow	Non-saline
Barisal, Barisal	100	Boro–aman–fallow	Non-saline
Munshiganj, Satkhira	5	Aman–fallow–fallow	Saline
Ashasuni, Satkhira	70	Boro–aman–fallow	Saline
Patharghata, Borguna	5	Aman–fallow–fallow	Saline

[a]Aus is lowland rice grown during April–August; [b]aman is lowland rice grown during July–January; [c]boro is lowland rice grown during December–May.

Soil texture was determined by the hydrometer method (Black *et al.*, 1965). Samples were analysed for electrical conductivity from the saturation paste (Richards, 1954); pH (1:2 soil:water ratio; McLean, 1982); organic carbon, which was converted to organic matter by multiplying by 1.724 (Nelson and Sommers, 1982); available P extracted with 0.5 M $NaHCO_3$ (pH 8.5; Knudsen and Beegle, 1988); exchangeable K extracted with 1.0 N ammonium acetate solution (Chapman, 1965); available S by 500 ppm $Ca(H_2PO_4)$ solution; and available Zn by 0.1 N HCl solution (PCARR, 1978). Each sample was analysed in duplicate. Total P, K and non-exchangeable K were analysed from tidal sediments and a tide-free soil. Total P and K were analysed by digesting 1 g sample in 10 ml acid mixture (750 ml HNO_3, 150 ml H_2SO_4 and 300 ml $HClO_4$). Phosphorus in the digest was determined with the vanadomolybdate yellow colour method (Yoshida *et al.*, 1976). Potassium was determined in diluted extraction solution by flame photometry, and non-exchangeable K was determined by extraction in boiling HNO_3 (Knudsen *et al.*, 1982).

Results and Discussion

Soil texture

The texture of Munshiganj, Ashasuni and Patharghata soils (saline) was silty clay loam, clay loam and silt loam, respectively (Table 11.2), whereas the texture of the three non-saline soils was silt loam (Table 11.3). In both the saline and non-saline delta soils, silt and clay fractions dominated over the sand fraction. This is typical for the parent materials of delta soils because larger particles, including most of the sand fraction, are deposited further upstream and many of the remaining fine particles (silt and clay particles) are deposited in the delta area due to the back-and-forth movement of water in the tidal zone. Fine-textured delta soils are expected to be highly suitable for lowland rice farming because of their high nutrient content and good water-holding capacity. However, the fine textures of delta deposits, especially when occurring in the subsoil, indicate the possibility of poor internal drainage, retarded salt leaching during the wet season and considerable salt input with capillary rise during the dry season (Panaullah, 1993).

Soil reaction

Most of the delta soils had pH values in the topsoil ranging from slightly acidic to moderately alkaline (Tables 11.2 and 11.3). The pH varied from 4.2 to 8.0 in saline soils (Table 11.2) and from 5.8 to 7.2 in non-saline soils (Table 11.3). Extreme acidity (pH 4.2) was found in only one field at the Munshiganj site, indicating that the soil was probably an actual acid sulfate soil. Many of the saline soils (6 fields of 19 analysed) showed an alkaline soil reaction, presumably resulting from repeated equilibration with surface waters and groundwaters that were influenced by seawater carrying neutral and chloride salts and with a pH of around 8.0. The slightly alkaline conditions of the saline soils analysed may cause micronutrient deficiency problems in rice, especially Zn and Fe.

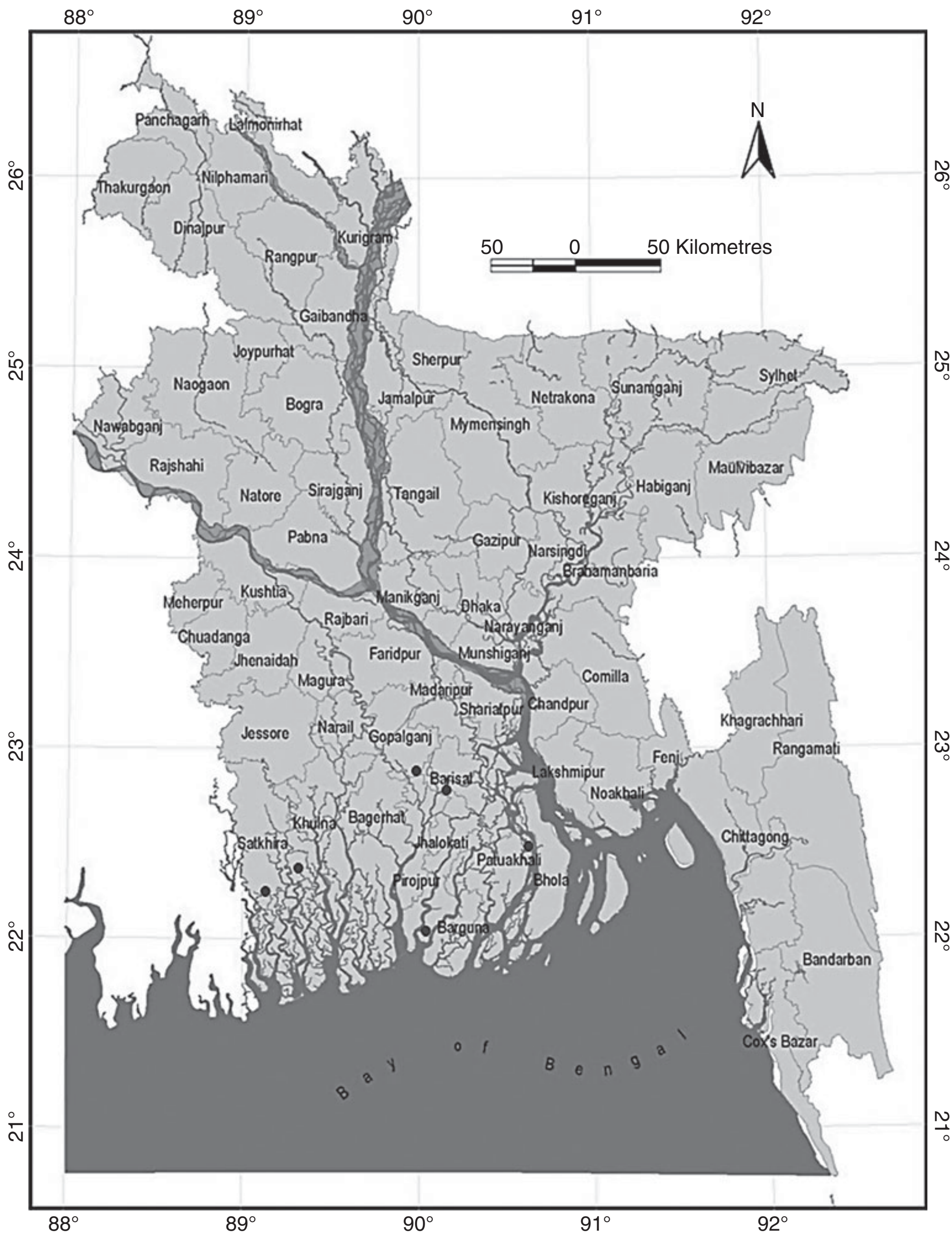

Fig. 11.1. Map of Bangladesh showing the dots near Barisal, Patuakhali, Satkhira and Borguna, representing the soil sampling sites.

Organic matter

Organic matter (OM) status of saline delta soils ranged from 1.2 to 2.7% at Munshiganj, from 1.5 to 3.6% at Ashasuni and from 1.2 to 1.5% at Patharghata (Table 11.2). In non-saline delta areas, high OM contents were observed at Bauphol (3.3–4.0%) and at Ujipur (4.2–6.0%),

Table 11.2. Characteristics of saline delta soils of Bangladesh at selected sampling sites.

Properties	Munshiganj (5 samples)	Ashasuni (5 samples)	Patharghata (9 samples)
Texture[a]	Silty clay loam	Clay loam	Silt loam
Sand (%)	18	21	20
Silt (%)	52	44	57
Clay (%)	30	35	23
pH	4.21–7.23	5.89–7.95	5.70–7.79
Organic matter (%)	1.19–2.67	1.50–3.60	1.15–1.45
EC (dS/m)	14–20	5–8	1–13
Olsen P (mg/kg)	2–59	2–30	6–22
Exchangeable K (cmol/kg)	0.94–2.49	0.32–0.53	0.25–0.30
Available S (mg/kg)	90–150	60–150	80–120
Available Zn (mg/kg)	1–5	0.7–0.9	0.8–1.5

[a]The texture analysis was conducted using a representative sample from each site.

Table 11.3. Characteristics of non-saline delta soils of Bangladesh at selected sampling sites.

Properties	Bauphol (20 samples)	Ujirpur (5 samples)	Barisal (15 samples)
Texture[a]	Silt loam	Silt loam	Silt loam
Sand (%)	17	25	16
Silt (%)	61	51	60
Clay (%)	22	24	24
pH	5.75–6.40	6.20–6.70	6.62–7.75
Organic matter (%)	3.29–3.99	4.20–6.04	1.13–1.89
EC (dS/m)	0.66–1.59	0.68–0.92	0.65–0.88
Olsen P (mg/kg)	5–11	8–11	12–14
Exchangeable K (cmol/kg)	0.22–0.40	0.17–0.32	0.22–0.25
Available S (mg/kg)	41–103	33–55	45–50
Available Zn (mg/kg)	1.0–1.5	0.6–1.5	0.8–1.5

[a]The texture analysis was conducted using a representative sample from each site.

but OM content was low at Barisal (1.1–1.9%). The high OM concentrations of Bauphol and Ujirpur soils could be attributed to the prolonged submergence (June–December) and growth of natural aquatic plants during the period when the soil was flooded. In addition, the waterlogging of delta soils might reduce OM decomposition, causing higher OM concentrations than in other soils of Bangladesh. The fine texture of delta soils might also have favoured OM accumulation. Tidal sediments often contain high OM concentrations (3.4% OM and 700 ppm soluble organic carbon in the example given in Table 11.4), thereby contributing to the observed high OM concentrations of these tidal flooded delta soils that normally remain underwater for 4–5 months each year.

Soil salinity

Electrical conductivity in the saline delta area during the sampling period (October–November) ranged from 14 to 20 dS/m at Munshiganj, from 5 to 8 dS/m at Ashasuni and from 1 to 13 dS/m at Patharghata (Table 11.2), showing a large variation in salinity between and within the sites. Temporal variation in soil salinity under natural field conditions was observed previously (Panaullah *et al*., 2000). The period of minimum soil salinity in Bangladesh is July–September, when high rainfalls and/or flooding leach and drain salts accumulated in the soil surface. After the recession of rains and floods, salinity starts to increase, reaching intermediate levels during January–February and maximum levels during March–April (Panaullah, 1993).

Table 11.4. Nutrient concentrations in tidal sediments and a tide-free soil from southern Bangladesh.

Properties	Tidal sediments	Tide-free soil
pH	6.84	7.64
Organic matter (%)	3.36	1.93
Water-soluble C (mg/kg)	676	491
Available P (mg/kg)	28	14
Available S (mg/kg)	85	23
Exchangeable K (cmol/kg)	0.52	0.31
Non-exchangeable K (cmol/kg)	1.07	2.38
Total P (mg/kg)	763	813
Total K (%)	1.00	0.48

Some saline soils in the Satkhira region have been brought under boro cultivation using non-saline groundwater. Due to equilibration with the irrigation water and leaching, soil salinity in boro fields remains below 4 dS/m and good grain yield can be obtained (Saleque *et al.*, 2005). Soil salinity often affects the T. aman crop during October if there is a spell with inadequate rainfall, coinciding with the highly sensitive booting and flowering stages of rice, which may cause considerable yield losses.

Available phosphorus

Available P (Olsen-P) in the saline delta area varied from 2 to 59 mg/kg (Table 11.2). At Munshiganj and Ashasuni, several of the soil samples analysed were highly deficient in P, whereas others had optimum to high P. According to Fairhurst *et al.* (2007), P deficiency is highly likely at Olsen P below 5 mg/kg and probable at values between 5 and 10 mg/kg. Less severe P deficiency occurred at the Patharghata site. In the non-saline delta area, severe P deficiency was observed only in some soils at the Bauphol site; soil-available P at Ujirpur and Barisal ranged from 8 to 14 mg/kg, which was generally adequate for lowland rice and medium yield. Tidal flooded delta soils are replenished with P through tidal sediments, which can contain considerable amounts of total and available P (763 mg/kg total P and 28 mg/kg available P in the example given in Table 11.4). Response to P application of lowland rice in delta soils is therefore expected to be relatively low, especially in T. aman rice, because of tidal sediments.

Potassium

The observed exchangeable K concentration in saline and non-saline delta soils was relatively high (Tables 11.2 and 11.3). In saline soils, the exchangeable K content at Munshiganj, Ashasuni and Patharghata was in the range of 0.94–2.49, 0.32–0.53 and 0.25–0.30 cmol/kg, respectively. In non-saline delta areas, exchangeable K concentrations at Bauphol, Ujirpur and Barisal were 0.22–0.40, 0.17–0.32 and 0.22–0.25 cmol/kg, respectively. Given the observed concentrations of exchangeable K and the reported threshold values (K deficiency is highly likely at exchangeable K below 0.15 cmol/kg and probable at values between 0.15 and 0.45 cmol/kg; Fairhurst *et al.*, 2007), lowland rice in delta soils would rarely respond to the application of K. Moreover, considerable K inputs from tidal sediments (Table 11.4) can further contribute to the K nutrition of rice crops in this area.

Sulfur

Available S concentrations in saline delta soils ranged from 60 to 150 mg/kg (Table 11.2), but were slightly lower in non-saline delta soils, ranging from 33 to 103 mg/kg (Table 11.3). Critical soil levels for occurrence of S deficiency in rice are suggested as below 9 mg/kg (Fairhurst *et al.*, 2007). Consequently, none of the delta soils analysed was deficient in S for wetland rice and considerable S inputs from the deposition of tidal sediments could be expected.

Zinc

Available Zn concentrations in almost all saline and non-saline delta soils analysed were below 2.0 mg/kg (Tables 11.2 and 11.3), which was below the critical level suggested by Fairhurst *et al*. (2007). High pH values and excessive wetness, as frequently experienced in these coastal saline soils, will further limit Zn availability for rice. Therefore, widespread Zn deficiency and response to Zn application could be expected. However, there are also considerable differences in Zn deficiency tolerance between rice varieties and only field tests with widely used varieties in the region can clarify the need for Zn application.

Correlation among the soil fertility indicators

To investigate the relation between the soil fertility indicators analysed in this study, correlation matrices for saline and non-saline soils and for the combined data set were established (Table 11.5). All three matrices indicated that higher pH values were related to lower OM concentrations and possibly related to a higher mineralization rate at higher pH. Another general trend is the mostly positive correlation between the availability of P, K, S and Zn (except for P versus the other nutrients in the data set from non-saline soils), suggesting that poor soils will frequently be limited in the availability of several elements. In non-saline soils, the soil pH was correlated negatively with available K, S and Zn, confirming the general notion that better nutrient availability occurred near neutral pH values.

Fertilizer management recommendations for rice in delta regions

In the past, most of the delta soils of Bangladesh received scanty attention, their characteristics were ill-defined and fertilizer responses were hardly studied. Farmers in the delta regions

Table 11.5. Correlation matrix and coefficients for soil characteristics: pH, organic matter (OM) and soil nutrients (Olsen P, exchangeable K, available S and Zn) in saline and non-saline delta soils of southern Bangladesh.

	OM	Olsen P	Exchangeable K	Available S	Available Zn
Non-saline soil ($n = 41$)					
pH	−0.35*	0.61**	−0.45**	−0.51**	−0.39*
OM		−0.44**	0.32*	0.18^{ns}	-0.04^{ns}
Olsen P			−0.54**	−0.35*	-0.24^{ns}
Exchangeable K				0.41**	0.24^{ns}
Available S					0.35*
Saline soil ($n = 19$)					
pH	-0.20^{ns}	-0.31^{ns}	0.09^{ns}	-0.13^{ns}	0.01^{ns}
OM		-0.17^{ns}	-0.04^{ns}	-0.25^{ns}	0.01^{ns}
Olsen P			0.02^{ns}	0.36^{ns}	0.78**
Exchangeable K				0.36^{ns}	0.32^{ns}
Available S					0.49*
Combined data set ($n = 60$)					
pH	−0.38**	-0.01^{ns}	0.18^{ns}	0.02^{ns}	−0.03
OM		-0.22^{ns}	-0.14^{ns}	-0.20^{ns}	−0.20
Olsen P			0.06^{ns}	0.29*	0.66**
Exchangeable K				0.49**	0.35**
Available S					0.43**

*, ** = significant at $P = 0.05\%$, 0.01; ^{ns} = not significant.

used to grow local rice varieties without any significant fertilizer application. Recently, salt-tolerant, high-yielding varieties such as BRRI dhan 40 and BRRI dhan 41 for T. aman and BRRI dhan 47 for the boro season were developed for both saline and non-saline delta areas. With the introduction of these varieties, which were also more responsive to inputs, inorganic fertilizer application was recommended. However, farmers did not always observe significant rice yield improvements, possibly because the indigenous nutrient supply was sufficiently high to support achievable yields or because other elements that were not applied were, in fact, limiting yield. Therefore, fertilizer recommendations for these areas need to be reconsidered and adjusted to the specific characteristics of the delta soils in Bangladesh.

Soil test results generally are interpreted using two different concepts – the sufficiency level of available nutrients (SLAN) concept and the basic cation saturation ratio (BCSR) concept (McLean, 1984; Haby *et al.*, 1990). According to the SLAN concept, there are defined critical levels of individual nutrients in the soil below which crops will respond to added fertilizers, and above which they probably will not respond (Eckert, 1987). Fertilizer recommendations in Bangladesh are based on the SLAN concept. However, discrepancies between soil test results and fertilizer response do occur. For example, 0.10 cmol/kg was defined by Saleque *et al.* (1990) and Bhuiyan *et al.* (1992) as a critical level for exchangeable K for lowland rice in Bangladesh. However, in the case of wetland rice, significant yield response to K application in some soils with neutral soil reaction (pH ~ 7.0) and available K concentrations of more than 0.2 cmol/kg was reported, whereas no yield response was observed in some light-textured acid soils (pH ~ 5.5) with available K concentrations below 0.1 cmol/kg (BRRI, 1987).

According to the BCSR concept, the ideal ratio of basic cations in the soil is attained when calcium occupies 65–85%, magnesium 6–12% and K 2–5% of the total exchangeable basic cations (McLean, 1984). If the K saturation is below 2% because of high calcium and magnesium saturation, K response is likely even if the absolute concentration is above the critical level. This situation is more likely in delta soils because of their high calcium and magnesium saturation (Panaullah, 1993). However, the BCSR concept was not found appropriate in the case of calcareous soils grown to wheat (Abedin *et al.*, 1998). Also, Kopittke and Menzies (2007) disapproved of the application of the BCSR concept to the interpretation of soil test results. They reported that the application of calcium, magnesium, or K following the BCSR concept would result in the inefficient use of fertilizer.

Neither the SLAN nor the BCSR concept considers soil pH and soil OM concentration in the interpretation of soil test results. But both characteristics have an important role in the availability of plant nutrients. Soil pH influences the solubility of P, iron, manganese, Zn and many other nutrients (Lindsey, 1979). Changes in pH due to soil submergence during wetland rice growth may alter considerably the availability of nutrients from those predicted by soils tests based on nutrient extractions from dry soil samples. Incubation of acid soils under anaerobic conditions increased the soil pH by up to two units and raised available P two- to threefold (Islam, 2005). Besides acting as a source of nutrients, soil OM also has very important functions related to nutrient availability and retention. Approaches such as those proposed by Janssen *et al.* (1990), which take soil pH, OM and available P and K concentrations into consideration (integrated in a model called 'quantitative evaluation of the fertility of tropical soils', or QUEFTS), might therefore offer opportunities to develop better fertilizer recommendations for rice in the delta soils of Bangladesh. These should also take into consideration the nutrient input from tidal sediments, which may contribute considerably to crop nutrition.

Conclusions

The analysis of saline and non-saline delta soils indicates the dominance of generally fine-textured soils, which is typical for delta soils. Most of the soils had favourable pH values, but several saline soils (31%) showed an alkaline soil reaction. Severe P deficiency was observed in several of the sampled fields, but soil P covered a wide range from deficient to abundant. In addition, the soil analysis indicated widespread Zn deficiency but mostly sufficient K supply and no occurrence of S deficiency. Considerable soil salinity occurs in some delta regions and rice cultivation is probably the best cropping option there because it contributes to the drainage and leaching of substantial amounts of salt from the topsoil. In fact, delta regions could sustain high yields, especially when combined with the use of modern salt-tolerant rice varieties and improved nutrient management recommendations, Hence, improved fertilizer recommendations for modern rice varieties grown in the delta soils of Bangladesh are needed urgently. They should be based on more detailed background studies of soil characteristics and fertilizer response trials for rice-based cropping systems in this region. Recommendations developed could be based on soil testing, but probably would need to combine different concepts for the interpretation of soil test values. Integrating these different elements could then contribute to an increase in rice production in delta soils and improve the livelihoods of poor farmers in the region.

References

Abedin, M.J., Saleque, M.A., Panaullah, G.M. and Mazid, M.A. (1998) Evaluation of two concepts of fertilization for wheat in calcareous soil of Bangladesh. *Journal of Plant Nutrition* 21, 1843–1854.

Barko, J.W., Gunnison, D. and Carpenter, S.R. (1991) Sediment interactions with submerged macrophyte growth and community dynamics. *Aquatic Botany* 41, 41–65.

Bhuiyan, N.I., Saha, P.K., Saleque, M.A. and Nuruzzaman, M. (1992) A new critical level of soil potassium for wetland rice. *Bangladesh Journal of Soil Science* 23, 1–14.

Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E. and Clark, F.E. (1965) *Methods of Soil Analysis. Part 1*. American Society of Agronomy, Madison, Wisconsin.

(BRRI) Bangladesh Rice Research Institute (1987) BRRI Annual Report for 1987.

Chapman, D.D. (1965) Total exchangeable bases. In: Black, C.A. (ed.) *Methods of Soil Analysis, Part 2*. SSSA, Madison, Wisconsin, pp. 902–904.

Darke, A.K. and Megonigal, J.P. (2003) Control of sediment deposition rates in two mid-Atlantic coast tidal fresh water wetlands. *Estuarine, Coastal and Shelf Science* 57, 259–272.

Eckert, D.J. (1987) Soil test interpretations: basic cation saturation ratios and sufficiency levels. In: Brown, J.R. (ed.) *Soil Testing: Sampling, Correlation, Calibration, and Interpretation. SSSA Special Publication No. 21*. SSSA, Madison, Wisconsin, pp. 53–64.

Fairhurst, T.H., Witt, C., Buresh, R.J. and Dobermann, A. (eds) (2007) *Rice: A Practical Guide to Nutrient Management*, 2nd edn. International Plant Nutrition Institute and International Potash Institute. International Rice Research Institute, Metro Manila, 89 pp.

Haby, V.A., Russelle, M.P. and Skogley, E.O. (1990) Testing soils for potassium, calcium, and magnesium. In: Westerman, R.L. (ed.) *Soil Testing and Plant Analysis*, 3rd edn. SSSA Book Ser. 3. SSSA, Madison, Wisconsin, pp. 181–227.

Islam, M.A. (2005) Phosphorus fractions, sorption characteristics and supplying capacity of piedmont plains in north-east Bangladesh. PhD thesis, Soil Science Department, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Salna, Bangladesh.

Islam, M.N., Islam, M.N. and Mowla, G. (1993) Hydrology, irrigation and salinity management in the coastal saline areas of Bangladesh. *Proceedings of the Workshop on Coastal Salinity and Crop Production in Bangladesh*. Bangladesh Rice Research Institute, Gazipur, Bangladesh, pp. 31–42.

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J. and van Reuler, H. (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46, 299–318.

Knudsen, D. and Beegle, D. (1988) Recommended phosphorus tests. In: Dahnke, W.C. (ed.) *Recommended Chemical Soil Test Procedures for the North Central Region. Bulletin No 499 (Revised)*. North Dakota Agricultural Experiment Station, Fargo, North Dakota, pp. 12–15.

Knudsen, D., Peterson, G.A. and Pratt, P.F. (1982) Lithium, sodium and potassium. In: Page, A.L., Miller, R.H. and Keeney, D.H. (eds) *Methods of Soil Analysis. Part 2*, 2nd edn. Agronomy Monograph 9. ASA and SSSA, Madison, Wisconsin, pp. 225–246.

Kopittke, P.M. and Menzies, N.W. (2007) A review of the use of the basic cation saturation ratio and the 'ideal' soil. *Soil Science Society of America Journal* 71, 259–265.

Lin, J. and Kuo, A.K. (2001) Secondary turbidity maximum in a partially mixed macrotidal estuary. *Estuaries* 25, 707–720.

Lindsey, W.L. (1979) *Chemical Equilibria in Soils*. John Wiley & Sons, New York.

McLean, E.O. (1982) Soil pH and lime requirement. In: Page, A.L., Miller, R.H. and Keeney, D.R. (eds) *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, 2nd edn. Agronomy Monograph 9. ASA and SSSA, Madison, Wisconsin, pp. 199–223.

McLean, E.O. (1984) Contrasting concepts in soil test interpretation: sufficiency levels of available nutrients versus basic cation saturation ratios. In: Peck, T.R., Cope, J.T. Jr and Whitney, D.A. (eds) *Soil Testing: Correlating and Interpreting the Analytical Results. ASA Special Publication No 29*. ASA, CSSA and SSSA, Madison, Wisconsin, pp. 39–54.

Nelson, D.W. and Sommers, L.E. (1982) Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H. and Keeney, D.R. (eds) *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, 2nd edn. Agronomy Monograph 9. ASA and SSSA, Madison, Wisconsin, pp. 539–577.

Odum, W.E. (1988) Comparative ecology of tidal freshwater and salt marshes. *Annual Review of Ecological Systems* 19, 147–176.

Panaullah, G. (1993) Soil salinity and associated problems in connection with crop production in the coastal regions of Bangladesh. *Proceedings of the Workshop on Coastal Salinity and Crop Production in Bangladesh*. Bangladesh Rice Research Institute, Gazipur, Bangladesh, pp. 1–30.

Panaullah, G.M., Salam, M.A., Azmal, A.K.M., Karim, S.M.R., Shahidullah, S.M., Bari, M.N. and Choudhury, N.N. (2000) Evaluation of rice germplasms suitable for the coastal saline soils of Bangladesh under fluctuating salinity. IFAD annual report for validation and delivery of new technologies for increasing the productivity of floodprone rice lands of South and South East Asia (tidal saline sub-ecosystem). Bangladesh Rice Research Institute, Gazipur, Bangladesh.

PCARR (Philippines Council for Agriculture and Resources Research) (1978) The Philippines recommends for soil fertility management. Los Baños, Philippines.

Richards, L.A. (1954) *Diagnosis and Improvement of Saline and Alkali Soils*. USDA, Washington, DC.

Saleque, M.A., Saha, P.K., Panaullah, G.M. and Bhuiyan, N.I. (1990) Calibration of soil potassium tests with yield of wet season lowland rice in Bangladesh. *Bangladesh Journal of Soil Science* 21, 1–10.

Saleque, M.A., Choudhury, N.N., Rezaul-Karim, S.M. and Panaullah, G.M. (2005) Mineral nutrition and yield of four rice genotypes in the farmers' fields of salt affected soils. *Journal of Plant Nutrition* 28, 865–875.

Yoshida, S., Forno, D.A., Cock, J.H. and Gomez, K.A. (1976) *Laboratory Manual for Physiological Studies of Rice*, 3rd edn. International Rice Research Institute, Manila, pp. 14–22.

12 Designing Resilient Rice Varieties for Coastal Deltas Using Modern Breeding Tools

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Abstract

Rice production in most areas of coastal deltas is affected adversely by numerous abiotic stresses, including salinity and other soil-related problems, submergence, stagnant flooding and drought. These stresses affect poor farmers disproportionately. We identify sources of tolerance of these abiotic stresses, understand the causal mechanisms and transfer tolerance into popular varieties and elite breeding lines using marker-assisted backcrossing (MABC). This approach also helps in pyramiding multiple QTLs and genes for tolerance. Previously, several salt-tolerance QTLs were identified, including *Saltol*, a major QTL on chromosome 1. Currently, *Saltol* is being introgressed into popular varieties such as IR64, BRRI dhan 28 and BR11. The long-term goal is to identify and combine multiple genes and QTLs controlling different tolerance traits for higher salt tolerance in high yielding rice varieties. Substantial progress in developing submergence-tolerant cultivars was made after cloning *SUB1*, a major QTL for submergence tolerance, and MABC was used successfully to introgress it into six popular varieties within 3 years, shortening the breeding cycle significantly. The *SUB1* locus provided a two- to threefold increase in yield over intolerant varieties under submergence in field trials. Developing varieties combining tolerance for both salinity and submergence is in progress through the introgression of *Saltol* and *SUB1* into popular varieties using MABC. Direct seeding is becoming more important during the dry season in coastal deltas because of its relatively lower cost. However, this approach is hindered by the risk of early flooding. We identified several genotypes with tolerance of flooding during germination, identified major QTLs and transferred tolerance into elite breeding lines. In most coastal areas, water stagnation for 20–50 cm for several months is a serious problem and modern rice varieties are sensitive to such conditions. Reasonable genetic variation in tolerance of stagnant flooding was observed and is being explored. Combining tolerance of abiotic stresses predominant in coastal areas, together with proper management strategies, could contribute substantially to increasing and sustaining rice production in these fragile coastal deltas.

Introduction

Coastal inland zones constitute the interface of land and fresh water with salt water and are characterized by wide variation in soil types, water and land uses. These ecosystems are extremely variable and dynamic, with apparent long-term seasonal changes, and are highly fragile because of the numerous natural hazards, as well as extensive human activities. Despite these uncertainties, coastal areas hold enormous potential for food production through enhanced agriculture and its eventual integration with aquaculture. Yet, these ecosystems are still underexploited in most coastal deltas, despite being overpopulated by mostly resource-poor farming communities, particularly in South and South-east Asia. These areas still remain the preferred sites of human settlements, which also render them more prone to conflicts between local resource users, leading to serious environmental and social problems as competition for land and sea resources rises, along with the ensuing further degradation of existing resources. Our present knowledge of the challenges facing these important ecosystems is still inadequate to formulate proper management strategies and policies and more efforts are needed both nationally and regionally.

Coastal areas generally have high population densities coupled with higher levels of poverty than most other ecosystems. For example, in Bangladesh and Vietnam, the national poverty levels are about 40 and 23%, whereas the corresponding levels in coastal areas are 49 and 40%, respectively. These challenges, together with poor infrastructure and development, create high pressure on existing natural resources. The diverse livelihood sources in coastal deltas are dominated generally by agriculture, followed by aquaculture/fisheries activities and open-access resources such as open-water fishing and employment.

Constraints to Rice Production in Coastal Deltas

Agricultural activities in coastal areas are dominated by rice farming during the wet season because of the persistent flooding or waterlogged conditions caused by monsoon rains that make it difficult to grow upland crops. However, most coastal areas are affected by high salt concentration in both soil and water, thus reducing rice production. The situation is even worse during the dry season due to drought, high salt intrusion and lack of freshwater resources. Furthermore, some coastal deltas also endure other soil problems such as high organic matter (peat soils), high acidity (acid sulfate soils), or nutritional problems such as iron and aluminum toxicities and P and Zn deficiencies (Ismail *et al*., 2007). During the wet season, excess water stress causes serious reductions in rice yields, despite the rice's tolerance of flooded soil conditions. This is because, in most of these areas, water stagnates to a higher level and for longer duration and, in some cases, the crop is completely inundated for variable periods. Both partial and complete flooding can affect grain yield negatively. The coexistence and severity of some of these problems in some parts of coastal deltas and the rapid environmental and social changes occurring in these areas (Gowing *et al*., 2006) often render them less productive.

Salt stress

About 27 million ha were reported as being affected to some extent by salt stress in the coastal areas of South and South-east Asia. Of this area, about 3.1 million ha were in India, 2.8 million ha in Bangladesh and 2.1 million ha in Vietnam (Ponnamperuma and Bandyopadhyay, 1980; Karim *et al*., 1990). These saline areas occur mainly in deltas, fringes, lagoons, coastal marshes and narrow coastal plains or terraces along the creeks. Salinity in these areas could be inherent, caused during the process of soil formation, or most commonly because of marine influences and subsequent periodical floods with tidal salt water. It can result from frequent inundation of land during high tides and ingress of seawater through drains, creeks and rivers, particularly during the dry season. The water table is normally shallow and, during dry periods, salt water moves to the soil surface through capillary rise and then evaporates, leaving the salt in the surface soil to accumulate to toxic amounts. Secondary salinization can also take place in coastal areas where poor-quality water is being used for irrigation during the dry season, coupled with high evaporative demands and improper drainage. A good example of this is the use of shallow tube wells for irrigating dry-season rice in Bangladesh, India and Thailand.

Salinity in coastal deltas is also more dynamic and varies with the season, being very high during the dry season, with the peak around May. Salinity in soil and water then decreases progressively with the onset of the monsoon rains from June to September, to reach levels close to normal conditions later in the season (Mondal *et al*., 2006; Singh *et al*., Chapter 19, this volume). The dynamic nature of this problem in coastal areas makes it difficult to handle through management without extensive investment. At the field level, a combination of germplasm improvement together with affordable management practices seems more feasible.

Rice is salt-sensitive (Maas and Hoffman, 1977), yet it is often grown in areas where saline soils prevail because it can grow well under flooded conditions that promote leaching of salts. Rice is sensitive to salinity at the seedling stage (Yeo *et al.*, 1990), becomes tolerant at the vegetative phase and again becomes very susceptible at the reproductive phase, which reduces grain yield greatly (Bhattacharya, 1981). Akbar *et al.* (1972) report that the most sensitive growth stages in rice occur during emergence and young seedling stage, as measured by seedling death and reduced growth rates, and during flowering, resulting in pollen sterility; however, tolerances at these two stages are only weakly associated (Moradi *et al.*, 2003).

Substantial progress has been made in understanding the physiology and genetics of tolerance of salinity in rice; however, this tolerance is complex and involves several mechanisms. Several traits contribute to tolerance during the early vegetative stage, including salt exclusion and control of ion homeostasis, higher tissue tolerance by compartmenting salt into vacuoles, responsive stomata that close faster on exposure to salt stress, upregulation of antioxidant systems for protection against reactive oxygen species generated during stress and vigorous growth to dilute salt concentration in plant tissue (Yeo and Flowers, 1986; Ismail *et al.*, 2007; Moradi and Ismail, 2007). During the reproductive stage, tolerant genotypes tend to exclude salt from flag leaves and developing panicles (Yeo and Flowers, 1986; Moradi *et al.*, 2003). Early-maturing varieties are useful in areas where salt stress is associated with terminal drought or lack of freshwater resources at the end of the season.

Although the extensive genetic variability reported in rice in response to salinity suggests that it is amenable to genetic manipulation, the complexity of the numerous traits involved in tolerance and the coexistence of multiple stresses slowed previous breeding efforts (Akbar *et al.*, 1972; Flowers and Yeo, 1981; Gregorio *et al.*, 2002). However, the fact that none of the known tolerant cultivars are superior in more than one or a few of these traits suggests considerable potential for further improvement in tolerance if superior alleles for all useful mechanisms could be combined. The recent advances in understanding the physiological and molecular bases of tolerance are providing better tools to overcome these obstacles and can enhance progress substantially by enabling more precise genetic manipulation and pyramiding of component traits.

Other soil problems

Besides salinity, soils in coastal areas also vary substantially in both chemical and physical characteristics. They also vary from being neutral to extremely acidic, as with acid sulfate and pyrite soils in coastal Vietnam and Indonesia. These soils develop as a result of the drainage of parent material rich in pyrite (FeS_2). The low pH (< 4) of these soils results from the oxidation of sulfur- and iron-containing compounds producing high acids through numerous processes (Dent, 1986). These soils also contain high Al and Fe released through reactions of these acids with clay minerals. Recently, some potential acid sulfate soils have developed into actual acid sulfate soils due to human activities that enhance the generation of acidity and its spread through drainage (Gowing *et al.*, 2006). Rice varieties tolerant of high acidity are needed to withstand such conditions and to replace the low-yielding, moderately tolerant landraces currently being used by farmers. Through shuttle-breeding research, a few rice lines have been developed, such as AS996 released in Vietnam (Lang *et al.*, Chapter 16). Coastal soils also differ in their organic matter content, from being extremely deficient, as in some sandy soils, to highly organic, as in the case of peat soils in South Kalimantan, Indonesia. Nutrient contents also fluctuate dramatically from being deficient (P, Zn, K) to toxic when the concentration is too high, as in the case of aluminum and iron in acid sulfate soils. These extreme conditions cause instability and reduce the productivity of these soils and, in some cases, hinder their agricultural use, particularly during the dry season, when these problems are aggravated further by drought and a lack of freshwater resources.

Excess water stress

Coastal deltas in humid tropical areas usually experience different amounts and types of excess water stress caused by various factors: (i) direct heavy rains during the monsoon season, particularly from June to September; (ii) rain in upper catchments during the wet season raises the water level in rivers and their tributaries; and (iii) during high tides when the high-density salt water pushes fresh water to rise to levels that cause transient floods. These conditions, coupled with poor or non-existing drainage facilities, create serious problems for rice and other crops, such as waterlogging, stagnant flooding with partial submergence of 20–60 cm for most of the season and, in severe cases, complete submergence for varying durations during the growing season. Various tolerance traits or mechanisms are necessary for high and stable productivity in these areas, including tolerance during germination and emergence in areas where direct seeding is practised, tolerance of repeated flash floods during the vegetative stage coupled with faster recovery and tolerance of long-term partial flooding (Table 12.1).

Direct seeding is being adopted increasingly in rainfed lowlands, including coastal zones, because of the high labour cost of transplanting, but submergence after sowing reduces stand establishment substantially because of the high sensitivity of rice to anaerobic conditions during germination. After screening a large set of diverse germplasm from different sources, we identified several lines with substantial tolerance of flooding during germination. These lines provide a platform for further studies and for breeding. We also developed a few populations to identify genetic determinants and mechanisms of tolerance to facilitate incorporating this important trait through breeding (Angaji *et al*., 2010; Ismail *et al*., 2009). Heavy rains or early floods likely to occur during July also pose serious problems for transplanted rice in these areas, and early crop establishment through direct seeding may help avoid further damage just after transplanting.

Complete submergence can occur any time during the season and for variable durations, and no modern high-yielding rice varieties can tolerate complete submergence or flash floods for more than a few days. However, a few tolerant landraces have been identified that can withstand inundation for up to 2 weeks. The effects of flooding on rice, as well as the physiological basis of tolerance, have been reviewed recently (Ram *et al*., 2002; Jackson and Ram, 2003; Sarkar *et al*., 2006). Plant survival in flooded areas depends on various aspects of floodwater environments,

Table 12.1. Types of flooding stress experienced in rainfed coastal and inland areas and traits required for tolerance in rice.

Flood type	Required tolerance traits
Early: at crop establishment	Tolerance during germination and early seedling growth Tolerance of delayed transplanting
Flash flooding for short duration (< 2 weeks)	Submergence tolerance (*Sub1* type)[a]
Flash flooding for longer duration (> 2 weeks)	Submergence tolerance greater than that conferred by *Sub 1* alone Better regeneration ability
Stagnant flooding (20–50 cm for most of the season)	Facultative but slow elongation Tolerance of water stagnation
Deep water (more than 50 cm for most of the season)	Elongation ability to escape complete submergence

[a]*Sub1* locus confers tolerance of complete submergence for up to 2 weeks.

particularly the limitation of gas diffusion, irradiance level and water temperature. Among the important plant traits associated with tolerance are the ability to maintain high, non-structural carbohydrate contents before and following submergence, slower underwater shoot extension, optimum alcohol fermentation under hypoxia, an efficient antioxidant protective system on exposure to high light intensity and high chlorophyll retention (Setter *et al*., 1997; Ram *et al*., 2002; Ella *et al*., 2003; Jackson and Ram, 2003; Sarkar *et al*., 2006). Carbohydrates remaining after submergence are necessary for faster recovery and correlate better with survival than carbohydrates before submergence (Das *et al*., 2005). A rapid regeneration following submergence is essential under frequent or prolonged flooding, as this can ensure early recovery and the production of sufficient biomass for high yield. Rice plants that exhibit only limited elongation during submergence are more tolerant of complete flooding and a strong association between limited underwater shoot growth and survival has been reported before (Jackson and Ram, 2003; Das *et al*., 2005).

Prolonged partial flooding affects rice severely during the wet season in coastal areas, affecting about 3 million ha annually in coastal India and more than 1 million ha in coastal Bangladesh. Modern rice varieties are not adapted to these conditions and their yield is severely reduced because of high mortality, lower tillering, reduced panicle size and high sterility. In a recent study, we compared the performance of a large set of diverse rice germplasm under control and partially flooded conditions in an effort to identify genotypes with reasonable tolerance. Only one-third of the accessions tested showed high survival and produced filled grains when partially flooded with a water depth of about 50–60 cm through maturity. To our surprise, most of the modern varieties showed high mortality, low tillering ability and poor yield under these partial flood conditions (Table 12.2). Apparently,

Table 12.2. Performance of diverse rice genotypes under stagnant flooding (SF) during the dry season of 2007 at IRRI. Percentage tiller reduction and yield loss compared with non-flooded conditions and simple correlation coefficients between measured traits.

	Stagnant flood (SF)[a]				
Entry	Survival (%)	Spikelet fertility (%)	Yield (t/ha)	Tiller reduction (%)	Yield loss (%)
Niaw San Pahtawng	100	14.7	0.8	44.4	81.5
IR69513-11-SR-1-UB-2-b-2-1-1	100	32.2	0.6	26.9	60.0
IR82812-7-4-3	100	14.5	0.5	36.0	93.7
Tepi Borua	90.9	34.9	0.8	33.3	8.3
IR70181-70-PMI 3-5-B-2	90.9	52.6	0.5	51.3	53.8
Pokkali/13-001	86.7	38.4	0.7	65.6	79.6
Pusa RH10	75.5	45.9	1.0	65.4	82.1
IR72862-27-3-2-3	70	46.2	1.9	65.6	38.4
IR82812-7-4-4	50	18.5	0.5	38.5	92.3
S. Mahsuri + SUB1	43.8	36.7	0.9	60.0	78.0
PTB39	40	37.3	0.3	77.8	77.5
IR81159-45-2-3-2	37.5	32.3	0.4	71.4	94.6
ADT31	33.3	60.7	0.2	75.0	71.5
IR42 (intolerant)	22.2	24.9	0.2	78.1	94.1
BESEWAR 013	7.7	82.0	0.08	77.8	74.1
F-values	4.46**	5.02**			
Simple correlation coefficients					
Survival under SF (%)			0.44	–0.76	
Spikelet fertility under SF				0.53	0.31

[a]SF was for > 100 days, starting at 30 days after transplanting, with 30-cm water level, which was increased gradually by 5 cm weekly and maintained at 60-cm depth. ***F*-values were significantly different at $P < 0.05$; SF data were from means of three replications.

high-yielding modern rice varieties cannot tolerate stagnant flooding for a long time and this is probably one of the main reasons why these varieties are not widely adopted in coastal areas and farmers continue to use their local low-yielding landraces. Our understanding of the basis of tolerance of these conditions is still inadequate; however, preliminary data showed that tillering ability under these conditions correlated highly with plant survival but was not related directly to spikelet fertility. For accessions that survived prolonged partial flooding, correlation coefficients between survival and yield were also low (Table 12.2). Our recent efforts focus on screening large numbers of rice accessions to identify highly tolerant genotypes for use in breeding and for further studies, and to discover important traits associated with tolerance. Breeding efforts for improving productivity in coastal areas must therefore consider the incorporation of tolerance of flooding during early crop establishment and the vegetative stage, as well as tolerance of partial long-term stagnant flooding, to develop varieties with broader adaptation.

Natural hazards

Some coastal deltas also face a wide range of natural hazards, from hurricanes and severe storms to floods and landslides, earthquakes and tsunamis, shoreline erosion and land subsidence. Hurricanes and typhoons are probably the most frequent disasters, particularly in the rice-growing coastal areas of South and Southeast Asia. Examples are the devastating 'super cyclone' that passed through Orissa, India, in October 1999, seriously affecting more than 15 million people, and the catastrophic cyclones that periodically hit coastal Bangladesh, as in April 1991, which led to the loss of about 138,000 lives. More recent calamities are the Sidr cyclone in November 2007 in southern Bangladesh and the Nargis cyclone in the Ayeyarwaddy Delta of Myanmar on 2–3 May 2008, which resulted in the loss of thousands of lives and severe loss to agriculture and other resources. Earthquakes and tsunamis are additional extremely dangerous natural hazards that threaten these areas. The 2004 Indian Ocean earthquake and tsunami increased international awareness of their devastating and disastrous nature. This earthquake triggered a series of lethal tsunamis that killed approximately 275,000 people, displaced more than 1 million and caused billions of dollars of property and infrastructural damage. These natural hazards, together with more frequent tribulations such as salinity, flooding and drought incidence, are projected to be more devastating with the alarming global warming and the consequent rise in sea level and increase in storm incidences in coastal areas (Peltier and Tushingham, 1989; Pessarakli and Szabolcs, 1999; Wassmann *et al*., 2004). Developing resilient rice varieties with better tolerance of the stresses provoked by these calamities will help mitigate their effects on the livelihoods and food security of the local people. In addition, strategies that capitalize on less vulnerable possibilities and time windows, such as dry-season farming and fisheries, should be exploited amply.

Agricultural production, particularly rice farming in coastal deltas, therefore faces an intricate array of abiotic stresses that vary substantially in intensity with time and location, causing erratic and uncertain situations. Currently, most of these coastal deltas are monocropped with rice during the monsoon season. Local rice varieties have moderate tolerance of these conditions, but their productivity is generally low. We target germplasm enhancement through the incorporation of tolerances of these complex stresses as an entry point for improvement and sustainability of productivity in these areas. This is because the development of high-yielding tolerant varieties can increase productivity substantially and, in most cases, double the yield, as in the case of salinity (Gregorio *et al*., 2002) and submergence (Sarkar *et al*., 2006; Xu *et al*., 2006; Neeraja *et al*., 2007; Septiningsih *et al*., 2009; Singh *et al*., 2009). In addition, these varieties will not have increased costs to farmers and, in most cases, they will provide more incentives to invest in inputs because of their better responsiveness and the assured returns. However, because these challenges vary widely in intensity and complexity and with location, suitable interventions often need to be site-specific.

The pressing need to combine tolerances of multiple abiotic stresses and the complexity of the traits involved in tolerance of each of these stresses (Jackson and Ram, 2003; Lafitte *et al.*, 2006; Ismail *et al.*, 2007) dictate the need for using innovative tools and breeding methods in addition to the current conventional strategies. This will help to incorporate adaptive traits associated with multiple stress tolerance while simultaneously retaining the high yield potential of existing popular rice varieties. Opportunely, tolerance of most of these stresses is controlled by a few quantitative trait loci (QTLs) with large effects. Incorporation of these QTLs into high-yielding varieties could help stabilize their yields significantly in stress-prone areas (Mackill, 2006). Current efforts at IRRI attempt to explore diverse germplasm collections and genetically dissect the causal mechanisms of tolerance to facilitate their use in breeding. We now focus on salinity and submergence as the major challenges in coastal areas. For more details, readers are referred to recent reviews that cover current developments on the physiological and molecular bases of tolerance of these abiotic stresses (Jackson and Ram, 2003; Bohnert *et al.*, 2006; Ismail *et al.*, 2007; Vij and Tyagi, 2007).

Modern Breeding Tools for Developing Rice Varieties Adapted to Coastal Areas

Genetic markers and marker-assisted breeding

Conventional breeding for abiotic stress tolerance has had modest success in developing tolerant varieties, but progress has been slow (Mackill *et al.*, 1993; Gregorio *et al.*, 2002, Senadhira *et al.*, 2002). A major obstacle is the negative linkage drag from the stress-tolerant landraces being used as donors, which usually have poor agronomic performance and several undesirable traits. Modern breeding tools promise to speed up the breeding process by eliminating unwanted background rapidly from the donor parent using marker-assisted backcrossing (MABC). Furthermore, pyramiding multiple stress-tolerance traits into a single variety using conventional breeding is a difficult task because of the time and resources involved to screen large populations for different traits, multiple donor introgressions at each target locus and the large number of backcrosses to the recurrent parent. After identifying major QTLs for tolerance, MABC can be used to combine multiple QTLs to achieve higher tolerance and reduce the size of each background introgression. It is important to identify QTLs with large effects that are stable across different environments so that the subsequent MABC to transfer these QTLs into popular varieties will be effective. We aim to identify major QTLs associated with the traits underlying tolerance of each of these abiotic stresses and to develop an effective MABC system to combine them into popular varieties and elite breeding lines.

Progress in mapping tolerance of salt stress

Several mapping studies identified QTLs associated with salinity tolerance in rice. For example, a study employing the tolerant indica landrace Nona Bokra with the sensitive japonica Koshihikari identified several large-effect QTLs, including the *SKC1* QTL on chromosome 1 and a QTL for shoot Na^+ concentration on chromosome 7 (Lin *et al.*, 2004). Similarly, a major QTL, named *Saltol*, was mapped on rice chromosome 1 using a recombinant inbred line (RIL) population between tolerant Pokkali and sensitive IR29 (Bonilla *et al.*, 2002). This QTL is involved in ion uptake regulation and it explains about 43% of the variation for seedling shoot Na^+/K^+ ratio. Near-isogenic lines have been developed for the *Saltol* region and the locus is currently being fine-mapped and annotated for further candidate gene analysis (Fig. 12.1a). Other QTLs were identified on chromosomes 3, 4, 10 and 12 for salinity tolerance at the seedling stage. Genetic stocks of RILs and backcross populations were developed at IRRI to allow further analysis of these QTLs to evaluate their usefulness for breeding varieties with improved tolerance. A precise MABC strategy employing foreground markers to select for the locus of interest and nearby recombinants on each side of the target QTL and background markers to select against unwanted introgressions was accomplished with the *SUB1* QTL for

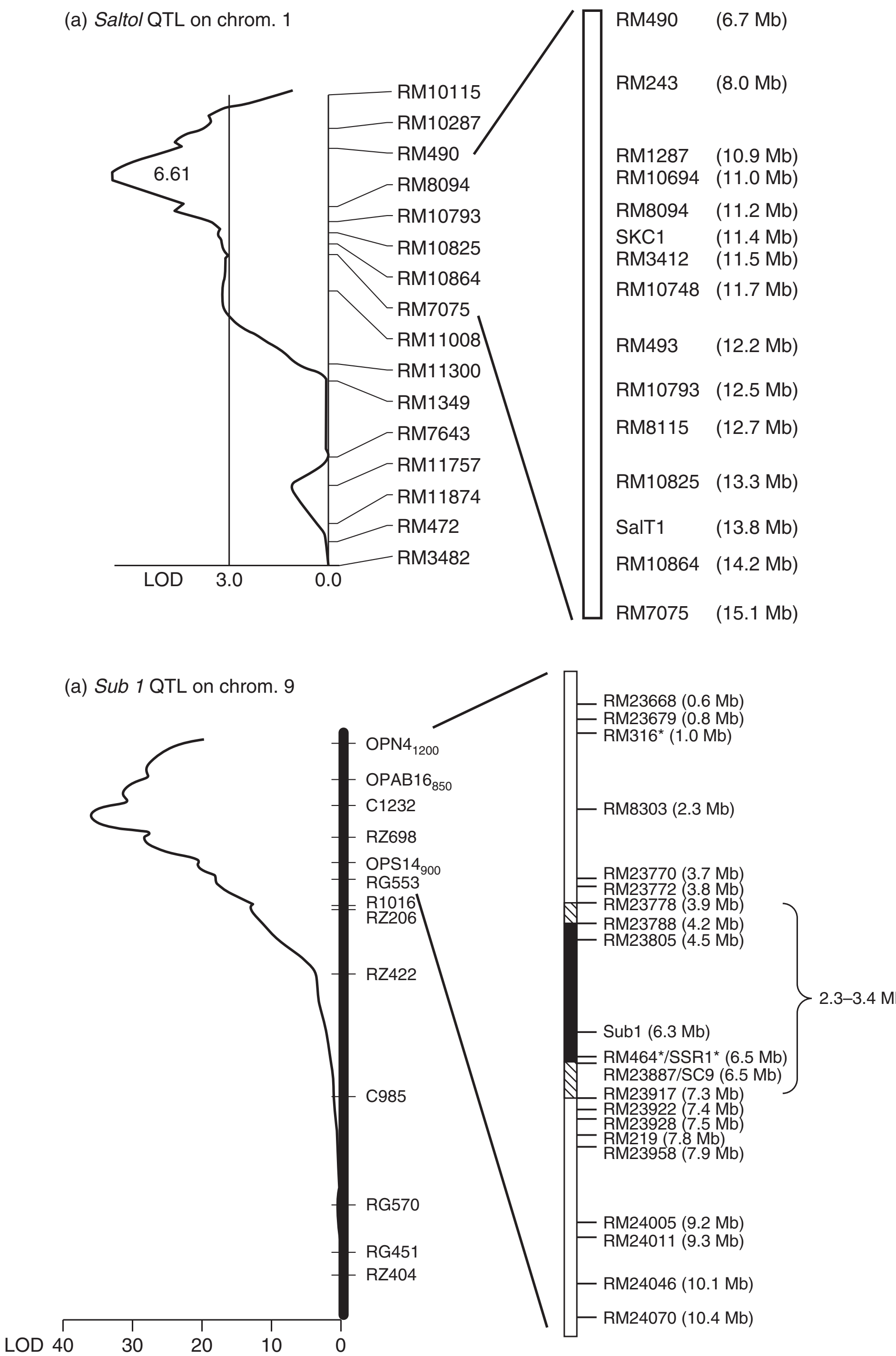

Fig. 12.1. QTL position of (a) *Saltol* (unpublished data), and (b) *Sub1* (data from Neeraja *et al.*, 2007) showing the markers and physical map of each region. FR13A introgression in the *Sub1* region is shown as a black box. Marker-assisted backcrossing for introgressing *Saltol* QTL into a few popular varieties is ongoing.

submergence tolerance (Xu *et al.*, 2006). This approach is currently being used to incorporate the Pokkali *Saltol* allele into popular varieties sensitive to salt stress and these varieties will be useful for coastal areas.

Diverse sets of rice germplasm are also being characterized to identify novel sources of salinity tolerance and potentially novel QTLs that can be incorporated into the MABC breeding programme. A set of 53 landraces and nine modern varieties from Bangladesh and ten check varieties from other countries were screened at the seedling stage to characterize them physiologically for the basis of salt tolerance. Based on measurements of overall phenotypic performance, Na^+ and K^+ concentration in leaves, plant vigour and chlorophyll concentration, several landraces from Bangladesh were identified as being highly tolerant and excellent Na^+ excluders (e.g. Akundi, Ashfol, Capsule, Jatai Balam, Kalarata and Kuti Patnai). To begin testing these sources for novel QTLs, an F_2 mapping population between Capsule and BR29 is being studied. In addition, eight accessions of Pokkali were screened for tolerance and genotyped with SSR markers to analyse the genetic relationships between the different Pokkali landraces. Significant genetic and phenotypic variations were detected, revealing the extensive diversity across the different Pokkali accessions. This information is important as Pokkali has been used extensively in breeding for salt tolerance. Furthermore, mapping populations are being developed to identify QTLs associated with tolerance during the reproductive stage, ultimately to combine tolerance at both stages for more resilient varieties as our previous studies indicated weak association between tolerances at these two sensitive stages (Moradi *et al.*, 2003). After identifying a number of QTLs controlling different mechanisms and providing tolerance at different stages, MABC can be used to develop rice varieties adapted to the specific conditions of the targeted coastal environments.

Progress in mapping tolerance of submergence

Tolerance of flooding during germination has been identified in rice germplasm (Yamauchi *et al.*, 1993) and a few small QTLs have been mapped (Ling *et al.*, 2004). Recently, we have identified new lines with higher tolerance of anaerobic conditions during germination and these lines are being used to study the mechanisms of tolerance (Ismail *et al.*, 2009) and to transfer tolerance into new breeding lines through backcrossing. Breeding for tolerance of flooding during germination began at IRRI in 2003, using Khaiyan, Khao Hlan On and Mazhan red as donors for this trait, and crosses were made with several mega-varieties adapted to both rainfed and irrigated ecosystems (Pamplona *et al.*, 2006). Advanced backcross populations (BC_2F_2 or BC_3F_2) have been developed and used for mapping QTLs associated with tolerance, and four QTLs with reasonably large effects have been identified and are being further fine-mapped (Angaji *et al.*, 2010). We are attempting to identify QTL- or gene-specific markers linked to these QTLs that can be used to accelerate their incorporation into breeding lines and varieties through MABC.

Over the past few decades, plant breeders have been attempting to develop rice varieties tolerant of complete submergence, but with limited progress. Some tolerant varieties have been released for cultivation, but these varieties have not been adopted on a large scale because of their low yields, poor grain quality, or other undesirable features that have made them unacceptable to farmers. Most of these difficulties have been overcome recently with the discovery and cloning of *SUB1*, a major QTL associated with submergence tolerance (Xu and Mackill, 1996; Xu *et al.*, 2006). An MABC approach has subsequently been developed and used to incorporate *SUB1* into numerous popular rice varieties (Fig. 12.1b; Neeraja *et al.*, 2007; Septiningsih *et al.*, 2009). The advantage of the *SUB1* locus has been assessed in field experiments demonstrating a two- to threefold yield increase (1–3.8 t/ha yield advantage) over intolerant varieties under submergence (Sarkar *et al.*, 2006; Singh *et al.*, 2009). The *SUB1* gene provides a marked improvement in submergence tolerance in all genetic backgrounds and environments tested so far. Yet, the level of tolerance is still below that of the original donor variety, FR13A. There is a need to identify and transfer additional genes from FR13A and probably additional donors, including those that confer rapid recovery after submergence, into improved lines along with *SUB1*. Varieties that combine tolerance of submergence during germination and the vegetative stage together with tolerance of partial long-term stagnant flooding would have a major advantage for achieving higher and more stable yield in coastal areas. Molecular markers specific to *SUB1* and to QTLs associated with tolerance of anaerobic conditions during germination are now being used to select new lines combining both traits.

Combining Adaptive Traits for Coastal Ecosystems: Challenges and Prospects

Conventional breeding has long been employed to develop new rice varieties combining tolerance of a particular stress with other adaptive and desirable agronomic traits; however, progress has been slow, particularly when tolerance of multiple stresses is required, as in the case of coastal areas. Opportunities to combine adaptive complex traits has recently become feasible with the progress made in developing molecular tools and information on the use of DNA markers in breeding. These new tools allow genome-based selection even without the necessity of knowing the genes involved. This approach proves effective in enhancing breeding efficiency by eliminating linkage drag and shortening the breeding cycle, as in the case of the *SUB1* gene (Neeraja *et al*., 2007; Septiningsih *et al*., 2009). Good progress has been made at IRRI in fine-mapping relatively large QTLs associated with tolerance of most abiotic stresses prevalent in coastal areas, such as salinity, flooding and P deficiency. Ultimately, the challenge of breeding resilient rice varieties for the high-stress environments of the coastal deltas can be met through combining these tolerance QTLs for multiple stresses into high-yielding varieties, building on the progress made so far. Subsequent steps will involve pyramiding these QTLs while retaining the adaptive features, high yield and excellent grain quality of the recurrent parents.

The tolerance provided by the QTLs now being targeted is mostly below that of the original donor landraces. Our current efforts aim to identify new sources of tolerance or target other important QTLs with additive effects. New donors are being identified for important stresses such as stagnant flooding. The use of MABC to pyramid these QTLs into suitable genetic backgrounds of varieties and breeding lines adaptive to coastal areas will help in accelerating the deployment and adoption of the new varieties. This will have an enormous impact on enhancing and stabilizing productivity in these coastal areas. The major current limitation to this approach is the relatively large resources needed during the development and use of an MABC system to combine these multiple traits.

Conclusions

The great investment in time and resources in developing molecular techniques for rice improvement is now beginning to pay off. The foundation has been laid for a new generation of high-yielding, stress-tolerant rice varieties that can be combined with proper natural resource management strategies to increase and stabilize production in unfavourable coastal areas. These varieties will also provide more options for farmers, in some cases, to intensify production under certain conditions, which will allow greater flexibility to diversify cropping patterns. With the increasing threat of environmental degradation and weather extremes caused by global climate change, there is no better time to redouble our efforts to develop improved rice varieties for such marginal environments, with the goal of reducing poverty, sustaining the food supply and enhancing the livelihoods of rice farmers living in these coastal delta regions.

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References

Akbar, M., Yabuno, T. and Nakao, S. (1972) Breeding for saline resistant varieties of rice. I. Variability for salt tolerance among some rice varieties. *Japanese Journal of Breeding* 22, 277–284.

Angaji, S.A., Septiningsih, E., Mackill, D.J. and Ismail, A.M. (2010) Identification of QTLs associated with tolerance to anaerobic conditions during germination in rice (*Oryza sativa* L.). *Euphytica* DOI 10.1007/s10681-009-0014-5.

Bhattacharya, R.K. (1981) Interaction between grain yield and some quantitative characters in rice adapted to saline soils. *Oryza* 18, 147–149.

Bohnert, H.J., Gong, Q., Li, P. and Ma, S. (2006) Unravelling abiotic stress tolerance mechanisms – getting genomics going. *Current Opinion in Plant Biology* 9, 180–188.

Bonilla, P., Dvorak, J., Mackill, D., Deal, K. and Gregorio, G. (2002) RLFP and SSLP mapping of salinity tolerance genes in chromosome 1 of rice (*Oryza sativa* L.) using recombinant inbred lines. *Philippine Agricultural Science* 85, 68–76.

Das, K.K., Sarkar, R.K. and Ismail, A.M. (2005) Elongation ability and non-structural carbohydrate levels in relation to submergence tolerance in rice. *Plant Science* 168, 131–136.

Dent, D. (1986) Acid sulfate soils: a baseline for research and development. Publication No 39. ILRI, Wageningen, the Netherlands, 204 pp.

Ella, E., Kawano, N., Yamauchi, Y., Tanaka, K. and Ismail, A.M. (2003) Blocking ethylene perception enhances flooding tolerance in rice seedlings. *Functional Plant Biology* 30, 813–819.

Flowers, T.J. and Yeo, A.R. (1981) Variability in the resistance of sodium chloride salinity within rice (*Oryza sativa* L.) varieties. *New Phytologist* 88, 363–373.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Kheim, N.T. (2006) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 48–60.

Gregorio, G.B., Senadhira, D., Mendoza, R.D., Manigbas, N.L., Roxas, J.P. and Guerta, C.Q. (2002) Progress in breeding for salinity tolerance and associated abiotic stresses in rice. *Field Crops Research* 76, 91–101.

Ismail, A.M., Heuer, S., Thomson, M.J. and Wissuwa, M. (2007) Genetic and genomic approaches to develop rice germplasm for problem soils. *Plant Molecular Biology* 65, 547–570.

Ismail, A.M., Ella, E.S., Vergara, G.V. and Mackill, D.J. (2009) Mechanisms associated with tolerance to flooding during germination and early seedling growth in rice (*Oryza sativa*). *Annals of Botany* 103, 197–209.

Jackson, M.B. and Ram, P.C. (2003) Physiological and molecular basis of susceptibility and tolerance of rice plants to complete submergence. *Annals of Botany* 91, 227–241.

Karim, Z.S., Hussain, G. and Ahmed, M. (1990) Salinity problems and crop intensification in the coastal region of Bangladesh. Soil Publication No 33. Soil and Irrigation Divisions, BARC, Dhaka.

Lafitte, R.H., Ismail, A.M. and Bennett, J. (2006) Abiotic stress tolerance in tropical rice: progress and the future. *Oryza* 43, 171–186.

Lin, H.X., Zhu, M.Z., Yano, M., Gao, J.P., Liang, Z.W., Su, W.A., Hu, X.H., Ren, Z.H. and Chao, D.Y. (2004) QTLs for Na^+ and K^+ uptake of the shoots and roots controlling rice salt tolerance. *Theoretical and Applied Genetics* 108, 253–260.

Ling, J., Ming-yu, H., Chun-ming, W. and Jian-min, W. (2004) Quantitative trait loci and epistatic analysis of seed anoxia germinability in rice (*Oryza sativa*). *Rice Science* 11, 238–244.

Maas, E. and Hoffman, G. (1977) Crop salt tolerance: current assessment. *Journal of Irrigation and Drainage Engineering* 103, 115–134.

Mackill, D.J. (2006) Breeding for resistance to abiotic stresses in rice: the value of quantitative trait loci. In: Lamkey, K.R. and Lee, M. (eds) *Plant Breeding*: The Arnel R. Hallauer International Symposium. Blackwell Publishing, Ames, Iowa, pp. 201–212.

Mackill, D.J., Amante, M.M., Vergaram, B.S. and Sarkarung, S. (1993) Improved semi-dwarf rice lines with tolerance to submergence of seedlings. *Crop Science* 33, 749–753.

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudhury, M.H.K., Chasi, A.M., Majumder, P.K., Islam, M.M. and Adhikary, S.K. (2006) Coastal water resources use or higher productivity: participatory research for increasing cropping intensity in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 72–85.

Moradi, F. and Ismail, A.M. (2007) Responses of photosynthesis, chlorophyll fluorescence and ROS scavenging system to salt stress during seedling and reproductive stages in rice. *Annals of Botany* 99, 1161–1173.

Moradi, F., Ismail, A.M., Gregorio, G.B. and Egdane, J.A. (2003) Salinity tolerance of rice during reproductive development and association with tolerance at the seedling stage. *Indian Journal of Plant Physiology* 8, 105–116.

Neeraja, C.N., Maghirang-Rodriguez, R., Pamplona, A., Heuer, S., Collard, B.C.Y., Septiningsih, E.M., Vergara, G., Sanchez, D., Xu, K., Ismail, A.M. and Mackill, D.J. (2007) A marker-assisted backcross approach for developing submergence-tolerant rice cultivars. *Theoretical and Applied Genetics* 115, 767–776.

Pamplona, A., Septiningsih, E., Sanchez, D., Ella, E., Vergara, G.V., Ismail, A.M. and Mackill, D.J. (2006) Breeding rice with tolerance to submergence during germination for irrigated and rainfed areas. *Abstracts of Papers, 2nd International Rice Congress*, 9–13 October 2006, New Delhi, India, p. 251.

Peltier, W.R. and Tushingham, A.M. (1989) Global sea level rise and the greenhouse effect: might they be connected? *Science* 244, 806–810.

Pessarakli, M. and Szabolcs, I. (1999) Soil salinity and sodicity as particular plant/crop stress factors. In: Pessarakli, M. (ed.) *Handbook of Plant and Crop Stress*. Dekker, New York, pp. 1–16.

Ponnamperuma, F.N. and Bandyopadhyay, A.K. (1980) Soil salinity as a constraint on food production in the humid tropics. In: *Priorities for Alleviating Soil-Related Constraints to Food Production in the Tropics*. IRRI, Los Baños, Philippines, pp. 203–216.

Ram, P.C., Singh, B.B., Singh, A.K., Ram, P., Singh, P.N., Singh, H.P., Boamfa, E.I., Harren, F.J.M., Santosa, E. and Jackson, M.B. (2002) Submergence tolerance in rainfed lowland rice: physiological basis and prospects for cultivar improvement through marker-aided breeding. *Field Crops Research* 76, 131–152.

Sarkar, R., Reddy, J.N., Sharma, S.G. and Ismail, A.M. (2006) Physiological basis of submergence tolerance in rice and implications for crop improvement. *Current Science* 91, 899–906.

Senadhira, D., Zapata-Arias, F.J., Gregorio, G.B., Alejar, M.S., Cruz, H.C. de la, Padolina, T.F. and Galvez, A.M. (2002) Development of the first salt-tolerant rice cultivar through *indica/indica* anther culture. *Field Crops Research* 76, 103–110.

Septiningsih, E.M., Pamplona, A.M., Sanchez, D.L., Maghirang-Rodriguez, R., Neeraja, C.N., Vergara, G.V., Heuer, S., Ismail, A.M. and Mackill, D.J. (2009) Development of submergence-tolerant rice cultivars: the *Sub1* gene and beyond. *Annals of Botany* 103, 151–160.

Setter, T.L., Ellis, M., Laureles, E.V., Ella, E.S., Senadhira, D., Mishra, S.B., Sarkarung, S. and Datta, S. (1997) Physiology and genetics of submergence tolerance in rice. *Annals of Botany* 79, 67–77.

Singh, S., Mackill, D.J. and Ismail, A.M. (2009) Responses of *SUB1* rice introgression lines to submergence in the field: yield and grain quality. *Field Crops Research* 113, 12–23.

Vij, S. and Tyagi, A.K. (2007) Emerging trends in the functional genomics of the abiotic stress response in crop plants. *Plant Biotechnology Journal* 5, 361–380.

Wassmann, R., Hien, N.X., Hoan, C.T. and Tuong, T.P. (2004) Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. *Climate Change* 66, 89–107.

Xu, K. and Mackill, D.J. (1996) A major locus for submergence tolerance mapped on rice chromosome 9. *Molecular Breeding* 2, 219–224.

Xu, K., Xu, X., Fukao, T., Canlas, P., Maghirang-Rodriguez, R., Heuer, S., Ismail, A.M., Bailey-Serres, J., Ronald, R.C. and Mackill, D.J. (2006) *Sub1A* is an ethylene-response-factor-like gene that confers submergence tolerance to rice. *Nature* 442, 705–708.

Yamauchi, M., Aguilar, A.M., Vaughan, D.A. and Seshu, D.V. (1993) Rice (*Oryza sativa* L.) germplasm suitable for direct sowing under flooded soil surface. *Euphytica* 67, 177–184.

Yeo, A.R. and Flowers, T.J. (1986) Salinity resistance in rice (*Oryza sativa* L.) and a pyramiding approach to breeding varieties for saline soils. *Australian Journal of Plant Physiology* 13, 161–173.

Yeo, A.R., Yeo, M.E., Flowers, S.A. and Flowers, T.J. (1990) Screening of rice (*Oryza sativa* L.) genotypes for physiological characters contributing to salinity resistance, and their relationship to overall performance. *Theoretical and Applied Genetics* 79, 377–384.

13 The Right Rice in the Right Place: Systematic Exchange and Farmer-based Evaluation of Rice Germplasm for Salt-affected Areas

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Abstract

Traditional approaches for introducing improved rice varieties to farmers have demonstrated significant impact in favourable ecosystems in Asia, but with limited success in unfavourable ecosystems, as in salt-affected areas. Developing rice varieties with wider adaptation and broader tolerance of prevailing stresses is more viable for these areas, where abiotic stresses are particularly variable and complex, and growing conditions are too risky to persuade farmers to invest in inputs. The Challenge Program on Water and Food-supported project (Project No 7) emphasizes the development and deployment of high-yielding, salt-tolerant rice varieties for coastal saline (Bangladesh, Vietnam and India), inland saline (Egypt and Iran) and sodic soils (India), where rice-based farming systems are being practised. Mostly, a superior performance of genotypes under experimental conditions does not guarantee their acceptance by farmers, and occasionally farmers reject genotypes that yield well if they do not satisfy their quality preferences. In view of this, a participatory varietal selection (PVS) approach, in which farmers participate in varietal screening and adaptation testing, was followed to accelerate the adoption of salt-tolerant varieties. The International Network for Genetic Evaluation of Rice (INGER), a global germplasm-testing platform coordinated by IRRI, is being used for the exchange of germplasm through the International Rice Soil Stress Tolerance Observational Nursery (IRSSTON). Promising lines were selected through PVS trials and some were released or nominated for release as varieties. Participating farmers increased their paddy yield from < 2 t/ha to > 3.5 t/ha, which encouraged neighbouring farmers to adopt these new varieties. Recently, BRRI dhan 47 was released as the first salt-tolerant variety for the boro (dry) season in the coast of Bangladesh. Progress has been made in reclaiming inland saline and sodic soils at Lucknow and Faizabad in India and CSR30, an aromatic fine-grain, salt-

tolerant variety, has recently become popular among farmers, besides other varieties. Proper management options for these salt-tolerant, high-yielding varieties have been developed and validated simultaneously in PVS trials. Introducing PVS has increased the adoption rate and helped to solicit systematic feedback from farmers, which has been a major guiding force in devising breeding strategies and in developing customized breeding materials.

Introduction

Worldwide, salt-affected areas are estimated to range from 340 million ha to 1.2 billion ha (Massoud, 1974; Ponnamperuma, 1984; Tanji, 1990; FAO, 2007). Millions of hectares of these salt-affected soils are suited for agricultural production but are underexploited because of salinity and other soil- and water-related problems (Abrol *et al.*, 1988). In South and South-east Asia, at least 20 million ha of rice lands are, to some extent, salt-affected. A vast magnitude of these areas is either barren or has low and unstable productivity, particularly in coastal deltas. Limited progress has been made in developing and disseminating suitable salt-tolerant varieties and proper management practices that can mitigate salt stress and enhance the productivity of these soils, despite the enormous genetic variability available for tolerance of salt stress in rice.

The main objective of the Global Challenge Program on Water and Food (CPWF) is in line with the millennium lecture of UN Secretary-General Kofi Annan – 'More crop per drop' (UN Information Service, 2000). Our focus is to contribute to this objective by exploiting marginal lands and water resources for food production through a project titled 'Development of Technologies to Harness the Productivity Potential of Salt-affected Areas of the Indo-Gangetic, Mekong and Nile River Basins'. The project attempts to improve food security and livelihoods of poor households living in salt-affected areas, such as coastal deltas, who are engaged predominantly in rice-based farming.

The project contributes to the four objectives of the CPWF: food security, poverty alleviation, improved health and environmental security. This is being achieved through developing and disseminating high-yielding, salt-tolerant rice varieties that fit into the rice-based farming systems in salt-affected areas; strengthening the breeding programmes of the national agricultural research and extension systems (NARES) by providing stable elite breeding lines with specific agronomic and grain quality characteristics that match farmers' preferences in target areas; and disseminating effective crop and natural resources management (CNRM) technologies to ensure better and sustained productivity of these marginal resources. This chapter highlights: (i) the development of rice varieties adapted to the diverse and complex conditions of coastal areas; (ii) the formulation of efficient breeding strategies to address the complex problems encountered in salt-affected areas; (iii) broader sharing of germplasm among collaborating partners; and (iv) acceleration of the adoption of effective technologies through participatory approaches.

Why is large-scale adoption of new technologies not observed in unfavourable ecosystems?

The project collaborates with NARES, representing a wide spectrum of unfavourable environments ranging from coastal to inland and saline to sodic/alkaline ecosystems. Genotypes suitable for coastal areas may or may not be fit for inland areas. The plant type requirements of even two adjacent coastal zones could be different and determined mostly by factors such as soil texture, rainfall pattern, growing seasons and the distance to and connectivity with the ocean through backwater channels that cause seawater intrusion during high tides. This is evident from the different traits required in varieties for the wet season in coastal areas of Can Tho Province (Vietnam), Satkhira (Bangladesh), Cuttack (India) and Cochin, the Pokkali area in India (Table 13.1). For example, photoperiod-sensitive varieties are not required for Vietnam's coastal delta but are

Table 13.1. Site characterization and plant-type requirements of the CPWF collaborative sites.

NARES partners/ countries Target area details and plant-type requirements		Central Rice Research Institute, Cuttack, India		Central Soil Salinity Research Institute–RRS, Lucknow	ND University of Agriculture and Technology, Faizabad, India	Rice Research Institute of Iran, Rasht, Iran	Bangladesh Rice Research Institute, Ghazipur, Bangladesh		Cuu Long Delta Rice Research Institute, Can Tho, Vietnam	Rice Research & Training Centre, Sakha, Egypt
Rice cropping season		Wet	Dry	Wet	Wet	April–September season	Dry	Wet	Same for all seasons	April–September season
Type of stress	Location	Coastal		Inland	Inland	Coastal	Coastal		Coastal	Inland and coastal
	Stress	Salinity		Sodicity	Sodicity	Salinity	Salinity		Salinity	Salinity
River basin/delta		Indo-Gangetic		Indo-Gangetic	Indo-Gangetic	Karkheh/ Caspian Sea	Indo-Gangetic		Mekong	Nile
Plant height (cm)		125	85	110–120	110–120	< 110	90–100	120–130	90–100	90–110
Maturity (days)		145–155	115	125	125	< 110	120–140	140–150	90–140	> 125
Photosensitivity		Yes	No	No	No	No	No	Yes	No	No
Grain type*		MS/MB	MS/MB	LS/MS/LB	LS/MS/LB	LS	LS/MS/LB	LS/MS/LB	LS	SB/MS
Degree of stress	ECe pH_2	6–12 –	6–12 –	– 9.4–10.0	– 9.4–10.0	~ 8 –	8–12 –	6–12 –	6–12 –	9–10 –
Stress at growth stage		Early and rep. stage	All growth stages	Transplanting to maturity	Transplanting to maturity	Transplanting to maturity	All growth stages	Transplanting to maturity	All growth stages	All growth stages
Any other requirement		Intermediate amylose		Intermediate amylose	Intermediate amylose	Grain quality, amylose, gel consistency and gelatinization temp.-med	Intermediate amylose	Intermediate amylose	Aroma, low and medium amylose	Japonica
Latest date for seed received at NARES		April–15 May	15 Sept–25 Oct	By mid-May	By mid-May	Early April	End of Sept	End of April	May and Oct	Mid-April

*LS, long slender; MS, medium slender; LB, long bold; MB, medium bold.

essential in other coastal areas. Additionally, requirements for traits such as duration to maturity, plant height, grain type and eating quality vary widely based on farmers' preferences. It is therefore imperative to design varieties that meet the agronomic, adaptive and quality requirements of each target environment and local farming communities, to ensure successful adoption by local farmers.

The complexity of coexisting stresses and the high genotype × environment interactions encountered in these unfavourable areas make it difficult to breed stress-tolerant varieties with broader adaptation. To ensure meeting site specificity, the project's sites initially were characterized biophysically and socio-economically and season- and site-specific requirements were determined (Table 13.1). This information then guided the selection of breeding lines that are most likely to be adopted at a specific site. Different germplasm modules were assembled for coastal saline-wet season (WS), coastal saline-dry season (DS) and inland saline and sodic/alkaline areas during the exchange and evaluation of breeding materials.

Rice is the most suitable crop for salt-affected areas

Nearly the entire coastal belt of the Mekong Delta in Vietnam, the Gangetic deltas in Bangladesh and India, the Nile Delta in Egypt and the Caspian Sea basin in northern Iran are prone to inundation of seawater during high tides, with the consequent inland salt intrusion through backflow water channels and rivers. Excessive rain and river outflow during the monsoon season regularly result in prolonged partial to complete submergence. Only high salt- and submergence-tolerant crops such as rice can be grown successfully in these areas. In sodic soils, low infiltration rate due to poor hydraulic conductivity and poor physical and chemical conditions of the soil cause waterlogging and stagnation on the soil surface and, again, only rice can survive such conditions. Rice is recommended as the first crop to start with during the reclamation of sodic soils (Singh *et al.*, 2004) and it is the crop most preferred by farmers living in these areas. In inland saline soils, however, rice cultivation depends on the availability of good-quality water and is therefore grown on a limited scale in some areas, such as in the Nile Delta. Similar conditions are found in coastal saline soils during the DS in the Gangetic deltas in India and Bangladesh. The project therefore envisages non-rice crops that are moderately tolerant of salt stress and that satisfy farmers' preferences and local markets (Singh *et al.*, Chapter 19, this volume). Selected salt-tolerant non-rice crops are being provided by the International Centre for Biosaline Agriculture (ICBA) in Dubai and the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in India (Fig. 13.1).

Reasons for the low productivity of rice in salt-affected ecosystems

The average yield of rice in salt-affected areas, and particularly in coastal deltas, is far below the national average of the respective countries. The possible causes for such low productivity are:

1. Continued cultivation of traditional low-yielding rice varieties and local landraces because of the lack of or limited accessibility to adapted salt-tolerant improved varieties.
2. In flood-prone rainfed areas, tolerance of submergence and/or partial flooding is necessary in the new varieties to ensure adoption.
3. Poor or no attention to integrated CNRM practices, particularly the use of inputs, due to the lack of information on effective management options and/or financial constraints.
4. Frequent incidences of other abiotic stresses, such as drought, acidity, nutritional imbalances and organic soils.

Consequently, a reduction in yield usually varies from 10 to 80%, and can even reach 100% in severe cases, particularly when rainfall is erratic (Zeng *et al.*, 2003; Alloway, 2004; Sahrawat, 2004; Chinnusamy *et al.*, 2005). Well-adapted rice varieties in coastal areas are mostly traditional landraces that are photoperiod-sensitive, relatively non-responsive to fertilizer and tall (prone to lodging), with limited yield potential (1.5–2.5 t/ha) and poor grain type. An exception is in Egypt, where improved

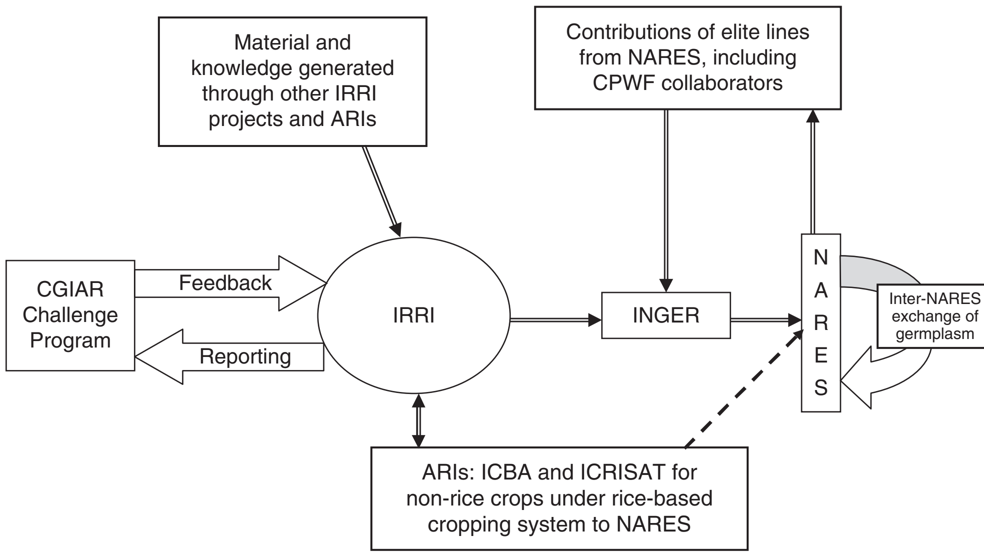

Fig. 13.1. Seed distribution pathway among IRRI and CPWF PN7 partners. ARIs, advanced research institutions; NARES, national agricultural research and extension systems; INGER, International Network for Genetic Evaluation of Rice; ICBA, International Centre for Bio-saline Agriculture; ICRISAT, International Crops Research Institute for Semi-Arid Tropics; PN7, Project No 7 of the CPWF.

salt-tolerant *japonica* varieties such as Giza 178 and Sakha 104 are being used. During the DS, farmers are forced to keep the land fallow due to high salinity, lack of good-quality irrigation water and lack of suitable salt-tolerant rice and non-rice crop varieties.

The major cause of poor yield in inland sodic and saline soils is the lack of freshwater resources and/or poor adoption of proper reclamation and mitigation measures. These options require additional investment that is beyond the reach of the resource-poor farmers in these areas. Most of these areas are either owned by local governments or by poor farmers who do not want to take risks. However, once these lands are reclaimed, they become incredibly productive (CSSRI, 2006). Thus, there is vast scope for bringing such lands back into production through proper reclamation coupled with the use of tolerant varieties, provided that the resources and technical help are made available to landholders. Improved rice varieties are now available for salt-affected areas, but with limited adoption. Efficient seed production, accessibility and technological know-how on use of these varieties and amendment options are major bottlenecks. The lack of adequate communication and extension networks, and training, and poor marketing infrastructure for other high-value crops further limit the adoption of available technologies.

Enhancing rice productivity in salt-affected areas

The efforts of the CPWF project are intended for producing more rice from rainfed ecologies as land and water resources in these areas are underused. To achieve this objective, the following issues need further attention:

1. Steadily raising the genetic yield potential of rice varieties adapted to rainfed areas.
2. Reducing the gap between potential and actual yields through proper crop and nutrient management.
3. Improving soil health through proper reclamation and mitigation strategies.

The major challenge is effectively to raise the yield potential of rice varieties adapted to rainfed, especially coastal, areas given the extreme diversity and complexity of the existing stresses. The obvious answer is to accelerate the development of salt-tolerant, high-yielding varieties that have broader adaptation. The gap between potential and realized yield in coastal areas could then be narrowed through effective management strategies. This gap is currently being lessened as new and improved salt-tolerant, fertilizer-responsive and high-yielding varieties are becoming available. However, the benefits from these varieties and technologies have not been fully realized in farmers' fields because of limited seed supply coupled with the limited knowledge on proper management options suitable for salt-affected areas. The average annual seed replacement rate for inbred rice varieties in India is 24.4% (Seednet, 2006), but the exact numbers on seed replacement in salt-affected areas, and specifically coastal areas, are likely to be much lower. This seed replacement rate needs to be increased to a rate that can at least match the national average, through strengthening seed production and marketing networks and by making seeds accessible to farmers through government and non-government agencies. Apparently, improving the productivity of these areas will depend particularly on the extent of success in developing suitable varieties, providing sufficient high-quality seeds and using proper management to sustain and stabilize productivity.

Approaches for selecting and sharing of suitable rice germplasm with different partners

Distribution of rice varieties and elite breeding lines to NARES is being handled mainly by IRRI. Major contributions come from IRRI's regular breeding programmes and from NARES partners. INGER, as a partnership among NARES and international agricultural research centres (IARCs) such as IRRI, is being used for the regular exchange of germplasm. Following the establishment of the International Rice Testing Program (IRTP) in 1975, INGER composed a soil salinity-based nursery – the International Rice Salinity Tolerance Observational Nursery (IRSTON). IRSTON provided a convenient network for the exchange of genetic material and information among partners engaged in breeding salt-tolerant rice varieties within the ambit of international treaties and regulations. IRSTON was recently transformed into the International Rice Soil Stress Tolerance Observational Nursery (IRSSTON) to include the elite material developed for other associated soil stresses such as acidity, alkalinity and iron toxicity.

The objective of IRSSTON is to evaluate advanced breeding lines and traditional varieties assembled from various countries, as well as from IRRI, to cover a wider range of saline, alkaline, acidic and other soil problems. Since trials are being conducted under variable stress conditions, few genotypes with proven tolerance of specific soil problems, such as salinity, alkalinity, Fe toxicity, acidity and Zn deficiency, are included as checks. The most commonly used genotypes are IR66946-3R-178-1-1, Nona-Bokra, BW267-3, CSR-90IR-2, Pokkali (tolerant) and IR29 (sensitive); however, these checks could be changed whenever better genotypes are identified. The direct exchange of specific germplasm between NARES, facilitated under various projects, is also very effective, such as the short-maturing, high-yielding varieties developed in Vietnam that have been selected for the dry season in south Bangladesh. Figure 13.1 illustrates the seed distribution chain involved in this network.

In addition to the major South and Southeast Asian countries participating in this network, IRSSTON was expanded recently to include countries in sub-Saharan Africa in collaboration with the West Africa Rice Development Association (WARDA). In 2006, the network was further strengthened and, in addition to the regular IRSSTON, 32 special sets of the IRSSTON (IRSSTON-SS) were distributed to ten countries in Asia and seven countries in Africa, including partners involved in the CPWF project. Advanced research institutions (ARIs), for example, ICBA in Dubai and ICRISAT in India, are providing specific non-rice crops to various NARES collaborators to be tested in the commonly rice-based cropping systems in these areas. Feedback from NARES partners has been a major source of input for strengthening future breeding strategies to develop customized breeding materials that match local demands. The network also facilitated regular feedback from all partners, including the CGIAR centres and the ARIs involved

(Fig. 13.1). Targeted exchange of selected germplasm and proper evaluation have already started generating dividends, with some elite lines such as IR72046-B-R-3-3-3-1 nominated for the national varietal release system as a potential commercial cultivar.

Generation and sharing of salt-tolerant breeding lines through INGER

The complexity of salinity tolerance in rice slowed progress in breeding salt-tolerant modern varieties (Flowers, 2004; Flowers and Flowers, 2005). Rice is salt-sensitive, with a threshold as low as 3 dS/m (Maas and Hoffman, 1977); however, the tolerance limit varies with developmental stage. For example, rice is relatively tolerant during germination, becomes very sensitive during the early seedling stage, gains tolerance during active tillering, becomes sensitive during reproduction and then gains relatively more tolerance during grain filling and towards maturity. Thus, the seedling and reproductive stages are most vulnerable to salt stress. Very poor correlation exists between tolerance at the seedling and reproductive stages, suggesting that regulation of tolerance at the two stages probably involves different sets of genes (Makihara *et al.*, 1999; Moradi *et al.*, 2003; Singh *et al.*, 2004). Tolerance during the seedling stage is important to ensure good crop establishment, particularly in coastal areas, where salinity of both water and soil is relatively high at the beginning of the season. Tolerance during the reproductive stage is particularly crucial as it affects grain formation directly (Rao *et al.*, 2008), and this is important in both coastal and inland areas when late-season drought is anticipated, and throughout the dry season. Thus, tolerance during both stages is required for widely adapted varieties.

Most of the germplasm shared through the IRSSTON network is developed at IRRI; however, some of the lines generated by NARES partners are also included in the INGER seed modules. IRRI's breeding programme for salinity tolerance uses modified bulk methods and rapid generation advance (RGA) facilities. Early generations (F_2 to F_5) with a large population size are evaluated for salinity tolerance and subjected to mild to moderate selection pressure. Advanced generations are then exposed to higher salt stress for rigorous selection. Selection for agronomically desirable advanced breeding lines is achieved in IRRI fields in parallel with selection for higher salinity tolerance (12–18 dS/m) at the seedling stage in hydroponics under controlled conditions (Gregorio *et al.*, 2002). Selection of breeding lines in the field (non-stress) is done at maturity based on desired agromorphological growth and yield traits, and only within lines that are tolerant of salt stress at the seedling stage. Selected lines under natural field conditions are evaluated during the WS at a saline field site in Ajuy, Iloilo Province, Philippines. Advanced lines are screened at least twice at this field site to assess their adaptability to natural salt-stress conditions. Repeated screening, preferably in long plots and rows rather than compact and square plots, is followed to minimize variability caused by the spatial heterogeneity of stress in natural fields. Final evaluation is then performed in replicated yield trials (RYT) to confirm the level of salt tolerance and the grain yield and quality of selected lines. The natural field sites provide an opportunity to screen plants for tolerance at both the seedling and reproductive stages. The selected genotypes are subsequently nominated for the regular IRSSTON or IRSSTON-SS for evaluation under NARES conditions through INGER.

Strategies for distributing breeding lines that fit specific target site requirements

The specific plant traits required at a particular site are the foremost criterion for assembling genotypes in a specific module (Table 13.1). Modules for the wet season in coastal areas are different from those needed for the dry season, as well as for the inland saline and sodic areas. Currently, only two modules, each comprising 30–40 entries, one for coastal saline soils for the WS and another for inland saline and sodic soils as well as coastal saline areas for the DS, are constituted as the IRSSTON-special sets (IRSSTON-SS). In 2006, 2304 seed packets through 32 sets of the two different modules of IRSSTON-SS were distributed to 23 NARES in 17 countries in Asia and Africa, including CPWF partners, and this increased to 39 sets in 2007. In addition, all collaborators also received the regular IRSSTON nursery, and some received specific sets based on their special requests.

To introduce new materials in the modules, while omitting unlikely desirable materials, about one-third of the entries were replaced with new elite lines every season. This approach allows the testing of each entry for at least 3 years under different environments, thus reducing the chances of selecting false entries. The use of additional checks for different kinds of soil stresses in the nurseries, in addition to local checks, ensures better monitoring and comparisons. In the first season, the entries are tested under a managed-stress environment in researcher-supervised trials (mother trials), and this is later visited and evaluated by several stakeholders such as researchers, local extension workers, state government officials, representatives from non-government organizations (NGOs) and farmers. The most promising genotypes (approximately five) selected from these trials are evaluated subsequently at a number of different sites in farmer-managed trials (baby trials). Selected lines (1–2 genotypes) that repeatedly perform well in these farmer-managed trials are then nominated for national release and their seeds multiplied for further dissemination. Since the process is cyclic, the new sets of mother trials at the experimental farm and baby trials in farmers' fields are evaluated every season. Figure 13.2 shows a flow diagram of this approach, and more details on this approach are provided in a separate chapter in this volume (Salam *et al*., Chapter 14). Feedback from NARES partners on the genotypic performance based on PVS trials across the environments and the ultimate use of genotypes as new improved varieties or as donors in crossing programmes helps to direct and strengthen the IRRI and NARES breeding programmes (Table 13.2). Table 13.3 lists the selected genotypes from 2006 IRSSTON-SS that performed well across the different environments at either seedling or reproductive stage, or at both stages. In addition to tolerance of salt stress, overall plant type and canopy structure are also considered during selection. Phenotypic acceptability scores at maturity (PACP) provide an indication for probable overall acceptance of the genotypes in a target environment. For example, IR59443-B-7-3-2 and IR61919-3B-18-3 had a PACP score of 3 in Orissa, India, suggesting that these two lines potentially could be adopted successfully by farmers in that area. Although many entries had good adaptability to specific target environments, only four entries were consistently rated high across at least two similar ecologies, IR50184-3B-18-2B-1, IR51499-2B-29-2B-1-1, IR61919-3B-7-2 and IR64197-3B-14-2.

Participatory varietal selection (PVS) empowers farmers and provides useful feedback

Through conventional breeding, plant breeders often consider yield, ability to withstand salt stress, flowering duration and plant height as the most important traits in developing varieties for salt-affected areas. However, farmers may have other important considerations, as often reflected in the mismatch between the breeding lines selected by farmers compared with those selected by breeders. Preference voting of farmers during evaluation of PVS trials was conducted during the wet and dry seasons of 2006 by CRRI, Cuttack, India, in coastal saline areas, where the electrical conductivity of the soil solution ranged from 8 to 13 dS/m, and in the WS of 2005 by CSSRI–RRS, Lucknow, India, in sodic soils with $pH_{1:2}$ of about 10.3 ($pH_{1:2}$ denotes the pH of the mix of one part soil and two parts distilled water, hereinafter denoted as pH). The PVS trial in the deltaic region of Orissa in Ersama block of Jagatsinghpur district, India, included six promising rice varieties in the WS evaluated by 27 farmers and another set of five promising varieties in the DS evaluated by 22 farmers.

Farmers' preferences of the best-performing genotypes were similar, in some cases, to those of the researchers, but the ranking of genotypes mostly differed (Table 13.4). For example, in the 2006 WS, Lunishree, with good yield and salinity tolerance, was not preferred by the majority of farmers because of its tendency to lodge and difficulty to thresh. Nearly 80% of the farmers selected SR26B and Patnai 23 and only a few farmers selected the three CRRI lines, despite their good plant type and high yield potential. In the 2006 DS, IR72046-B-R-3-3-3-1 was preferred by almost

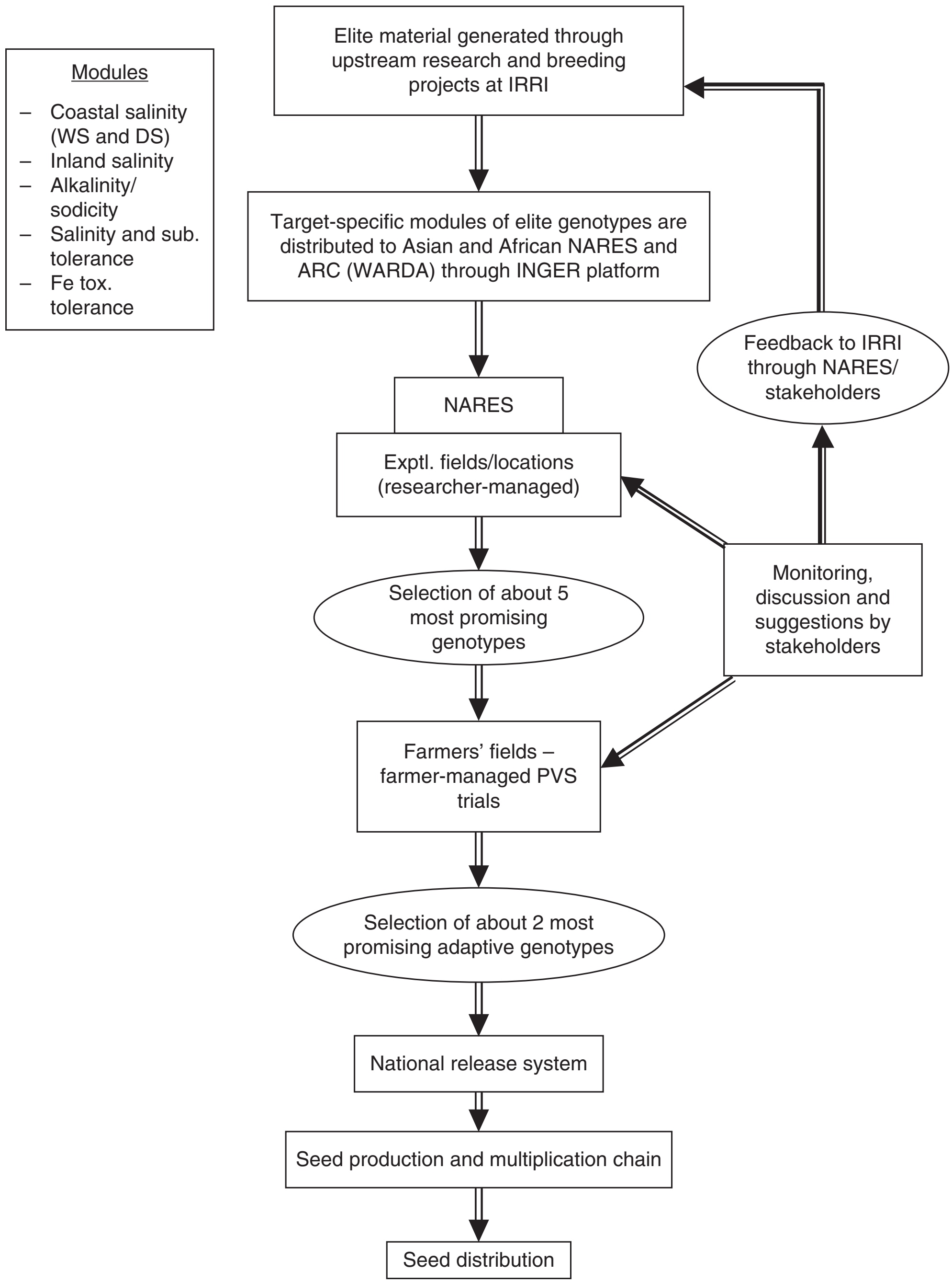

Fig. 13.2. Flow chart of dissemination of elite genotypes and participatory varietal selection (PVS) at NARES. ARC, Africa Rice Center (previously WARDA – West Africa Rice Development Association); NARES, national agricultural research and extension systems; INGER, International Network for Genetic Evaluation of Rice.

Table 13.2. Genotypes selected through participatory varietal selection trials and being used by NARES.

		Average performance over different NARES locations							
				Salt-tolerance score*					
S. number	Designation	Flowering (days)	Ht[a] (cm)	Veg stage	Rep stage	PACP score	Grain yield (kg/ha)	Grain type[b]	Being used as
1	IR50184-3B-18-2B-1	109	95	2.0	5.2	3.7	2968	LS	Donor
2	IR51499-2B-29-2B-1-1	106	95	4.0	7.0	5.0	2609	MS	Donor
3	IR61919-3B-7-2	93	95	4.0	5.7	3.7	3064	LS	Donor
4	IR64197-3B-14-2	91	92	5.0	5.9	5.0	3046	LS	Donor
5	IR65833-4B-17-1-3	117	103	2.0	5.3	4.3	3010	LS	Donor
6	IR68652-3B-20-3	117	102	2.5	4.9	5.0	3387	LS	Donor
7	IR70023-4B-R-12-2-3-1	111	115	5.0	5.4	5.7	3115	LS	Donor and yield testing
8	IR71829-3R-73-1-2	110	112	4.0	6.1	5.0	2994	LS	Donor and yield testing
9	IR73055-8-1-1-3-1	107	109	5.0	6.0	5.7	3907	LS	Donor and yield testing
10	IR72580-B-24-3-3-3-2	112	98	3.5	6.3	5.7	3039	LS	Donor and yield testing
11	IR72049-B-R-4-1-1-3-1	115	100	3.0	5.7	5.7	3004	LS	Donor and yield testing
12	IR61247-3B-8-2-1	111	84	5.0	4.0	3.0	2907	LS	Donor and yield testing
13	CSR-90IR-2	104	108	4.5	4.9	5.0	2385	LS	Donor and yield testing
14	IR61919-3B-18-3	92	94	3.5	4.0	4.3	2626	LS	Yield testing
15	IR59443-B-7-3-2	114	83	4.0	5.0	3.0	2873	LS	Yield testing

*Salt-tolerance scores on 1–9 scale where 1 is best and 9 is worst. [a]Ht, plant height; veg, vegetative stage; rep, reproductive stage; PACP score, phenotypic acceptability of the genotype at maturity on 1–9 scale (1 is best and 9 is worst). [b]LS, long slender; MS, medium slender.

Table 13.3. Genotypes selected by NARES for salt-affected areas based on their tolerance at the vegetative and reproductive stages.

		Average performance of genotypes at NARES sites					
				Salt-tolerance score*			
S. number	Designation	Flowering (days)	Ht[a] (cm)	Veg stage	Rep stage	Grain yield (kg/ha)	Grain type[b]
Vegetative stage							
1	IR50184-3B-18-2B-1	109	95	2.0	5.2	2968	LS
2	IR51337-2B-9-2B-2-2	107	99	3.0	4.3	2465	LS
3	IR51491-AC10	101	109	2.5	5.3	2102	MS
4	IR65833-4B-17-1-3	117	103	2.0	5.3	3010	LS
5	IR68652-3B-20-3	117	102	2.5	4.9	3387	LS
6	IR71829-3R-10-3	110	107	3.0	6.4	1650	LS
7	IR72048-B-R-16-2-3-3	96	114	1.0	5.7	1886	LS
8	IR72049-B-R-22-3-1-1	91	119	1.0	6.0	1886	LS
9	IR72046-B-R-8-3-1-2	81	105	1.0	7.0	2200	LS
10	IR71829-3R-82-1-1	105	110	2.5	5.9	2481	LS
11	IR71895-3R-9-3-1	100	113	2.5	7.3	1850	LS
12	IR71866-3R-1-2-1	107	102	3.0	5.7	2387	LS
13	IR71907-3R-2-1-1	97	100	3.0	5.0	2687	LS
14	IR59418-7B-21-3	109	79	2.0	3.7	2918	LS
15	TCCP266-1-3B-10-2-1	96	78	2.3	3.7	4198	LS
16	IR72593-B-13-3-3-1	108	79	3.0	5.0	2749	LS
17	IR72049-B-R-4-1-1-3-1	115	100	3.0	5.7	3004	LS
18	IR72593-B-3-2-3-3	112	89	2.3	3.3	3367	LS
19	IR71895-3R-60-3-1	122	82	3.0	4.3	3771	LS
20	IR75395-2B-B-19-2-1-2	115	92	2.7	3.3	4061	LS
21	IR76346-B-B-10-1-1-1	113	87	2.0	5.3	2963	LS
Reproductive stage							
1	TCCP266-1-3B-10-2-1	96	78	2.3	3.7	4198	LS
2	IR72593-B-18-2-2-2	112	85	4.0	3.0	3036	LS
3	IR75395-2B-B-19-2-1-2	115	92	2.7	3.3	4061	LS
Both stages							
1	TCCP266-1-3B-10-2-1	96	78	2.3	3.7	4198	LS
2	IR75395-2B-B-19-2-1-2	115	92	2.7	3.3	4061	LS
Checks							
1	IR29	95	93	7.0	8.0	1500	LS
2	IR66946-3R-178-1-1 (FL478)	100	94	2.5	7.3	1787	LS
3	Nona Bokra	111	117	2.5	4.0	3308	SB
4	CSR-90IR-2	104	106	2.5	4.5	2027	LS
5	Pokkali	114	130	3.0	4.0	2294	SB

*Salt-tolerance scores on 1–9 scale where 1 is best and 9 is worst. [a]Ht, plant height; veg, vegetative stage; rep, reproductive stage. [b]LS, long slender; MS, medium slender; SB, short bold.

all the farmers, while 80% or more farmers selected Annapurna and IR72593-B-19-2-3-1. Annapurna has a red kernel but has good eating quality. Canning 7 also has good yield potential, but is not highly rated because its grain shatters at maturity. Farmers' preferences based on their own selection indices were quite close to the researchers' preferences in coastal saline soils, but this was less so under sodic soils. However, rank correlations (r_s) for all preferences under coastal saline and sodic soils were statistically non-significant

Table 13.4. Farmers' preference versus researchers' ranking of breeding lines and varieties tested through PVS trials.

Varieties used in PVS	Varietal ranking: Farmers	Varietal ranking: Researchers	Rank correlation r_s	Table value at $n-2$ df: 5%	Table value at $n-2$ df: 1%
Location: Ersama Block, Jagatsinghpur District, Orissa, India					
2006 wet season					
SR26B	1	1	0.771[ns]	0.811	0.917
Patnai 23	2	3			
Lunishree	3	2			
CR2096-71-2	4	5			
CR2069-16-1	5	6			
CR2093-7-1	6	4			
2006 dry season					
IR72046-B-R-3-3-3-1	1	1	0.700[ns]	0.878	0.959
Annapurna	2	3			
IR72593-B-19-2-3-1	3	4			
CSR4	4	2			
Canning 7	5	5			
Location: Mataria Village, Unnao District, Uttar Pradesh, India					
2005 wet season		25% gypsum requirement plots			
2K219	1	2	0.018[ns]	0.754	0.874
CSR30	2	6			
2K262	3	3			
IRRI-2K8	4	5			
CSR23	5	4			
CSR27	6	7			
CSR36	7	1			

[ns]Non-significant correlation between the ranks given by farmers and researchers.

(Table 13.4). This shows the poor association between what researchers think and what farmers perceive. Farmers' perceptions as assessed through PVS trials therefore are a valuable input for breeding materials that are particularly suited to these fragile salt-affected ecologies. The mismatch in the rankings given to genotypes by farmers and researchers supports the role of PVS in ensuring the suitability of new varieties to local conditions and farmers' preferences.

Through focus group discussions (FGDs) conducted with farmers, it became obvious that farmers took pride in being part of the varietal development process through PVS trials that allowed them to express their preferences. Both men's and women's inputs are needed, as certain preferences are gender specific and are affected by other social factors. Furthermore, other traits such as the quality of straw for fodder or for use as a building material are considered by some farmers as essential during the selection process. Finally, taste and cooking quality need to be assessed carefully. For example, farmers may prefer a bold grain shape or a good volume-expansion ratio of cooked rice to give a feeling of satisfaction after eating. PVS also provides opportunities for farmers to test new lines and compare these with their own varieties using their usual management practices and equipment. Apparently, all these factors could be considered successfully through PVS trials, thus increasing the chances of the adoption of new varieties.

Proper management practices to realize and sustain yield potential in salt-affected areas

Although built-in plant tolerance is the most environmentally friendly and economically feasible option for resource-poor farmers to cope with abiotic stresses, this genetic tolerance has limited impact and, in most cases, is not sufficient to reflect substantial yield improvement and stability. Appropriate management technologies and mitigating strategies are often important ingredients of yield improvement. Compared with genetic enhancement, natural resource management (NRM) could have comparatively less contribution towards achievable yield under favourable ecosystems, but could be equally important in unfavourable ecosystems (Tyagi and Minhas, 1998). Salt-tolerant varieties are normally more responsive to amendments and mitigation options, and lack of proper management is often reflected in a yield reduction. This is clearly evident from 12 farmers' field experiments conducted at CRRI, Cuttack, India, in which farmers' varieties and management (FVFM) practices were compared with modern varieties and improved management options in various combinations. In the 2005 WS, the average yield using farmers' varieties and improved management (FVIM) was 2.24 t/ha compared with 1.83 t/ha in FVFM. Similarly, there was a yield advantage of 47% when using improved varieties and farmers' management (IVFM; 2.70 t/ha). But, when farmers opted for improved varieties and improved management (IVIM), the increment was substantial, with a 91% gain in grain yield (3.5 t/ha). In the 2006 DS, the yield advantages of FVIM, IVFM and IVIM were 46, 23 and 75%, respectively, in comparison with FVFM (1.99 t/ha). These results indicate clearly that improved technologies, through either the use of better varieties or management, enhance the productivity of coastal areas, but maximum yield advantages could be ensured from combining improved varieties and improved management options. The yields in the 2005 WS and 2006 DS were almost the same under IVIM, but the per cent yield increase declined from an average of 91% in the 2005 WS to 75% in the 2006 DS. The reason for this was that, just by observing the performance of trials in farmers' fields under the project, other neighbouring farmers were able to improve their yields using their own variety, from 1.83 to 1.99 t/ha (Fig. 13.3), through better management. The higher yields have convinced even the non-participating farmers in the project area to grow the newly developed varieties. Interestingly, management had a bigger role in the DS than in the WS, and this is probably because the salinity in the DS is much higher than in the WS, when salt is often washed away with the onset of the monsoon (Fig. 13.3).

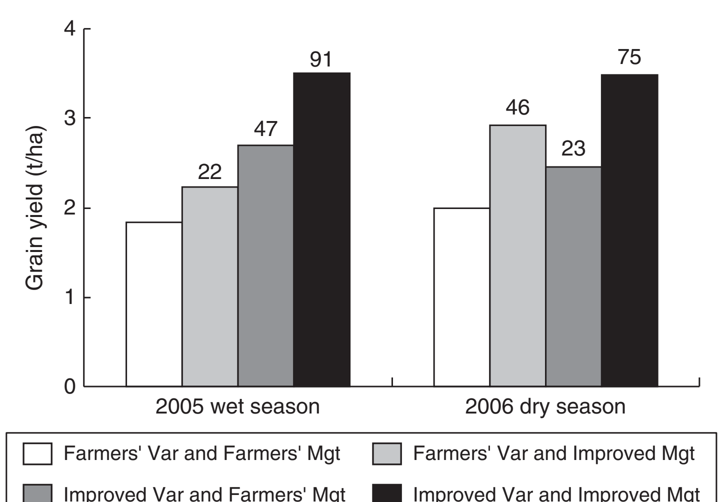

Fig. 13.3. Yield enhancement as a result of combining improved management practices and salt-tolerant rice varieties in farmers' fields in coastal saline soils of Orissa. Numbers indicate the percentage increase in yield obtained over that of farmers' varieties and management.

Nursery and nutrient management options together with proper handling of seedlings during transplanting could reduce seedling mortality and improve the crop stand, which is often the most important yield determinant in salt-affected areas. Various soil reclamation methods and water management techniques could also be effective in mitigating the harmful effects of salt during the most sensitive stages of plant growth. All these strategies need to be validated and adjusted in conjunction with the development of salt-tolerant varieties. Our approach is to disseminate these options in association with new breeding lines through PVS trials.

Promising lines adopted by CPWF collaborators through PVS trials

The varietal development programme for salt-affected areas under this project in India includes several sites, managed by three institutes, that represent different types of salt stress (Table 13.1). These institutions conduct researcher-managed and farmer-managed trials to select suitable rice varieties at target areas. An example is the PVS trials being conducted in coastal Orissa under CRRI. Fifteen promising salt-tolerant rice varieties/elite lines along with a susceptible check (IR29) and a popular variety (Khandagiri) were evaluated in farmers' fields during the 2006 DS. IR72046-B-R-3-3-3-1 attained the highest yield of 3.67 t/ha and Canning 7, Annapurna, IR72593-B-19-2-3-1 and CSR4 had comparable grain yields of 3.17–3.5 t/ha. These genotypes were selected by both men and women farmers through PVS activities. In the 2007 DS, IR72046-B-R-3-3-3-1 was grown by 15 farmers from different villages and it yielded 3.2–4.8 t/ha (average 4.2 t/ha). IR72046-B-R-3-3-3-1 performed well even under high salinity (10–12 dS/m), where farmers' varieties failed. In view of the great demand for this line, its seeds were being multiplied in the 2007 WS for distribution to more farmers in the next season. In the WS from 2005 onward, farmers selected SR26B, Patnai 23, Lunishree, CR2093-7-1, CR2069-16-1 and CR2096-71-2, and they were able to increase their paddy yield from < 2.0 t/ha to 3.5 t/ha. CRRI, Cuttack, has already nominated five new lines (IR72046-B-R-3-3-3-1, CR2094-46-3, CR2069-16-1, CR2096-71-2 and CR2093-7-1) to the All India Coordinated Rice Improvement Program (ACRIP) for multi-location testing and potential release as commercial varieties for coastal saline soils.

The PVS trial network along the saline coastal belt of South Bangladesh is led by the Bangladesh Rice Research Institute (BRRI). Work on the evaluation of a few lines (PVS-B3, PVS-B8, PVS-B19) selected out of 245 salt-tolerant lines was intensified in coastal saline soils during the dry season under the CPWF project. In January 2007, the National Seed Board of Bangladesh released PVS-B3 as BRRI dhan 47 (IR63307-4B-4-3; Salam *et al.*, 2007) for commercial cultivation in saline coastal areas, including Debhata, Kaliganj, Tala, Ashasuni and Satkhira-sadar provinces (see Salam *et al.*, Chapter 14). Seeds were provided to farmers for outscaling. Observations made during these processes were that: (i) grain yield varied from 4.2 to 7.5 t/ha in the boro season, with an average yield of 6.1 t/ha; (ii) a few farmers used ponds to store fresh rainwater for use in the DS, but most of them applied irrigation water from shallow tube wells – farmers who had higher salinity in irrigation water expressed the highest satisfaction with BRRI dhan 47; (iii) in these fields, only BRRI dhan 47 was successful, whereas other varieties could not survive; and (iv) currently, there is great demand for the seeds of BRRI dhan 47 in salt-affected districts.

The inland salinity and sodicity sites in Lucknow and Faizabad, Uttar Pradesh, India, also evaluated promising lines and varieties through PVS trials. CSR30, an aromatic, fine-grain, salt-tolerant rice variety, was a common choice among farmers at both locations. Other entries such as 2K262 and 2K219 were preferred by farmers (79.2 and 50%, respectively) in the PVS trials conducted by CSSRI Regional Research Station, Lucknow (Table 13.4), whereas NDRK5089, Narendra Usar dhan 3 and NDRK5083 were ranked as the first three choices by farmers in the PVS trials conducted by NDUAT, Faizabad. The choice of the best genotype in the PVS trials by researchers was not always consistent with that of farmers. The researchers preferred Narendra Usar dhan 3 because of its high yield (3.0 t/ha) against NDRK5089 (2.8 t/ha), CSR30 (2.4 t/ha) and NDRK5083 (2.4 t/ha). The farmers chose CSR30, a basmati-type rice, because of its high grain quality and high market value. The economic value of the 2.4 t/ha yield of CSR30 is equivalent to more than 4.0 t/ha yield of other non-basmati rice varieties. Sarjoo 52, an existing popular variety, yielded poorly in comparison with the other lines tested in the PVS trials under farmers' sodic fields with pH ranging from 9.5 to 10.0. This project has also led to the empowerment of participating farmers, who were given the opportunity to make their own decisions and selections while providing feedback to breeders and agronomists.

Introducing salt-tolerant varieties in salt-affected coastal areas will increase food security

A qualitative impact assessment study was conducted in the coastal saline areas through FGDs in selected villages that were involved in the CPWF project. During the initial phase of the project, farmers were slow to accept new varieties and any suggested management options. However, after the benefits of these technologies were demonstrated, farmers began to see their advantages, as witnessed by increasing adoption, even by neighbouring farmers. The impact study revealed that the adoption of improved germplasm and crop and water management practices increased the yields of the main WS crop significantly and allowed expansion of rice areas in the DS, resulting in a rice surplus and enhanced farmers' income (Paris *et al.*, Chapter 24, this volume). Farmers' awareness of these modern varieties improved substantially and they even requested varieties with multi-stress tolerance, particularly with tolerance of stagnant, long-term flooding commonly experienced during the wet season. Farmers also noticed improved tillering and increased grain length and number of grains in these new varieties. For eating quality, farmers preferred bolder grains over the improved varieties with slender grains, even though the latter had better market value (Zolvinski, 2008).

Farmers reported that the new varieties doubled and sometimes even tripled their yields when compared with their traditional varieties that had average yields of 1.0–1.5 t/ha. Farmers in two villages were also able to harvest rice paddy sufficient for their annual consumption and sometimes with some surplus for the market. These farmers experienced food shortages prior to adopting these technologies. As households no longer needed to buy rice, the extent of migration for off-farm employment decreased. Farmers also appreciated the salt-tolerant non-rice crops grown in tandem with DS rice. Sunflower, for example, which can be pressed for cooking oil, provided additional savings. Farmers' mental outlook also changed. As one farmer put it, 'We no longer think about whether we will have enough to eat the next day'.

Enough confidence was built between farmers and researchers that this project had contributed to the food security of the rice-farming families in salt-affected areas. However, farmers are still conservative and, over the longer term, will continue to test new varieties to validate them under a wider range of environmental conditions. They will continue to compare these varieties with their traditional varieties that, under these conditions of multiple and complex stresses, assure reliable but low yields. Ultimately, the farmers are the 'experts' in knowing how to make a living in these harsh ecosystems and their experiences guide their judgement about technology adoption.

Conclusions and Recommendations

Farmers in coastal areas remain uncertain of their harvest due to complexities of the ecosystem and the lack of or limited access to suitable germplasm and associated management options. Under the multi-stakeholder project funded by the CPWF for salt-affected areas, partners strived to provide better-adapted rice genotypes, non-rice crops and associated management options to the farmers in various target areas, depending on their specific plant-type requirements. Farmers were more responsive to adapt new interventions through the PVS concept. Additional farmers are being encouraged to adopt these technologies each year based on farmer-to-farmer exchange of information. This induction effect percolated down well after the completion of the first 3 years of the project. Farmers in the coastal areas are able to increase their yields from < 2 t/ha to about 3.5 t/ha. Newly selected genotypes through PVS trials are being outscaled and accomplishments are already visible at the project sites. There is great buoyancy among the farmers and researchers alike for achieving food security of rice-farming families in saline coastal deltas whose livelihoods depend on rice. The project envisaged the following recommendations:

- The close collaboration of all partners has proved to be extremely fruitful in building a strong partnership and in speeding the progress of technology validation and adoption.
- There is a need to strengthen seed supply systems further for use in testing in adaptive trials. Some farmers or farmers' communities could be trained as seed growers.
- Greater efforts by NARES institutions, NGOs and government agencies are needed to ensure efficient and rapid dissemination of the technologies to remote farmers.
- PVS should be considered an integral component of varietal testing and validation when growing conditions are unfavourable and challenges are target specific.
- Detailed information on the extent of salt-affected areas in different countries needs to be assessed more accurately to determine additional exploration domains.

Acknowledgements

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References

Abrol, I.P., Yadav, J.S.P. and Massoud F.I. (1988) Salt-affected soils and their management. *FAO Soils Bulletin No 39*, FAO, Rome, 131 pp.

Alloway, B.J. (2004) *Zinc in Soils and Crop Nutrition*. International Zinc Association, Belgium, 128 pp.

Chinnusamy, V., Jagendorf, A. and Zhu, J.K. (2005) Understanding and improving salt tolerance in plants. *Crop Science* 45, 437–448.

CSSRI (2006) *CSSRI: A Journey to Excellence (1969–2006)*. Central Soil Salinity Research Institute, Karnal, India, 156 pp.

Flowers, T.J. (2004) Improving crop salt tolerance. *Journal of Experimental Botany* 55(396), 307–319.

Flowers, T.J. and Flowers, S.A. (2005) Why does salinity pose such a difficult problem for plant breeders? *Agricultural Water Management* 78, 15–24.

FAO (Food and Agriculture Organization) (2007) Database (http:/apps.fao.org/page/collections?subset =agriculture, accessed 22 December 2007).

Gregorio, G.B., Senadhira, D., Mendoza, R.D., Manigbas, N.L., Roxas, J.P. and Guerta, C.Q. (2002) Progress in breeding for salinity tolerance and associated abiotic stresses in rice. *Field Crops Research* 76, 91–101.

Maas, E.V. and Hoffman, G.J. (1977) Crop salt tolerance: current assessment. *American Society of Civil Engineers Journal of the Irrigation and Drainage Division* 103, 115–134.

Makihara, D., Makoto, T., Miho, M., Yoshihiko, H. and Toshiro, K. (1999) Effect of salinity on the growth and development of rice (*Oryza sativa* L.) varieties. *Japanese Journal of Tropical Agriculture* 43(4), 285–294.

Massoud, F.I. (1974) Salinity and alkalinity. In: *A World Assessment of Soil Degradation: An International Programme of Soil Conservation (Report of an Expert Consultation on Soil Conservation)*. FAO, UNEP, Rome, pp. 16–17.

Moradi, F., Ismail, A.M., Gregorio, G.B. and Egdane, J.A. (2003) Salinity tolerance of rice during reproductive development and association with tolerance at the seedling stage. *Indian Journal of Plant Physiology* 8, 105–116.

Ponnamperuma, F.N. (1984) Role of cultivar tolerance in increasing rice production on saline lands. In: Staples, R.C. and Toenniessen, G.H. (eds) *Salinity Tolerance in Plants: Strategies for Crop Improvement*. Wiley, New York, pp. 255–271.

Rao, P.S., Mishra, B., Gupta, S.R. and Rathore, A. (2008) Reproductive stage tolerance to salinity and alkalinity stresses in rice genotypes. *Plant Breeding* 127, 256–261.

Sahrawat, K.L. (2004) Iron toxicity in wetland rice and the role of other nutrients. *Journal of Plant Nutrition* 27(8), 1471–1504.

Salam, M.A., Rahman, M.A., Bhuiyan, M.A.R., Uddin, K., Sarker, M.R.A., Yasmeen, R. and Rahman, M.S. (2007) BRRI dhan 47: a salt-tolerant variety for the boro season. *International Rice Research Notes* 32, 42–43.

Seednet (2006) State-wise replacement rate increase of important crops (http:/seednet.gov.in/Material/SRR.pdf, accessed 6 October 2007).

Singh, R.K., Singh, K.N., Mishra, B., Sharma, S.K. and Tyagi, N.K. (2004) Harnessing plant salt tolerance for overcoming sodicity constraints: an Indian experience. In: *Advances in Sodic Land Reclamation*. Concept Paper for the International Conference on ‘Sustainable Management of Sodic Soils’ held at Lucknow, India, 9–14 February 2004. UP Council of Agricultural Research (UPCAR), Lucknow, India, pp. 81–120.

Tanji, K.K. (1990) Agricultural salinity assessment and management. In: Tanji, K.K. (ed.) *ASCE Manuals and Reports on Engineering Practice No 71*. American Society of Civil Engineers, New York, 619 p.

Tyagi, N.K. and Minhas, P.S. (1998) *Agriculture Salinity Management in India*. CSSRI (Indian Council of Agricultural Research), Karnal, India, 526 p.

UN Information Service (2000) Press Release No UNIS SG/2543 dt. 13 April 2000 (www.unis.unvienna.org/unis/pressrels/2000/sg2543.html, accessed 7 September 2007).

Zeng, L., Lesch, S.M. and Grieve, C.M. (2003) Rice growth and yield respond to changes in water depth and salinity stress. *Agricultural Water Management* 59, 67–75.

Zolvinski, S. (2008) Listening to farmers: qualitative impact assessments in unfavorable rice environments. *IRRI Technical Bulletin No 12*. IRRI, Los Baños, Philippines, 47 pp.

14 Rice Varieties and Cultural Management Practices for High and Sustained Productivity in the Coastal Wetlands of Southern Bangladesh

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Abstract

The importance of including farmers in targeted breeding and participatory variety selection (PVS) to ensure the adoption of high-yielding varieties was demonstrated in the coastal wetlands of the Ganges–Brahamputra Delta of southern Bangladesh. Five sites were selected for conducting 'mother and baby' trials. About 245 salt-tolerant genotypes from the International Rice Research Institute (IRRI) and Bangladesh Rice Research Institute (BRRI) were divided into three mother trial sets of 72 genotypes for the wet ('T. aman') season, 76 for the irrigated dry ('boro') season and 85 for the dry direct-seeded ('aus') season. During the PVS trials, farmers chose the best one or two genotypes from mother trials to grow in their fields as baby trials. Through local non-government organizations (NGOs: Proshika, Gurpukur, Uttaran and Sushilan), a total of 199 resource-poor farmers, including 15 women, selected 34 genotypes for the three seasons. Farmers were given 500 g of seeds of each selection for baby trials under their own management. For the 'boro' season, IR64401-2B-14-1-1, IR60483-2B-17-2-1-2 and BR5777-4-2-1-HR2 were selected. For the 'T. aman' season, IR66401-2B-14-1-1 was preferred for its short growth duration and high yield. For the direct-seeded 'aus' season, three genotypes, IR72593-B19-2-3-1, IR64419-3B-12-2 and IR64419-3B-4-3, were identified because of their short growth duration. IR63307-4B-4-3 was identified through PVS trials and was released as BRRI dhan 47 for commercial use in coastal Bangladesh in 2006. Out of 53 landraces collected from these coastal areas, four genotypes – Capsule, Ashfal, Ashfal balam and Chikiram Patnai – were identified as new salt-tolerant donors. Moreover, 16 modern genotypes, including four varieties from Vietnam, were identified as tolerant of salt stress at the seedling stage (EC of 12 dS/m). OM1490 had short duration similar to that of BRRI dhan 28, a popular dry-season variety, but produced more than 1 t/ha extra grain yield. In addition, OM2718, AS996 and BR7109-5R-4 had growth duration similar to BRRI dhan 47 and a yield advantage of more than 1 t/ha. In contrast to BRRI dhan 47, these new lines were non-shattering. Adding ash along with the recommended N, P, K and Zn at 120, 80, 30 and 0.5 kg/ha, respectively, did not increase the grain yield of all varieties in saline areas because of the high soil potassium saturation (> 20%). Moreover, farmers in these areas had been growing salt-sensitive rice varieties successfully by practising:

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(i) high transplanting rates of 5–6 seedlings/hill; (ii) draining the field, followed by irrigation with fresh water from shallow tube wells; and (iii) shifting the shallow tube-well installation after 3–5 years to tap less salt water. Monitoring of the salinity in nearby rivers (Retna) suggested the possibility of their use for rice irrigation from June to the middle of February, when salinity was mostly below 4 dS/m, with potential for an additional dry-season crop.

Introduction

Rice is the dominant cereal in the Bangladeshi diet. The annual population growth has recently slowed down to 1.7%, yet sustaining the growth of the rice supply at that rate is still difficult because the favourable irrigated ecosystem has already been fully covered by high-yielding modern rice varieties (HYVs). Further growth in rice production will depend on developing suitable HYVs for use in the unfavourable and less exploited coastal wetlands and flood-prone areas, where traditional varieties are still being grown to a large extent. Salinity and other related stresses are major constraints to rice production, affecting more than 2.8 million ha of coastal areas in Bangladesh because of seawater intrusion. However, this area is expected to increase with global warming and the anticipated rise in sea level. Nevertheless, the government is making efforts to protect these lands from the intrusion of salt water by continuing to construct embankments and polders. Besides salinity, long-term stagnant flooding of 20–60 cm prevails in these coastal areas and only varieties with reasonable tolerance of such conditions can be grown successfully.

Historically, farmers have used traditional rice varieties in these areas during the wet season, despite their very low yield and grain quality even at low to moderate salinity (< 6.0 dS/m). Furthermore, vast areas remain fallow during the dry season because of high salinity (10–16 dS/m). Existing modern varieties are not adapted to this ecosystem because of their sensitivity to salinity and flooding caused by tidal fluctuations or monsoon rains. Few photosensitive tall local rice varieties are still being grown in these areas because of their modest tolerance of stagnant flooding and salt stress. High-yielding rice varieties that can tolerate moderate salt stress (6–8 dS/m) were developed, such as BR23, BRRI dhan 40 and BRRI dhan 41. However, the adoption of these varieties is still limited because of their shorter seedlings at the time of transplanting and sensitivity to prolonged water stagnation during the vegetative stage.

Numerous rivers and canals traverse the deltas in coastal Bangladesh, with freshwater supplies for most of the year that potentially can be used for growing dry-season crops if proper measures are taken to monitor water salinity and appropriate varieties are made available. Currently, a large area remains fallow during the dry season (November–April) because of high soil and water salinity. However, a few farmers still manage to grow short-duration, salt-sensitive rice varieties during this dry period, using irrigation from shallow tube wells. Apparently, substantial efforts need to be devoted to streamlining the development of salt-tolerant, high-yielding rice varieties with better adaptation to these areas, together with the development of best management practices for both wet- and dry-season rice. A significant portion of the rice food supply for Bangladesh could then be met in the future by increasing the productivity of these areas, which currently are highly underused.

The pressing challenge is to develop efficient methods to speed up the breeding of high-yielding, salt-tolerant varieties with resistance to multiple stresses, including other soil-related disorders and different types of floods experienced in these areas. Germplasm enhancement for salinity and other abiotic stresses is ongoing at the International Rice Research Institute (IRRI) and the Bangladesh Rice Research Institute (BRRI), and advanced lines are routinely made available to the national agricultural research and extension systems (NARES). Adoption of improved materials in these coastal areas of Bangladesh often requires the incorporation of particular adaptive traits to survive multiple stresses, as well as specific grain and eating quality to meet local preferences. This will entail the site-specific evaluation of breeding lines in partnership with farmers under their own management, an approach often referred to as participatory varietal selection, or PVS. Moreover, introducing best management and mitigation strategies as a component of PVS trials will help persuade farmers to adopt these new interventions. This study achieves the following objectives: (i) identify appropriate high-yielding breeding lines suitable for both the wet and dry seasons through PVS trials involving farmers, NGOs and local government personnel; (ii) identify salt-tolerant genotypes among the local landraces being used by farmers to be used as donors in breeding; and (iii) package and test appropriate crop, nutrient and water management practices for increasing the productivity of the coastal deltas of Bangladesh.

Materials and Methods

Participatory varietal selection (PVS)

The BRRI and the IRRI together developed advanced rice breeding lines that could tolerate 8–10 dS/m of salt stress, and with a range of plant characters and grain types. These lines were evaluated at the BRRI regional research stations at Sonagazi and Satkhira as the breeding and testing sites for the coastal saline ecosystem of southern Bangladesh. Three sets composed of 72 breeding lines for the wet season ('T. aman'), 76 lines for the irrigated ('boro') season and 86 lines for the 'aus' season were selected for further evaluation under mother (researcher-managed) and baby (farmer-managed) PVS trials. The PVS trials were conducted at five sites representing salt-affected coastal districts. Initial soil salinity in all trial plots was above the critical level for rice (> 4.0 dS/m) and ranged from 5.9 to 8.3 dS/m, except at Noakhali in the 'T. aman' season (3.6 dS/m). Salinity was highest in the dry season (6.9–10.5 dS/m; average of 8.7 dS/m), followed by the wet seasons in 'aus' and 'T. aman' (8.1 and 6.2 dS/m, respectively).

The mother trial for 'T. aman' was conducted at four sites – Char-Sonapur (Sonagazi), Char-Lawrence (Laxmipur), Char-Jabbar (Noakhali) and Benarpota (Satkhira) – in 2001, followed by baby trials in 2002 and then evaluation in farmers' fields at three villages in 2003. A mother trial under the 'aus' ecosystem was established at the Sonagazi BRRI farm in 2002 and at Upakul Villa (Char-Lawrence, Laxmipur) in 2003. Similarly, a mother trial for the 'boro' season was conducted at Benarpota (Satkhira) and Gobindopur (Kaliganj) sites in 2000–2001 and at Benarpota in 2001–2002, followed by baby trials in the 2001/2 and 2002/3 seasons. Field days were organized for baby trials in each season to allow farmers to evaluate the different entries while walking through the trials.

Non-replicated mother trials and researcher-managed on-farm experiments were conducted in partnership with farmers. Farmers evaluated the PVS trials at crop maturity. The Department of Agricultural Extension (DAE) and five NGOs (Gurpukur, Uttaran, Sushilan, Proshika and BRAC) organized 25–40 resource-poor farmers, including up to 15 women, for the mother trials across the sites in each cropping season. A briefing on the importance of involving farmers in selection and variety development through PVS was given to all partners at the start of the process. Participating farmers were divided into three to four groups of eight to ten farmers each, and each group was led by a researcher. Each farmer was given a simple PVS evaluation sheet to help choose one or two genotypes for baby trials to be conducted under their own management. After the field visit, PVS sheets were collected and two to three farmers from each group were randomly called to share their views and opinions on the selections they made and the criteria they used as a feedback mechanism. All farmers involved in the PVS trials were supplied with 500 g of seeds of the selected genotypes to be grown in their own fields as baby trials. Farmers who would later walk through these baby trials (farm-walk) could select lines from these trials for use in subsequent seasons. The baby trials and plots grown with seeds selected through the farm-walk were monitored using a household-level questionnaire. This process would therefore ensure out-scaling through the participation of additional new farmers each season.

Screening for salinity tolerance using hydroponic culture solution

A collection of 163 rice germplasm accessions composed of 53 landraces from coastal deltas, four Bangladeshi modern varieties, ten lines developed through somaclonal variation, 27 anther culture (AC)-derived lines, 62 IRRI elite breeding lines and seven varieties from Vietnam was evaluated for tolerance of salt stress at the seedling stage in hydroponics. Pre-germinated seeds were sown on a nylon net fitted with styrofoam floated on plastic trays filled with full-strength nutrient solution, as described by Yoshida *et al*. (1976). Fourteen days after sowing, the electrical conductivity (EC) of the nutrient solution was increased to 6 dS/m using NaCl, and subsequently raised to 12 dS/m by a gradual increase of 2 dS/m every other day. Pokkali and IR29 were used as salt-stress-tolerant and -susceptible checks, respectively. Plants were evaluated visually 3 weeks after the start of the treatment (after reaching an EC of 12 dS/m) using the standard evaluation system (SES) of the IRRI (IRRI, 1998), at which time the salt-sensitive check showed severe stress symptoms. The SES uses a scale of 1– 9, where 1 means no symptoms of injury (highly tolerant) and 9 means highly sensitive, when plants are dead or dying. The experiment was carried out in 2006 in the greenhouse of the Plant Physiology Division of the BRRI.

Evaluation of somaclonal (SC) and anther culture (AC) lines under field conditions

Two somaclonal lines developed from the popular rice variety BRRI dhan 29 through seed culture in a medium with salinity of 15 dS/m and two AC-derived lines were evaluated at the BRRI regional station at Satkhira farm. The AC lines were developed from crosses involving the salt-tolerant donors IR52724 and BRRI dhan 40 with the high-yielding modern varieties BRRI dhan 36 and BRRI dhan 29 developed for the irrigated (boro) season (Faruque *et al*., 1998). BRRI dhan 29 (salt-sensitive) was used as the standard check. The trial was conducted during the dry season (irrigated) of 2006/7. The field layout followed a randomized complete block (RCB) design with three replications and plot size of 5.4 m × 2 m. Forty-day-old seedlings were transplanted at two to three seedlings per hill, with spacing of 25 cm × 15 cm. Fertilizer at 80:60:40:0.5 kg of N, P, K and Zn per hectare was used with an equal split application of N as basal and then at 15, 30 and 50 days after transplanting (DAT). The total amount of P, K and Zn was applied during the final steps of land preparation. Irrigation water was provided from a shallow tube well with an EC of < 1 dS/m. The initial soil (dry soil) salinity ranged from 6 to 8 dS/m. Data on plant height, growth duration, visual symptoms using the SES (IRRI, 1998), spikelet sterility (%), grain shattering, yield and phenotypic acceptance at maturity were collected.

Evaluation in salt-affected areas

This study was conducted at the BRRI regional station at Satkhira, southern Bangladesh, during the dry season of 2005/06 and 2006/07 under irrigated conditions. A total of 106 rice elite breeding lines were grown in 2005–2006. Nine genotypes were selected and compared for growth duration, phenotypic acceptance, salt-stress tolerance and yield performance relative to BRRI dhan 28 (salt-sensitive) and BRRI dhan 47 (salt-tolerant) checks. Both breeding lines and the check varieties were evaluated during 2006–2007, in an RCB design with three replications. The same crop management practices were followed as described earlier, including irrigation from shallow tube wells. Data on grain shattering, growth duration, plant height, per cent spikelet sterility, yield and phenotypic acceptance at maturity were collected and analysed.

Crop and nutrient management practices

Salt-sensitive (BRRI dhan 28) and salt-tolerant (BRRI dhan 47) varieties were evaluated under four fertilizer managements: T_1 = recommended N, P, K and Zn (120:80:30:0.5 kg N, P, K and Zn per hectare, respectively), $T_2 = T_1$ + additional 50 kg/ha K, $T_3 = T_1$ + additional 5000 kg/ha ash at 15 DAT and $T_4 = T_1$ + additional 20 kg/ha N. The experiment was conducted under irrigated conditions during the 2006/7 dry season, using an RCB design with three replications. The source of N, P, K and Zn was urea, triple superphosphate, muriate of potash and zinc sulfate, respectively. The trial was conducted on-station (BRRI Satkhira) and on-farm (Tala). Soils at both sites were analysed for pH, organic carbon, total N, available P, exchangeable K and soil salinity. P, K and Zn were applied during final land preparation in the respective treatment plots, except in T_2, where K was applied in two equal splits (at final land preparation and panicle initiation). Nitrogen was applied in three equal splits at 15, 30 and 45 DAT. Water from shallow tube wells (EC < 3 dS/m) was used for irrigation. The soil and water salinity of each treatment plot was measured at intervals of 15 days from 15 to 90 DAT. Grain yield was evaluated to compare the effect of the different nutrient management packages. Other crop management practices were the same as those used by local farmers in their respective areas.

Monitoring salinity in river water

The Betna River flows adjacent to the BRRI farm in Satkhira and salt concentration in this river increases sharply during the dry season. Farmers usually avoid using its water for irrigation during the 'boro' season. The objective of this monitoring was to assess the time window when the salinity in the river water was sufficiently low to be used safely for irrigation during the dry season. Salinity (EC) of the river water at points adjacent to the BRRI regional station at Satkhira was monitored weekly during high and low tides during the dry season from November 2006 to April 2007 using a handheld EC meter.

Results and Discussion

Participatory varietal selection

PVS is a decentralized process that allows farmers, NGOs and extension workers to be involved actively in the selection and evaluation of elite rice breeding lines at target areas, using their own selection criteria and growing conditions. Plant materials with desired agronomic and quality characteristics such as plant type, duration to maturity, grain yield and quality are selected by farmers under their own field conditions and management. This is in contrast to the conventional approach, in which breeding lines are bred and evaluated by researchers and then handed over to farmers and which, in most cases, do not meet their expectations. Five sites were established to ensure fast dissemination of the elite germplasm and serve as replications for data analysis. These five sites selected for conducting mother (researcher-managed trials with numerous entries) and baby (farmer-managed trials with fewer, 1–3, genotypes) trials were located in the salt-stress-prone coastal belt of southern Bangladesh in Sonagazi, Laxmipur, Noakhali, Satkhira and Kaliganj Provinces. The 245 salt-tolerant genotypes used initially in this study were evaluated in three mother trials, rainfed (72 lines), irrigated (76) and dry direct-seeded 'aus' (85). NGOs (BRAC, Proshika, Gurpukur, Uttaran and Sushilan) and Department of Agricultural Extension personnel, as well as local farmers, participated in the trials.

PVS trials during the rainfed ('T. aman') season

A total of 87 farmers participated in four PVS mother trials. Out of the 72 lines evaluated in these trials, farmers selected ten lines designated as PVS-T1 to PVS-T10, with T referring to 'T. aman' (Table 14.1). Large variation among farmers and locations was apparent in the choice of these genotypes, suggesting that these advanced breeding lines had some site-specific characteristics. Overall, BRRI dhan 40 (PVS-T9) and BRRI dhan 41 (PVS-T10) were chosen by most farmers, followed by PVS-T7. The most important traits considered by farmers when choosing among genotypes included tolerance of lodging, high yield, disease free, uniformity at maturity and short growth duration. The ranking of different genotypes by farmers was clearly location dependent, which indicated variability among these lines in adaptive and quality traits specific to each location and farmers' preferences in such a complex environment.

Considerable variation in yield and other agronomic characteristics was observed among the ten selected PVS-T genotypes (Table 14.2). Most farmers preferred varieties that had a growth duration of 140 ± 5 days, except for PVS-T4, which matured earlier and was chosen mainly at Satkhira and Sonagazi for highlands, as this could help in crop diversification by growing another upland crop after harvest. Farmers

Table 14.1. Selected genotypes from the mother trial and the number of farmers who selected each line in the PVS trials across five locations during the wet season (T. aman) of 2001/2.

		Number of farmers				
Entry	Designation	Sonagazi	Noakhali	Laxmipur	Satkhira	Total
PVS-T1	BR5778-156-1-3-HR1	5	2	–	16	23
PVS-T2	BR5778-156-1-3-HR14	15	8	–	28	51
PVS-T3	BR5778-156-1-3-HR15	16	4	–	16	36
PVS-T4	IR66401-2B-14-1-1	3	–	1	9	13
PVS-T5	BR5999-82-3-2-HR1	18	3	14	3	38
PVS-T6	BR5999-82-3-2-HR10	10	3	13	5	31
PVS-T7	BR5999-82-3-2-HR16	6	13	28	8	55
PVS-T8	BR5333-34-4-6	14	–	–	–	14
PVS-T9	BRRI dhan 40	16	19	19	9	63
PVS-T10	BRRI dhan 41	28	18	28	12	86

Table 14.2. Agronomic performance of selected PVS-T genotypes in mother trials across four locations during the wet season (T. aman) of 2001/2.

			Yield (t/ha)				
Entry	Plant height (cm)	Duration (days)	Sonagazi	Noakhali	Laxmipur	Satkhira	Mean
PVS-T1	126	135	1.4	5.9	2.1	3.8	3.3
PVS-T2	120	135	1.2	4.7	2.1	3.7	3.0
PVS-T3	124	136	1.2	5.4	2.3	4.3	3.3
PVS-T4	106	126	2.0	2.9	1.5	3.0	2.3
PVS-T5	130	135	3.6	6.4	5.2	4.7	5.0
PVS-T6	130	136	3.5	5.4	4.5	4.7	4.5
PVS-T7	130	135	2.2	4.4	3.8	3.8	3.5
PVS-T8	112	146	2.9	5.4	4.1	–	4.1
PVS-T9	136	138	1.7	4.9	4.5	3.8	3.7
PVS-T10	138	144	2.8	4.4	4.2	3.7	3.7
$LSD_{0.05}$							0.25

grew their selected PVS-T genotypes as baby trials in 2002, using their own management practices. Data from household-level questionnaires showed that 50% of the farmers were discouraged by the results of the baby trials because of the high water stagnation in the field, where standing water depth ranged from 30 to 50 cm from transplanting to maximum tillering stage. A total of 96 farmers participated in the farm-walks through the baby trials in three villages that were not affected seriously by water stagnation. Five PVS-T genotypes were selected by farmers (Table 14.3). Two sister lines (PVS-T5 and PVS-T7) were selected at Sonapur, while two sister lines (PVS-T1 and PVS-T2) and PVS-T4 were chosen at the Satkhira and Kaliganj sites.

All the farmers that participated in the farm-walk grew their selected genotypes under their own management practices in 'T. aman' of 2003. PVS-T4 showed high temperature sensitivity during the reproductive phase, heterogeneity during heading and high panicle sterility. PVS-T4 is a short-duration genotype; thus, flowering coincided with the high temperature spell (> 35 °C) during early to mid-October. On the other hand, PVS-T1, PVS-T2, PVS-T5 and PVS-T7 are relatively tall and prone to lodging at high wind speed (30–50 km/h), which is a recurrent phenomenon in these coastal areas during early November. These results suggested that the current genotypes were probably not suitable for the wet season, which prompted termination of

Table 14.3. Performance of PVS-T genotypes in baby trials and number of farmers that participated in farm-walks for selection during the wet (T. aman) season of 2002/3.

Genotypes	Plant height (cm)	Growth duration (days)	Number of farmers[a]	Yield (t/ha) L1[b]	L2	L3	Mean
PVS-T1	132	126	27	4.5	5.0	–	4.8
PVS-T2	133	126	28	5.0	5.1	–	5.1
PVS-T4	91	112	34	4.5	3.4	–	4.0
PVS-T5	140	141	29	–	–	5.0	5.0
PVS-T7	139	140	17	–	–	5.0	5.0
$LSD_{0.05}$							0.89

[a]Number of farmers that selected each entry; [b]locations at L1, Parkumira, Tala; L2, Gobindapur, Kaliganj; L3, Sonapur, Feni.

further testing of these genotypes during 'T. aman' in subsequent seasons. However, the information and feedback obtained during these trials were found to be valuable in formulating breeding strategies to develop genotypes that were most likely to be adapted to these conditions. Any breeding programme for these coastal wetland areas needs to consider the optimum duration and tolerance of stagnant flooding, lodging and salinity, besides other desirable agronomic and quality traits (Ismail *et al.*, 2008).

PVS trials during the 'aus' season

In 2002, a mother trial comprising 85 short-duration (120–130 days) IRRI breeding lines was conducted at the BRRI farm in Sonagazi, a salt-stress-prone area, under the 'aus' system. The cultural practices being followed and the main characters of the 'aus' system in these coastal wetland areas are:

- Dry direct seeding is commonly followed using the dibbling method, in which seeds are placed in subsurface moist soil to avoid high salinity and moisture stress during germination.
- Drought as well as salt stress (6–8 dS/m) is common during seedling and tillering stages.
- Water stagnation of 20–50 cm occurs at tillering through maturity stage, depending on land elevation.
- Harvesting of the 'aus' crop needs to be completed at or before mid-August to allow transplanting of the main wet-season ('T. aman') rice crop.

The mother trial for the 'aus' season was established at the BRRI regional station at Sonagazi, with these conditions in mind. Dry direct seeding was accomplished using the dibbling method. The crop was affected by drought after seeding and then by water stagnation of 20–30 cm at maximum tillering through maturity. This PVS activity was conducted in collaboration with the DAE and two NGOs (Proshika and BRAC), wherein 29 farmers, including two women, were involved in evaluating the mother trial at crop maturity in August 2002. Twelve salt-tolerant genotypes were selected, all of which had higher yield and were shorter than BRRI dhan 27, a high-yielding variety commonly used during the 'aus' season.

In the following season of 2003, another mother trial was conducted at Upakul Villa, Char Alexgender, Laxmipur, in southern Bangladesh, using 22 genotypes, including the 12 PVS-A lines selected in 2002. Proshika, BRAC and the DAE invited 31 farmers, including five women, to participate in this PVS activity. The farmers selected four PVS-A (A = 'aus') genotypes at maturity (Table 14.4). About 0.5 kg of seeds of each of the PVS genotypes was distributed to the farmers for the next baby trials on their own farms during the 2004 and subsequent 'aus' seasons.

PVS trials during the 'boro' season

The researcher-managed on-farm mother trial for the dry ('boro') season composed of 76 salt-tolerant (8–10 dS/m) genotypes was conducted at Satkhira and Kaligonj sites in 2000/1. Thirty-seven farmers participated in the PVS activity at crop maturity, jointly with the DAE,

Table 14.4. Performance of selected genotypes in mother trials and number of farmers who selected each aus PVS entry at Char Alexgender, Laxmipur, during the aus season of 2002/3.

Entry	Designation	Number of farmers	Plant height (cm)	Growth duration (days)	Yield (t/ha)
PVS-A2	IR72046-B-R-6-3-1	7	85	117	3.0
PVS-A6	IR63307-4B-4-3	11	103	120	3.1
PVS-A9	IR64419-3B-4-3	16	91	104	2.7
PVS-A10	BRRI dhan 27	10	123	100	2.2
$LSD_{0.05}$					0.49

three NGOs (Gurpukur, Uttaran and Sushilan), government officials and local leaders (union councils). A total of 24 genotypes were selected by participating farmers and were designated PVS-B1 to PVS-B24 (B = 'boro'). Since handling of such a large number of genotypes in baby trials was difficult, only seeds of PVS-B1 to PVS-B8 were distributed to farmers, and another set of PVS trials was conducted in 2001/2 with the remaining PVS-B genotypes.

In 2001/2, another mother trial was conducted at Benerpota and 42 farmers from Kaliganj, Tala and Satkhira, including 15 women, participated in the PVS activity. A total of 12 genotypes were selected by farmers (Table 14.5). The performance of the selected PVS-B genotypes was, to a great extent, appreciated by farmers because of their yield and short growth duration. The major attributes considered by farmers during the selection process were yield and yield-contributing characters (high number of panicles per plant and grains per panicle, low sterility), as well as short duration to maturity. Salinity was low in the field at the time of transplanting, about 2–3 dS/m, but then increased gradually to approach the critical level of 4 dS/m starting in late April and afterwards increasing substantially to reach about 8–10 dS/m later in the season. This trend is the main reason that triggers farmers to select short-duration genotypes to avoid higher salinity during the more sensitive reproductive stage, when both soil and water salinity become exceptionally high.

The farmers who participated in the PVS exercise were then given about 0.5 kg of seeds of their selected PVS-B genotypes for use in baby trials during the 2002/3 'boro' season. Farm-walks were conducted at seven villages with 211 farmer participants. Ultimately, five genotypes were shortlisted and proposed for further evaluation through the national variety release system (Table 14.6). Seeds of these five genotypes, together with a local check, were distributed to ten farmers for further evaluation in subsequent 'boro' seasons, and the data generated from these trials served as the basis for the nomination of these lines to be released as

Table 14.5. Performance of genotypes selected from the mother trial and number of farmers who selected each entry at Benerpota, Satkhira, during the boro season of 2001/2.

PVS entry	Designation	Number of farmers	Plant height (cm)	Yield (t/ha)
PVS-B2	BR5778-156-1-3-HR1	4	99	6.7
PVS-B3	IR63307-4B-4-3	7	121	6.1
PVS-B4	IR64419-3B-4-3	2	94	5.6
PVS-B5	IR65192-4B-14-1	3	78	6.3
PVS-B6	AT309-1-GAZ	5	90	4.9
PVS-B7	IR10206-29-2-1	3	93	6.7
PVS-B8	BR5777-11-2-4-1-HR2	32	93	6.7
PVS-B9	IR63275-B-1-1-3-3-2	7	104	5.7
PVS-B12	IR72046-B-R-1-3-1	5	97	7.0
PVS-B13	IR72046-B-R-6-2-2	5	93	6.4
PVS-B19	IR66401-2B-14-1-1	27	96	6.2
PVS-B20	IR60483-2B-17-2-1-2	10	96	6.3
$LSD_{0.05}$				0.76

Table 14.6. Performance of PVS-B genotypes in baby trials and the number of farmers who selected each genotype during the boro season of 2002/3.

Genotype	Plant height (cm)	Growth duration (days)	Number of farmers	Yield (t/ha) L1[a]	L2	L3	L4	L5	L6	L7	Mean
PVS-B3	96	149	25	–	–	–	–	–	6.0	–	6.00
PVS-B8	91	153	36	6.0	6.2	6.0	6.0	–	–	–	6.05
PVS-B9	97	154	57	6.2	6.4	–	6.5	–	–	6.4	6.38
PVS-B13	93	145	27	–	–	–	–	6.0	–	–	6.00
PVS-B19	99	152	108	6.5	6.1	6.8	6.8	–	–	–	6.48
$LSD_{0.05}$											0.35

[a]L1, Satkhira Sadar; L2, Ashashuni; L3, Kaliganj; L4, Sakdah; L5, Uttaran; L6, Benerpota; L7, Kashipur.

commercial varieties for the coastal wetlands of southern Bangladesh. Seed samples of these five PVS-B genotypes were also submitted to the Seed Certification Agency of Bangladesh for the distinct, uniformity and stability (DUS) evaluation, as a requirement for national varietal release.

The PVS approach involving resource-poor farmers as the ultimate beneficiaries and local NGOs, government agencies and extension personnel as the main players in the process proved to be extremely successful in these coastal areas. This is because of the tremendous variability in this ecosystem with respect to persisting hydrological and soil limitations, variability in seasonal conditions that dictates varieties with specific agronomic and adaptive traits and variation in farmers' preferences with respect to plant type and grain quality aspects. The involvement of farmers from the initial stages of the process gave them a sense of ownership and confidence. In addition, the involvement of local and national government authorities helped in the upscaling and recognition of the varieties being selected, and could facilitate their release. Currently, five genotypes each for the 'T. aman' and 'boro' season have been identified by farmers through PVS trials and are spreading fast among farmers in the region. These lines have already been included in the national variety release system of Bangladesh for release as commercial varieties and one of these lines has already been released as BRRI dhan 47 in 2006, for use in saline areas during the 'boro' season (Salam *et al.*, 2007; Islam *et al.*, 2008).

Generating new salt-tolerant germplasm

Screening for salinity tolerance using hydroponic culture solution

About 53 rice landraces were collected from the rainfed lowlands of coastal Bangladesh to help conserve this precious germplasm and to evaluate it for traits such as tolerance of salt stress and stagnant floods, which are potentially useful for breeding. These lines were subsequently screened for their tolerance of salinity in hydroponics using a salt stress of about 12 dS/m during the seedling stage. The evaluation was made using SES scores. Four landraces were identified that had a score of 1 and ten others were rated 3 (Table 14.7). These local varieties are tall and have taller seedlings at the time of transplanting, which is a prerequisite for transplanted rice in these coastal areas during the wet season, where > 80% of the fields become inundated with 20–50 cm of water throughout most of the season. On the other hand, the high-yielding modern varieties developed for the coastal areas of Bangladesh, such as BR23 and BRRI dhan 40, are moderately tolerant of salt stress (Table 14.7) and are suitable only on higher lands because of their shorter seedlings at the time of transplanting. This study identified at least four genotypes successfully, Capsule, Ashfal, Ashfal balam and Chikiram Patnai, that were more adapted to the conditions of this coastal ecosystem and were tolerant of stagnant flooding and salt stress, but had lower yield than modern rice varieties. The selected lines are potential

Table 14.7. Promising salt-tolerant landraces of coastal Bangladesh and IRRI and BRRI breeding lines bred for the irrigated (boro) ecosystem identified using hydroponics under greenhouse conditions at BRRI, Gazipur, Bangladesh.

Landraces		Breeding lines	
Entry	SES rating[a]	Entry	SES rating
Sadamota	3	BR7109-5R-2	3
Gadi Muri	3	BR7109-5R-4	3
Kajalsail	3	BR7084-310-AC8	3
Rajasail	5	BR7084-3R-39	5
Nonabokra	3	IR65192-3B-14-1-1	5
Ashfal balam	1	IR66946-3R-178-1-1	3
Patnai23	3	IR68657-3B-19-3	5
Ashfal	1	BR7084-310-AC3	5
Capsule	1	IR72049-B-R-22-3-1-1	3
Kalamosa	3	IR72593-B-3-2-3-3	3
Changai	3	OM4498	5
Sadabalam	3	OM1490	5
Jamainadu	3	OM2718	5
Chikiram Patnai	1	AS996	5
Nonasail	3	IR63311-B-3R-B-10-3	3
BR23	5	IR73571-3B-7-1	3
BRRI dhan 40	5	BRRI dhan 47 (tolerant variety)	3
Pokkali (tolerant check)	1	BRRI dhan 28 (sensitive variety)	7
IR29 (susceptible check)	9	Pokkali (tolerant check)	3
		IR29 (susceptible check)	9

[a]Standard evaluation system of IRRI with 1 indicating normal growth and 9 indicating that plants are dead or dying (IRRI, 1998).

donors in breeding programmes because their tolerance of salt stress is similar to that of Pokkali, the landrace from India traditionally being used as a donor, but they have better plant type and grain quality. These lines are now being used to develop mapping populations to identify new QTLs and genes for tolerance of salinity.

A set of 106 rainfed lowland elite breeding lines bred at IRRI and BRRI for the irrigated ecosystem was also evaluated using the hydroponic culture system. These genotypes were screened at 12 dS/m during the seedling stage and several of them showed an SES score of 3–5 (Table 14.7). The tolerant check Pokkali had a score of 3 and the sensitive check IR29 had a score of 9, whereas BRRI dhan 28, the popular variety for the irrigated ecosystem in Bangladesh, scored 7 and the newly released salt-tolerant BRRI dhan 47 scored 3. Performance of the lines in this trial could be affected by the cold stress experienced during the trial, with the minimum temperature ranging from 15 to 20°C. A set of 16 genotypes that were tolerant to moderately tolerant was identified for further mother trials in naturally saline field conditions to evaluate their grain yield and other agronomic and quality traits during the 'boro' season.

Evaluation of somaclonal (SC) and anther culture (AC) lines under field conditions

All the SC and AC lines, together with BRRI dhan 29, were non-shattering types (Table 14.8). Maturity duration of the AC lines was 1 week longer than that of the SC lines, and they also matured 4 days later than the long-duration popular variety, BRRI dhan 29. The high spikelet sterility of the AC lines reduced their grain yield. Consequently, these lines showed poor phenotypic acceptance at maturity and significantly lower yield than the standard variety, BRRI dhan 29. It is worth mentioning that BRRI dhan 29 is still not popular among farmers in the salt-affected areas of southern Bangladesh because of its long growth duration. Long-duration varieties normally mature at a time when salinity becomes too high toward the end of the season, subjecting the crop to severe salt stress during

Table 14.8. Performance of selected somaclonal, anther culture and conventionally developed breeding lines at BRRI regional station in Satkhira, southern Bangladesh, during the boro season of 2006/7.

Genotypes	Shattering[a]	Growth duration (days)	Phenotypic acceptance at maturity	Plant height (cm)	Sterility (%)	Yield (t/ha)
SC and AC lines[b]						
BRRI dhan 29-SC3-27	NS	153	5	97	35	7.5a
BRRI dhan 29-SC3-28	NS	153	5	93	28	7.8a
BR7084-310-AC9	NS	160	6	85	44	5.5b
BR7084-310-AC21	NS	161	6	88	41	5.7b
BRRI dhan 29 (check)	NS	156	5	92	29	7.8a
Conventionally developed breeding lines						
BR7109-5R-2	NS	145	5	90.8	27	7.2
BR7109-5R-4	NS	145	4	92.2	28	7.6
BR7084-3R-39	NS	142	4	81.8	29	6.7
IR65192-3B-14-1-1	NS	140	5	91.8	14	6.8
IR68657-3B-19-3	NS	143	5	94.4	38	7.0
OM1490	NS	137	4	81.2	31	7.0
OM4498	NS	143	5	75.6	28	7.5
OM2718	NS	140	4	83.5	23	7.7
AS996	NS	142	4	86.2	32	7.5
BRRI dhan 28 (check)	NS	136	5	91.2	26	5.7
BRRI dhan 47 (check)	S	142	5	89.6	25	6.8
$LSD_{0.05}$						0.66

[a]NS, non-shattering, S, shattering; [b]means followed by the same letter are not statistically different at $P < 0.05$.

the most sensitive stages from panicle initiation through flowering and pollination. The SC lines matured a few days earlier than BRRI dhan 29 and had yields similar to those of the standard check, suggesting that some of these lines could be adopted by farmers. These early-maturing SC lines were included in subsequent PVS trials for further evaluation.

Evaluation of genotypes under naturally saline field conditions

During the dry season of 2005/6, a total of 106 genotypes were evaluated in the field in areas known to be affected by salt stress. Nine of these breeding lines were selected at maturity, based on their growth duration, yield and other traits preferred by farmers. Four of the selected lines (OM1490, OM4498, OM2718, AS996) were introduced from Vietnam as early-maturing, high-yielding varieties bred for irrigated conditions of the coastal ecosystems of South Vietnam (courtesy of Dr N.T. Lang, Cuu Long Delta Rice Research Institute, Vietnam). BRRI dhan 47 was used as a salt-tolerant check. This variety is known for its good threshing ability but it tends to shatter at maturity (Table 14.9), which is a disadvantage as shattering increases losses during harvest and transport to threshing grounds. All the newly selected lines were non-shattering, similar to BRRI dhan 28, the most popular variety during the ‘boro’ season. Selected genotypes matured at about the same time as BRRI dhan 47, except OM1490, which had growth duration similar to that of BRRI dhan 28. Moreover, OM1490 showed better acceptability at maturity and a yield advantage of 1.0 t/ha over BRRI dhan 28, indicating its potential as a future variety in this region. All selected genotypes had similar height at maturity, except OM4498, which was shorter. Spikelet sterility was lowest in IR65192-3B-14-1-1 and highest in AS996, with the remaining genotypes

Table 14.9. Grain yield (t/ha) of BRRI dhan 28 and BRRI dhan 47 in salt-affected soils under different nutrient management practices. The trial was conducted at the BRRI regional station at Satkhira, southern Bangladesh, and in an adjacent farmer's field under irrigated conditions during the dry season of 2007.

	BRRI station at Satkhira[b]		Farmer's field at Tala[b]	
Treatment[a]	BRRI dhan 28	BRRI dhan 47	BRRI dhan 28	BRRI dhan 47
T_1	6.12b	6.64a	6.53a	6.53a
T_2	6.35b	6.64a	6.18b	6.53a
T_3	6.47b	6.82a	6.29b	6.47b
T_4	6.41b	6.73a	6.24b	6.64a
Mean (varieties)	6.34b	6.66a	6.31b	6.64a

[a]T_1, recommended N, P, K and Zn fertilizer dose (120:80:30:0.5 N-P-K-Zn kg/ha); T_2, like T_1 but additional 50 kg K/ha; T_3, like T_1 but additional 5 t ash/ha at 15 days after transplanting; T_4, T_1 + additional 20 kg N/ha; [b]means followed by the same letter are not statistically different at $P < 0.05$.

showing sterility that was comparable with that of the checks. All selected genotypes had higher grain yield (6.8–7.7 t/ha) than the standard checks, BRRI dhan 28 (5.7 t/ha) and BRRI dhan 47 (6.4 t/ha). Moreover, OM2718, BR7109-5R-4 and AS996 yielded 1.0 t/ha more than the salt-tolerant BRRI dhan 47. These new lines seemed to hold great potential as future varieties for these saline coastal areas and were subsequently included in the PVS trial system for further evaluation and for nomination for the national variety release system.

Water and nutrient management in coastal saline areas

Monitoring river water salinity

Numerous rivers and water canals traverse the coastal deltas of southern Bangladesh. However, these freshwater resources become saline after the monsoon season because of the slow water flow from upper catchments and the intrusion of salt water from the sea through high tides. As a consequence, most of these coastal areas are monocropped with rice during the monsoon season, despite the tremendous potential for crop diversification and intensification by introducing additional crops during the dry season. The potential for use of these resources through the introduction of short-maturing, high-yielding rice varieties, together with proper water management, particularly surface-water storage before river water becomes too saline, has been established previously, with the potential to at least double annual productivity (Mondal *et al.*, 2006). Careful monitoring of salinity in these surface-water resources is a prerequisite to determining the proper window of time for their storage and use. This study was undertaken to monitor water salinity in the Betna River, which flowed adjacent to the BRRI regional station in Satkhira, southern Bangladesh. Water salinity was monitored daily during high and low tides from June 2006 to April 2007 (Fig. 14.1). Evidently, river water can be used directly for irrigation from June up to the middle of February, when salinity remains below 4 dS/m. The extent of water salinity during the high tide is particularly important when the water surface of the river rises to a level that can easily be used for irrigating rice fields using pre-existing sluice gates. The most critical time when river water salinity starts to rise is around mid-February, at which time fresh water can be stored in pre-existing drainage and irrigation canals during high tides, and this water can then be used for irrigation to extend the dry season. In fact, substantial opportunity exists for using these water resources to increase and diversify food sources in these highly impoverished and overpopulated areas, and this could contribute substantially to the country's food security. This will, however, require more research involving local government agencies and NGOs, to establish a system of monitoring and water storage for use during the dry season.

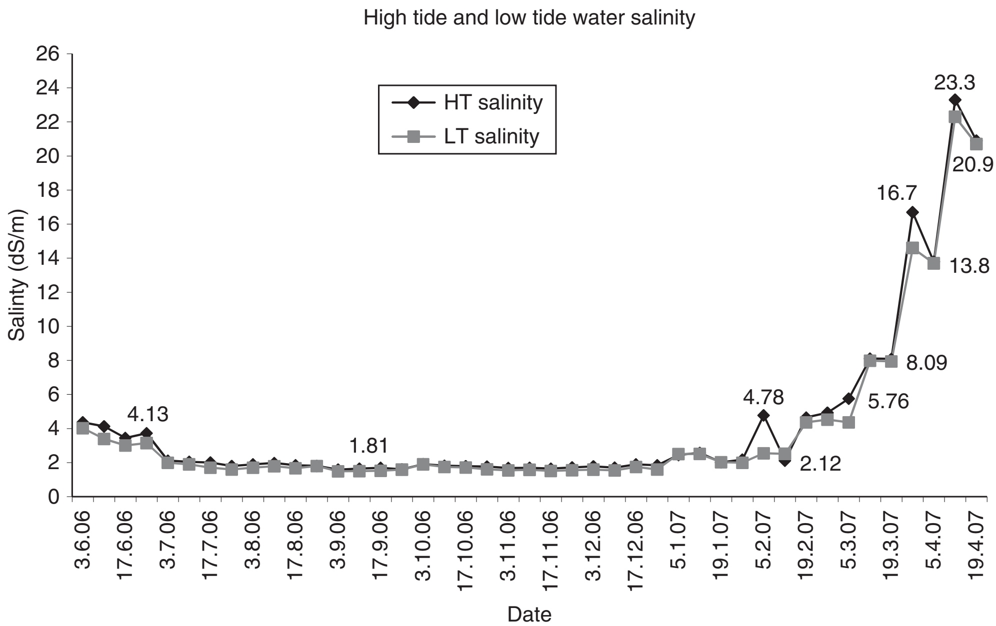

Fig. 14.1. Salinity of the Betna River during high and low tides at the sluice gate point of BRRI farm, Satkhira, southern Bangladesh, from June 2006 to April 2007.

Nutrient and crop management

An increase in sodium concentration in soil and/or water is known to alter the availability and uptake of other plant nutrients. For example, the uptake of potassium and nitrogen is known to decrease with increasing Na^+ concentration in the root zone. An experiment was conducted to test whether the nutrient management recommendations now being used in non-saline areas in southern Bangladesh would need to be adjusted for saline soils. The experiment tested the effect of extra K as an additional 50 kg of K_2O_5 or 5 t/ha of ash and an extra 20 kg/ha of N, plus the recommended N, P, K and Zn of 120:80:30:0.5, respectively. Two separate experiments were conducted, one at the BRRI regional station in Satkhira and the other in a nearby farmer's field. In both trials, salt-tolerant BRRI dhan 47 and salt-sensitive BRRI dhan 28 were used.

The soil pH (8.0), available P (10 ppm) and exchangeable K (0.9 meq/100 g) were similar at both sites. Soil at the BRRI regional station was slightly more saline, with an EC of 5.5 dS/m compared with that of the farmer's field (5.0 dS/m), and with higher organic carbon (2.96%) and total N (0.7%) than the farmer's field (2.52 and 0.17%, respectively). These data suggested similar salinity and N and K status at both sites and that both N and K were probably not limiting. BRRI dhan 47 had significantly higher grain yield than BRRI dhan 28 at both locations (Table 14.9), which was expected because this genotype had higher salt tolerance (Salam *et al.*, 2007). The interaction of management × variety, management × location and location × variety was not significant. Application of K as an additional 50 kg/ha (T_2) or as ash at 5 t/ha (T_3) over the recommended dose (T_1) did not increase grain yield. This was probably because of the high K concentration (0.9 cmol/kg) of the soil, which was much higher than the critical level of 0.1 cmol/kg. Saleque *et al.* (1990) and Bhuiyan *et al.* (1992) reported similar responses to K. The soil was also rich in P and N and, similarly, no response was observed when extra N was applied. Such a situation could prevail in saline soils if they were rich in calcium and magnesium (Panaullah, 1993). Shah *et al.* (2004) reported that the application of an additional 20 kg/ha of K or 5 t/ha of ash increased rice grain yield. This was probably because the K saturation value was lower in the soil at the site where this trial was conducted. Apparently, the role of additional K from either organic or inorganic sources in these saline soils awaits further investigations. Soils in these deltas are probably rich in nutrients as a consequence of silt deposits from flood water during the monsoon season.

Farmers in this area had been growing salt-sensitive rice varieties using the following crop management practices: (i) the use of five to six seedlings per hill during transplanting to compensate for high seedling mortality; (ii) draining their fields and then irrigating them with fresh water to wash salt residues before transplanting, when possible; and (iii) shifting shallow tube-well locations after 3–5 years of use to new locations with relatively less salinity in irrigation water. Our recent studies (Ram *et al.*, 2008) also suggested that proper nutrient and seedling management in the seedbed could contribute substantially to seedling survival and better crop establishment on transplanting in saline soils, and that grain yield of salt-tolerant rice varieties was more responsive to the use of inputs. Apparently, more studies are needed to establish a package of best nutrient and crop management practices for these saline soils to ensure better crop establishment and higher and more stable grain yield, particularly for the newly developed salt-tolerant varieties.

Conclusions

Conventional breeding has shown limited progress in developing varieties adapted to unfavourable rice ecosystems over the past few decades as compared with the progress made in the irrigated ecosystem. This is particularly because the extensive variability in these target areas, the nature and complexity of abiotic stresses persistent at each site and the rice grain quality aspects preferred by local farmers made it impracticable to develop varieties that could have wider adaptation. For these reasons, a farmer participatory approach was followed for the evaluation of breeding lines, involving both men and women farmers and other organizations such as NGOs and local government agencies. Through this process, considerable progress was made in identifying breeding lines that were adapted to the three main growing seasons in the coastal saline areas of southern Bangladesh: the wet (‘T. aman’), dry (‘boro’) and direct-seeded ‘aus’ seasons. An initial set of 245 breeding lines was tested over the three seasons in both mother and baby trial settings in five locations along the coastal saline belt of southern Bangladesh. In each mother trial, farmers were asked to select one or two breeding lines to evaluate them in subsequent seasons in their own fields as baby trials. Initially, a total of 34 genotypes were selected for the three seasons, for testing in farmers’ fields, and a few of them were further identified by farmers as the most suitable for each season. For ‘T. aman’, three genotypes, IR64401-2B-14-1-1, IR60483-2B-17-2-1-2 and BR5777-4-2-1-HR2, were recognized by most farmers. The breeding line IR66401-2B-14-1-1 was selected by relatively fewer farmers, but was still being considered by some of them because of its shorter growth duration of 124 days compared with 135–148 days for other genotypes, coupled with its high yield. For the direct-seeded ‘aus’ season, three genotypes, IR72593-B19-2-3-1, IR64419-3B-12-2 and IR64419-3B-4-3, were identified because of their shorter growth duration, with the two lines IR72593-B19-2-3-1 and IR64419-3B-4-3 having greater yield potential. For the ‘boro’ season, IR63307-4B-4-3 was selected through PVS trials and was released as the commercial variety BRRI dhan 47 in 2006 for the coastal wetlands of southern Bangladesh. These PVS trials were jointly coordinated by the Department of Agricultural Extension, NGOs and farmers, and all participants were persuaded by the effectiveness of this approach for identifying germplasm suitable to these unfavourable areas. This participatory strategy gave farmers an opportunity to be part of the decision-making process, which helped them to develop a sense of ownership and become more confident in using the newly identified lines, as well as in sharing them with their neighbours, which also facilitated further dissemination.

Besides the progress made through these PVS trials, efforts were made to collect and evaluate native landraces historically grown by farmers in these regions, mainly for their conservation and for potential use as donors of adaptive traits in breeding. Out of 53 lines evaluated, four landraces, Capsule, Ashfal, Ashfal balam and Chikiram Patnai, were identified with high salinity tolerance similar to that of Pokkali. Sixteen high-yielding, short-maturing varieties, including four introductions from South Vietnam (OM1490, OM2718, AS996, OM4498), were also identified as salt-tolerant, non-shattering types for the dry season.

Developing salt-tolerant, high-yielding modern varieties adapted to these coastal environments provided an entry point for a longer-term strategy to increase and sustain productivity in these highly populated but impoverished communities. These tolerant varieties could then respond better to input and other management practices. However, packages of efficient and affordable good agronomic practices suitable for these new varieties need to be developed and validated with farmers. Preliminary studies have shown that tremendous opportunities exist for increasing annual productivity through the proper use and conservation of available surface freshwater resources. More efforts are also needed to determine nutrient requirements and other management options that could facilitate a further increase in productivity and stability in these coastal deltas, taking into account the endogenous knowledge currently being used by farmers.

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References

Bhuiyan, N.I., Saha, P.K., Saleque, M.A. and Nuruzzaman, M. (1992) A new critical level of soil potassium for wetland rice. *Bangladesh Journal of Soil Science* 23, 1–14.

Faruque, M.O., Farzana, T., Seraj, Z.I., Sarker, R.H. and Khatun, A.A. (1998) Variation in green plant regeneration response from anthers of indica rice and their hybrids with japonica cv. Taipei 309. *Plant Cell, Tissue and Organ Culture* 54, 191–195.

IRRI (1998) *Standard Evaluation System for Rice*, 4th edn. International Rice Research Institute, Manila, 52 pp.

Islam, M.R., Salam, M.A., Bhuiyan, R.A., Rahman, M.A., Yasmeen, R., Rahman, M.S., Uddin, M.K., Gregorio, G.B. and Ismail, A.M. (2008) BRRI dhan 47: a salt tolerant rice variety for 'boro' season isolated through participatory variety selection. *International Journal of Bio-Research in Bangladesh* 5(1), 1–6.

Ismail, A.M., Thomson, M.J., Singh, R.K., Gregorio, G.B. and Mackill, D.J. (2008) Designing rice varieties adapted to coastal areas of South and South-east Asia. *Journal of Indian Society of Coastal Agricultural Research* 26, 69–73.

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudhury, M.H.K., Chasi, A.M., Majumder, P.K., Islam, M.M. and Adhikary, S.K. (2006) Coastal water resources use or higher productivity?: participatory research for increasing cropping intensity in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 72–85.

Panaullah, G. (1993) Soil salinity and associated problems in connection with crop production in the coastal regions of Bangladesh. In: *Proceedings of the Workshop on Coastal Salinity and Crop Production in Bangladesh*. Bangladesh Rice Research Institute, pp. 1–30.

Ram, P.C., Singh, P.N., Verma, O.P., Ismail, A.M., Singh, N., Srivastava, P., Singh, S.P. and Singh, R.K. (2008) Improving water and land productivity through technology integration in saline sodic soils of the Indo-Gangetic Basin. In: Hunphreys, E., Bayot, R.S., van Barkel, M., Gichuki, F., Svendsen, M., Wester, P., Huber-Lee, A., Cook, S., Douthwaite, B., Haonh, C.T., Johnson, N., Nguyen-Khoa, S., Vidal, A., MacIntyre, I. and MacIntyre, R. (eds) *Fighting Poverty Through Sustainable Water Use. Volume II*. Proceedings of the CGIAR Challenge Program on Water and Food, 2nd International Forum on Water and Food, 10–14 November 2008, Addis Ababa, Ethiopia. CGIAR Challenge Program on Water and Food, Colombo (http://ifwf2.org/?q=resources), pp. 163–166.

Salam, M.A., Rahman, M.A., Bhuiyan, M.A.R., Uddin, K., Sarker, M.R.A., Yasmeen, R. and Rahman, M.S. (2007) BRRI dhan 47: a salt-tolerant variety for the 'boro' season. *International Rice Research Notes* 32, 42–43.
Saleque, M.A., Saha, P.K., Panaullah, G.M. and Bhuiyan, N.I. (1990) Calibration of soil potassium tests with yield of wet season lowland rice in Bangladesh. *Bangladesh Journal of Soil Science* 21, 1–10.
Shah, M.A.L., Rashid, M.A. and Rahman, M.S. (2004) Application of potash in rice. *BRRI Publication* 142, 6.
Yoshida, S., Forno, D.A., Cock, J.H. and Gomez, K.A. (1976) *Laboratory Manual for Physiological Studies of Rice*. International Rice Research Institute (IRRI), Los Baños, Philippines.

15 Boro Rice for Food Security in Coastal West Bengal, India

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Abstract

The boro (winter dry season) rice farming system covers 0.36 million ha in four coastal districts of West Bengal, India, of which 0.08 million ha are irrigated from 'back-feed' tidal water. The boro growing areas are mild to moderately saline, in which irrigation through shallow tube wells or back-feed river water is available. The salinity of irrigation water varies from 1.0 to 4.0 dS/m or more, depending on the source of irrigation water and the time period in the year. Because of salinity, yield loss of up to 37% is observed in boro rice. The important determinants for adopting a rice–boro rice system in West Bengal, India, are mostly biophysical and technical factors and, to a lesser extent, socio-economic factors. This system is being adopted mainly by small and marginal farmers. Boro rice adds extra grain production for food security and about a 48% increase in household income. The adoption of early-maturing, moderately salt-tolerant rice varieties, coupled with the early establishment of boro rice and proper fertilizer and water management, will increase and sustain boro rice production in these coastal areas.

Introduction

The coastal lands of West Bengal comprise parts of four districts, 24-Parganas (North), 24-Parganas (South), Midnapur (East) and Howrah, covering a geographical area of 21,295 km^2, which constitute about 24% of the total state land area. In these coastal lands, rice is grown on about 1.121 million ha during different seasons and is commonly affected by various levels of soil and water salinity. Out of this area, about 0.08 million ha are grown during the boro season (DAWB, 2006). The entire area of the region is broadly divided into: (i) non-saline but stagnant flood areas where water stagnates in the field for longer duration because of impeded drainage; and (ii) saline areas developed because of the ingress of tidal salt water through rivers, rivulets and creeks. These areas typically suffer from salinity in the later stages of crop growth. Rice is grown under different toposequences (Ambast *et al.*, 1998) ranging from uplands (15%) and medium lands (25%) to lowlands (60%). A farm household survey carried out in the coastal lands of the four districts revealed that about 30% of the surveyed parcels (land area owned by one farmer) were non-saline, 55% were moderately saline and 15% were severely saline (Bardhanroy *et al.*, 2004). Severe salinity during the dry season is predominant in the low-lying areas at or below sea level and moderate salinity is more prominent in shallow lowlands.

Cropping systems

The coastal region of West Bengal is predominantly monocropped with kharif (wet season) rice, but the boro rice system is increasingly

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

Table 15.1. Distribution of cropping patterns as affected by salinity in the coastal region of West Bengal (%).

Cropping pattern	Non-saline	Moderate salinity (1.5–3.5 dS/m)	Severe salinity (> 4 dS/m)	Total
Rice–fallow	16	25	2	43
Rice–vegetable/ spices	2	6	0	8
Rice–boro rice	4	22	2	28
Rice–fish	0	1	6	7
Fish–fish	4	7	3	14

Chi-square = 125.2, $P < 0.0001$; values shown are proportions (%) of total land area cropped with rice.
Household survey data generated through IRRI–Government of West Bengal (GOWB) collaborative programme during 2000–2002.

being adopted as irrigation water becomes available (Bardhanroy and Dey, 1992). The monocropped rice–fallow system still occupies about 43% of the total land area, whereas the double-cropped boro rice system covers about 28% of the area, mostly concentrated in moderately saline lands because of better access to irrigation water through gravity channels, low-lift pumps and tube wells (Table 15.1). These lands are prone to moderate flooding during the rainy season. Among the non-rice crops, watermelon, red pepper, cucumber, pumpkin, ridge gourd and, recently, sunflower are found to be the most remunerative under moderate saline conditions (Ambast *et al.*, 1998; Singh *et al.*, 2006) in the dry season. In highly saline areas, brackishwater aquaculture has been adopted between December and May instead of boro rice, due to the scarcity of fresh water for irrigation. This is then followed by transplanted floating rice between August and December in deepwater areas (Bardhanroy and Dey, 1992).

Surveys of the areas planted under different non-rice crops over the years revealed a decline in the area under red pepper and an increase in the area under boro rice and sunflower (Table 15.2). The lack of proper storage and processing facilities and transport and marketing infrastructure is the major constraint to the large-scale adoption of non-rice crops, including red pepper. Rice plus fish and vegetable farming systems in salt-affected areas have been reported to be economically viable as they improve food security and ensure greater yield stability (Lopez *et al.*, 2004). On the other hand, the area and contribution of boro rice to the total rice production of the coastal districts have increased steadily over the years.

Table 15.2. Area under boro rice, red pepper and sunflower during the dry season in coastal districts of West Bengal during 1990 and 2006. Data are averages over three districts (Howrah, 24-Parganas South and Midnapur East).

Crop area (million ha)	1990	2006
Boro rice	0.208	0.246
Red pepper	0.016	0.003
Sunflower	0.0005	0.081
Total	0.225	0.33

DAWB (2006).

While its contribution to total rice production in these areas in 1980 was only 14%, it increased to 35% in 2005. Thus, boro rice currently plays a significant role in the food security of this region (Fig. 15.1).

The biophysical environment of boro rice in West Bengal

The coastal areas of West Bengal are characterized by moderately high temperatures and relatively minimum diurnal and annual temperature changes compared with its other agroclimatic zones. The cooler months are November–February, when the average air temperature remains within 16–28°C. The average annual precipitation varies from 1450 to 1925 mm, with 18–25% coefficient of variability. Most of the rainfall in the region occurs between June and October; however, the boro rice-growing season (November–March) receives only about 4% of the total annual

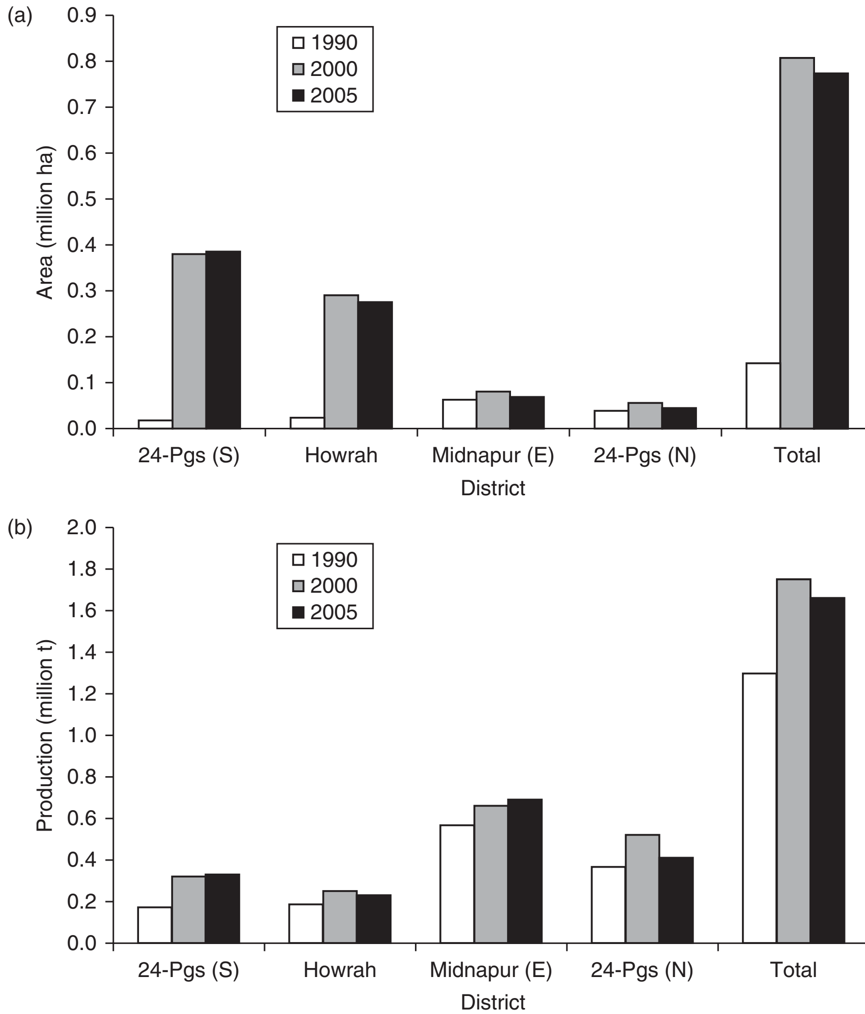

Fig. 15.1. (a) Area and (b) production of boro rice in coastal lands of West Bengal. Evaluation Branch, DOA, GOWB (1990, 2000, 2005).

rainfall. Relative humidity remains high at about 85%, even in March, April and May. This high humidity is beneficial as it reduces evapotranspiration losses and supplies water to the plants in the form of dew in the rabi season (Bandyopadhyay and Bandyopadhyay, 1982). The soils are alluvial, rich in sodium, calcium and magnesium, with plentiful organic matter at different stages of decomposition. The soil pH varies from 7.0 to 8.5.

Boro rice grown by 'back-feed' river water using tidal power constitutes about 23% (0.08 million ha) of the total boro lands in the coastal areas. During high tides, seawater pushes up the fresh river water, causing a rise in the river water level. During the boro rice-growing season (December–March), this water is introduced about three to four times into canals built originally during the British era to drain out stagnant water during the rainy season. The quantity of back-feed river water depends on the nature of the tides. In a year of low monsoon and shallow tides, all the canals may not have an equal share of back-feed river

Table 15.3. Ranges of soil salinity (dS/m) in rice-growing areas in different months at 24-Parganas District in the south of West Bengal.

Months	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Salinity	2–8.4	1–5.0	1–3.5	1.8–3.1	2.3–3.9	3–4.8	4.8–5.8	6.3–7.5	6.1–7.0	5.2–8.8	4.6–10.1	3.3–11.8

The period from November to March represents the boro growing period.
Bandyopadhyay and Bandyopadhyay (1982).

water and it becomes increasingly saline by the third or fourth irrigation, causing salinity stress during the sensitive reproductive stages in certain years. Boro rice grown using underground water is also subject to more salinity during years of less rainfall.

Soil and water salinity in rice-growing areas

Soil salinity is generally lower during the monsoon season but rises slowly and progressively during drier months. Soil samples collected from Canning, Sagar and Bakkhali revealed similar trends (Table 15.3). Since boro is irrigated mostly with underground water through shallow tube wells in areas where back-feed river water is not available, salinity increases progressively with the number of hours of water discharge (Table 15.4). Samples taken in February (late vegetative stage) showed increasing salinity. As such, early harvest of boro rice may help avoid salinity stress during later crop stages. The salinity of back-feed river water at two measurement points was found to be less critical during the early stages of boro rice; however, increased salinity in both underground and surface water may affect the crop during the late reproductive and maturity stages if boro rice is planted late (Table 15.5).

Productivity of boro rice

The average yield of boro rice in the coastal districts of West Bengal has shown little variation during the past few years. Yield variation among years is low due to the planting of the same varieties and to following the same management practices. It is to be noted that, in earlier years, the area of boro rice increased steadily and then declined. This decline was due to the lack of assured irrigation at the tail end of the irrigation canals, particularly in years of low rainfall. Among the districts, the productivity of Howrah is quite low (4155 kg/ha), as about 70% of the boro rice in this district is grown using back-feed river water with tidal power. The rice yields of 24-Parganas North (4656 kg/ha) and Midnapur East (4576 kg/ha) were notably higher (Table 15.6).

A socio-economic study was conducted with the following objectives: (i) to quantify more precisely the extent of the rice–boro rice system in the coastal areas of West Bengal; (ii) to determine the variation in water quality and management practices followed by farmers for boro rice production; (iii) to evaluate the sustainability of the system and its contribution to the production of extra rice for food and extra household income; and (iv) to identify

Table 15.4. Water salinity after different durations of discharge of a shallow tube well during February 2005 at Gosaba, West Bengal.

Water salinity after different durations of discharge (hours)	Salinity (dS/m)
0–50	< 0.5–1
50–100	1.0–1.5
100–150	1.5–2.5
150–200	2.5–4
200–250	> 4

Table 15.5. Salinity (dS/m) of back-feed river water during boro rice-growing period taken at Falta and Diamond Harbour entry point during January–April, 2005.

Month	Falta	Diamond Harbour
January	1.0–1.5	1.5–2.0
February	1.5–2.0	2.0–2.5
March	2.0–2.5	2.5–3.5
April	3.5–4.0	> 4.0

Block-level data collected by researchers from Falta, Diamond Harbour and 24-Parganas South.

Table 15.6. Grain yield (kg/ha) of boro rice in four coastal districts of West Bengal.

District	1990	2000	2005	Mean
24-P (South)	4321	4064	4943	4442
Howrah	4310	4118	4038	4155
Midnapur (East)	4662	4541	4527	4576
24-P (North)	4632	4699	4637	4656
State highest yield	4881	4859	4639	

DAWB (estimation of area and production for principal crops in West Bengal 1990, 2000, 2005).

knowledge gaps and areas for further improvement of boro rice through better varieties and management practices suitable for these salt-affected coastal areas.

Methodology

The study presented in this paper was conducted between 2000 and 2004 through two projects. The first study dealt with the evaluation of the performance of modern rice varieties in saline soils during the boro season using information collected from both on-station and on-farm trials to identify constraints to the adoption of these improved boro rice varieties. On-station trials with improved rice varieties were evaluated in replicated experiments conducted over two dry seasons during 2001–2003. However, few modern varieties were evaluated in non-replicated on-farm demonstrations at three sites where boro rice was grown exclusively using back-feed river water during the 2004/5 boro season. The second part of the study analysed results of a survey carried out in the four coastal districts of 24-Parganas (North and South), Midnapur (East) and Howrah involving 179 farmer households in 15 villages. The selection of villages was done purposively to represent different salinity and management practices, and focused on the adoption of rice–boro rice and rice–aquaculture systems and their contribution to food security and livelihood improvement of farmers in coastal areas.

A village-level extensive survey was conducted to collect information on land-use patterns, ecosystem characteristics, infrastructure facilities, farming practices, prices of agricultural inputs and outputs, terms and conditions of tenancy, labour markets, etc., through focus group discussions with village leaders. A list of all households in the villages was collected from local government institutions and a 10% sample was drawn from each village to generate household-level data. The household-level survey collected data on the socio-economic background of the household, biophysical characteristics of the different parcels of land owned and operated by the household, the use of the parcels in different seasons, input use and the production of different enterprises and farmers' perceptions regarding the sustainability of the emerging farming systems. Secondary information on changes in the farming systems was also collected from various local organizations and unpublished documents.

Measurements of salinity, soil characteristics and land elevation were recorded based on farmers' own assessments (indigenous knowledge). Because of the large size of the farms and land parcels, it was not possible to check the accuracy of the information through specific measurements. The PROBIT method of multivariate regression using qualitative dependent variables (Maddala, 1992) was applied to parcel-level data to analyse the factors affecting the adoption of rice–rice and rice–aquaculture farming systems. A multivariate regression model was also used to analyse the effect of the new farming systems on the yield of wet-season rice to assess system sustainability.

Results and Discussion

Replicated trials using modern high-yielding rice varieties (HYV) conducted at the Salt Paddy Research Station, Gosaba, during the boro seasons of 2001/3 revealed that varieties such as Satabdi and Mohan performed well in coastal environments, with a yield of about 4.7 t/ha (Table 15.7). The salinity of the irrigation water obtained from the rainwater reservoir was

Table 15.7. Grain yield (kg/ha) of five modern rice varieties during the dry seasons of 2001–2003 at the Salt Paddy Research Station at Gosaba, West Bengal.

Variety	2001/2	2002/3	Mean
PNR381	3230	3216	3223
Satabdi	3100	6333	4716
Mohan	4450	4983	4716
Heera	2520	2983	2751
IR36	4530	4606	4568
Mean	3566	4424	3995
C.D. (5%)	1100	440	

highest, about 3 dS/m, during the flowering stage in March. Based on these findings, these varieties were selected and tested in farmers' fields and recommended for adoption. In addition, varieties such as Lalat and Khitish were also adopted during the boro season in these coastal areas. Hybrid rice also showed promising results in these areas. Poonam and Swain (2006) reported grain yield of 6.4 t/ha from the hybrid PA6201 compared with 5.6 t/ha obtained from IR64 in coastal Orissa. The application of *Azolla* together with 50 kg N/ha also resulted in an additional 21–35% yield of dry-season rice in the coastal saline soils of eastern India (Mahata *et al.*, 2006). These results suggested that combining the use of modern high-yielding varieties with proper crop management could enhance boro rice production substantially in these coastal areas.

During 2004/5, the average yield of boro rice in the state was about 4859 kg/ha, but was again lowest in 24-Parganas South at about 4046 kg/ha. On-farm yield trials in three locations in this district (Bishnupur, Falta and Diamond Harbour) revealed that Lalat and Mohan varieties produced significantly higher grain yields across different locations (Table 15.8). The salinity of back-feed water measured at Diamond Harbour and Bishnupur was relatively higher than that at Falta, resulting in 37% less grain yield than the state average and 15% less grain yield than the district average at Bishnupur. Rice cultivars differ significantly in their responses to salt stress in these areas, where various growth and yield parameters are known to be affected negatively by increasing salinity (Zayed *et al.*, 2004).

Socio-economic and biophysical aspects of the adoption of boro rice in coastal West Bengal

The coastal region of West Bengal is densely populated (945 persons/km^2), with dominating rural communities of both landowners and agricultural labour from landless families. Nearly 83% of the land area is operated by small and marginal farmers. The cropping intensity in the region is about 144%, which is lower than the state average of 177%. Household size is associated positively with the intensity of salinity. Household lands suffering

Table 15.8. Grain yield (kg/ha) of six modern rice varieties grown under back-feed river water during the 2004/5 boro season at 24-Parganas (South), West Bengal.

Variety	Bishnupur	Falta	Diamond Harbour	Mean
Khitish	3174	3492	3660	3442
Satabdi	3402	4285	3200	3629
Lalat	4782	6349	4287	5139
Ratna	2857	3174	4086	3372
Krishnahamsa	3174	3968	3466	3536
Mohan	3809	6309	4725	4958
Mean	3533	4596	3904	4013

DAWB (2006).

from severe salinity (> 5 dS/m) have an average size of 0.73 ha compared with only 0.27 ha for non-saline areas.

The traditional cropping pattern in the coastal areas was wet-season rice followed by fallow, with fallow lands used for cattle grazing during the dry season. Farmers could not grow rice in the dry season because of the lack of adequate fresh water and higher salinity in the water pushed by tides when the flow of fresh water in the river system became low. Farmers used to grow salt-tolerant, non-rice crops such as sesame, sweet potato and red pepper, but on small fractions of their lands. In recent years, the availability of short-duration, moderately salt-tolerant rice varieties and small-scale irrigation infrastructure (sluices and canals) has allowed access to non-saline fresh water for a longer period, and farmers have had better opportunities to grow modern rice varieties during the dry season. Also, the growing knowledge of semi-intensive shrimp and prawn farming and the availability of strong market demand for fish locally and abroad have allowed an increase in shrimp culture during the dry season using brackish water from tides and mixed rice and fish cultivation during the wet season. This shift became apparent during the late 1970s, but the major changes occurred during the 1980s and 1990s. Currently, rice–boro rice and rice–aquaculture are the two major farming systems that are being adopted in the coastal region. A multivariate analysis to identify the major determinants of the two systems revealed that biophysical and technical factors were more important for the adoption of either system than socio-economic factors (David and Otsuka, 1994; Hossain, 1998). Examples of these are farm size, tenancy, level of education of the farmer and access to credit (Table 15.9).

The dependent variable in the adoption function is a dichotomous qualitative variable with the value of one if the farmer adopts the new system on a particular land and zero if it is otherwise. It is hypothesized that the decision to adopt a new system depends on the biophysical characteristics of the land – particularly its elevation, soil type, salinity and access to irrigation – as the factors that affect the suitability of a technology and its relative returns compared with the existing farmers' systems. It is also hypothesized that the socio-economic characteristics of the farm household that influence the subsistence motive – access to knowledge and information regarding new technology and marketing and access to finance and credit – could also affect farmers' decisions for adoption. These variables are farm size, whether the farm is owned or rented, the educational status of the household head and the amount of loans received from institutional sources. Because of the dichotomous qualitative dependent variable, we

Table 15.9. Association between farming systems and biophysical and socio-economic variables of farmers. The study was conducted in 15 sample villages of the coastal district during 2000–2002.

Variables	Pearson's chi-square	Level of significance	Test for linear association (level of significance)
Biophysical			
Toposequence (elevation of parcel)	30.8	0.000	0.015
Soil type	24.8	0.002	0.169
Soil quality (level of salinity)	125.8	0.000	0.000
Irrigation availability	132.5	0.000	0.005
Socio-economic			
Farm size	31.4	0.000	0.979
Tenancy	8.1	0.089	0.686
Education of farmer	11.9	0.154	0.455
Access to credit	27.8	0.000	0.009

A farmer's decision to adopt a technology depends on socio-economic and biophysical factors. Here, we pooled parcel-level data on land use, biophysical characteristics of the parcel and socio-economic characteristics of the farm operator to identify the factors affecting the adoption of rice–boro rice and rice–fish culture.

used the PROBIT model (Maddala, 1992) to estimate the parameters of the adoption function.

The findings revealed that there is a higher probability of adopting the rice–boro rice system if the household has access to irrigation, is situated at medium elevation, is subjected to lower depth of flooding during the wet season and has clay soil (Table 15.10). The data further suggest that the availability of moderately salt-tolerant rice varieties and the development of irrigation management practices that prevent salinity build-up in soil or water during the critical stages of crop growth are imperative for the adoption of boro rice. The variables representing farm size, availability of credit and educational status were found to be statistically significant but negative. This shows that it is the less educated farmers with smaller landholdings who are adopting this intensive rice system, and the availability of finance is not a constraint to the adoption of input-intensive boro rice. Presumably, it is subsistence pressure that is compelling farmers to opt for the rice–boro rice system. The amount of investment needed for growing modern varieties is also not high enough to preclude cash-starved farmers from doing so.

Compared with the rice–boro rice system, the most important variable affecting the adoption of a rice–aquaculture system is soil salinity during the dry season and the depth of flooding of the soil during the wet season. The probability of adopting a rice–aquaculture system is higher if the soil is highly saline, with loamy or sandy texture, and the land is situated at very low elevation with a high depth of flooding. These lands are not suitable for a rice–boro rice system. Among the socio-economic variables studied, only farm size has a statistically significant effect on the decision to adopt a rice–aquaculture system. The positive value of the coefficient indicates that farmers with larger landholdings are the ones who adopt the system more frequently than farmers with smaller landholdings.

In the rice–boro rice system, farmers can get about 85% higher rice production than with the rice–fallow system. Family net income per hectare of land was about US$185 (Indian rupees (INR) 6564) for the rice–boro rice system

Table 15.10. Factors affecting the adoption of rice–boro rice and rice–aquaculture farming systems in West Bengal. The study was conducted at 15 sample villages of the coastal district during 2000–2002.

Factor	Unit	Mean value of variables	Rice–boro rice system (*n* = 112)	Rice–aquaculture system (*n* = 78)
Farm size	ha	1.02	–0.46**	0.26**
Education	Illiterate = 0	0.87	(–3.80)	(2.56)
	Primary = 1	1.21	–0.20*	–0.005
	Secondary = 2		(–2.18)	(–0.006)
Access to credit	Yes = 1	0.28	–0.42*	0.30
	No = 0		(–2.18)	(1.65)
Irrigation	Irrigated = 1	0.37	1.61**	–0.80**
	Rainfed = 0		(8.55)	(–3.69)
Moderate salinity	Yes = 1	0.59	0.46*	–0.096
	No = 0		(2.44)	(–0.47)
Severe salinity	Yes = 1	0.14	–0.18	1.383**
	No = 0		(0.63)	(5.44)
High elevation	Yes = 1	0.16	0.59	–0.376
	No = 0		(1.81)	(–1.25)
Medium elevation	Yes = 1	0.72	0.74*	–0.592*
	No = 0		(2.64)	(–2.23)
Loamy soil	Yes = 1	0.29	–0.72	0.40*
	No = 0		(–3.68)	(2.08)
Constant			–1.07**	–0.78**
			(–3.49)	(–2.68)
Chi-square			137	93
Log likelihood ratio			–233	–147

*,**, significant at *P < 0.01 and **P < 0.05, respectively.
The figures in parentheses are the standard deviations (+/–) of the mean values.

compared with only US$125 (INR4377) for the rice–fallow system.

The availability of irrigation water in moderate saline areas prompted farmers with smallholdings to grow boro rice; however, water was not assured in the later stages of crop growth and salinity also increased sharply, resulting in lower yields in some years. A lack of suitable salt-tolerant varieties also contributed to lower average production. Aquaculture is adopted in areas that are more saline and by farmers with larger households, or outside contractors.

Apparently, the adoption of boro rice increases average household income by about 48%, besides providing extra rice grains that further ensure food security. The adoption of boro rice also generates employment opportunities for the rural poor and landless labour. Introducing the use of back-feed water in canals during the dry season and maintaining it for a longer duration has also brought some qualitative changes in remote villages. The canals are now being used for transportation year-round. Farmers can transport agricultural inputs and domestic essentials much faster and cheaper. As such, the adoption of this new technology is spreading in wider areas and the availability of household goods, medicine, etc., in remote areas has also increased significantly. The transport costs involved in moving agricultural inputs and outputs between farms and markets affect the intensity of farmland use and the production decisions of farm households significantly.

Issues for increasing the productivity of boro rice in coastal areas

Boro rice seems to provide a great opportunity for ensuring food security and enhancing farmers' household income in coastal areas. However, further research is needed to overcome the current constraints associated with this system. Research and development priorities for further improvement in grain yield and sustainability of this system could involve the following:

- Development of high-yielding, early-maturing (120 days), moderately salt-tolerant (2–4 dS/m) rice varieties.
- Identification of rice hybrids suitable for the region.
- Evaluation of aerobic rice for better water productivity during the dry season when freshwater resources become scarce, particularly in areas with lower salinity.
- Early establishment and harvest of boro rice to avoid salinity build-up in irrigation water during the reproductive stage. This can be achieved, in part, through direct seeding in puddled soil using drum seeders.
- Development and adoption of suitable nutrient and water management technologies for different plant types such as modern varieties, hybrids and aerobic rice varieties.
- Adoption of medium duration (130–135 days) modern rice varieties during the wet season to ensure early release of lands for early establishment of boro rice.
- Development of suitable crop care packages, including effective postharvest and storage practices.

Conclusions

Tidal waves, high precipitation and partial stagnant water flooding are the major constraints to higher rice productivity during the wet season in the coastal districts of West Bengal. In addition, these areas are prone to infrequent natural hazards, including cyclonic storms. The current trend in global climate change is further expected to affect rice production negatively during the wet season in coastal areas. Consequently, the relatively hazard-free months of the dry season allow the growing of boro rice, with higher potential productivity. The possibility of increasing the area in the boro season is limited by the availability of fresh irrigation water; therefore, combining improved varieties with proper crop management practices will play a significant role in increasing and stabilizing boro rice production. The socio-economic conditions of the farmers in these coastal areas seem to favour the adoption of these improved technologies.

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References

Ambast, S.K., Sen, H. and Tyagi, N.K. (1998) Rainwater management for multiple cropping in rainfed humid Sundarban Delta (W.B.). Bulletin No 2/98. Regional Research Station, Central Soil Salinity Research Institute, Canning Town (W.B.), India, p. 69.

Bandyopadhyay, A.K. and Bandyopadhyay, B.K. (1982) Coastal saline soils of West Bengal and their management for rice cultivation. In: *Rice in West Bengal*. Directorate of Agriculture, Government of West Bengal, Calcutta, pp. 119–127.

Bardhanroy, S.K. and Dey, M.M. (1992) Visible changes in cropping pattern in deepwater ecosystem of West Bengal. *Eastern India Farming System Research and Extension Newsletter* 6(3), 8–10.

Bardhanroy, S.K., Saha, N.K., Gascon, F.E.B. and Hossain, M. (2004) Adoption of rice–rice and rice–fish farming system in Coastal West Bengal: determinants and impact. (Abstract) National Symposium on Recent Advances in Rice-Based Farming System, 17–19 September 2004. CRRI, Cuttack, India, p. 107.

David, C. and Otsuka, K. (eds) (1994) *Modern Rice Technology and Income Distribution in Asia*. Lynne Rienner Publisher and International Rice Research Institute, London.

DAWB (Directorate of Agriculture, West Bengal) (2006) *Estimation of Area and Production of Principal Crops in West Bengal, 2004–05*.

GOWB (Government of West Bengal) (1990, 2000 and 2005) Estimate of area and production of principal crops in West Bengal. Evaluation Wing, Directorate of Agriculture, Government of West Bengal, Kolkata, West Bengal.

Hossain, M. (1998) Nature and impact of green revolution in Bangladesh. *IFPRI Research Report No 67*. IFPRI, Washington, DC.

Lopez, M.V., Mendoza, T.C. and Genio, E.R. (2004) Sustainability of modified rice-based production system for salt affected areas. *Journal of Sustainable Agriculture* 23(4), 5–17.

Maddala, G.S. (1992) *Introduction to Econometrics*, 2nd edn. Macmillan, New York.

Mahata, K.R., Singh, D.P., Saha, S. and Ismail, A.M. (2006) Integrated nutrient management for enhancing rice productivity in coastal saline soils of eastern India. *Abstracts of the 2nd International Rice Congress*, 2006, New Delhi, pp. 369–370.

Poonam, A. and Swain, P. (2006) Physiological efficiency of rice hybrids under irrigated transplanted conditions of Coastal Orissa. (Abstract) *2nd International Rice Congress*, 2006, New Delhi, pp. 484–485.

Singh, D.P., Mahata, K.R., Saha, S. and Ismail, A.M. (2006) Crop diversification options for rice-based cropping system for higher land and water productivity in coastal saline areas of eastern India. *Abstracts of the 2nd International Rice Congress*, 2006, New Delhi, p. 475.

Zayed, B.A., Badawl, A.T., Shehata, S.M., Ghauem, S.A. and El-Wahab, A.E.A. (2004) Effect of salt stress on growth and proline accumulation of rice cultivars differing in salt resistance. *Egyptian Journal of Agricultural Research* 82(1), 219–229.

16 Strategies for Improving and Stabilizing Rice Productivity in the Coastal Zones of the Mekong Delta, Vietnam

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Abstract
Since the early 1990s, Vietnam has witnessed a colossal leap in agricultural production, with an annual increment of 4.3% and an increase in food production of 5.8%. Consequently, Vietnam moved from incidences of chronic hunger to being one of the world's biggest rice exporters, with considerable improvement in farmers' livelihoods. However, most farmers living in coastal salt-affected areas of the Mekong Delta have not benefited sufficiently from these developments, owing to the low productivity of these areas caused by persistent rapid population growth, diminishing agricultural lands due to industrial expansion, land degradation and persisting abiotic stresses such as K and P deficiencies and, in some cases, toxicities to high Al and Fe, besides excessive salts and low pH. Crop yields in these areas are generally low and are decreasing progressively, particularly in saline areas where farmers still use traditional varieties and practices. Potential threats of food shortage are therefore anticipated in the long run. None the less, effective measures are being attempted to mitigate these soil problems and use these soil resources effectively for food production. New salt-tolerant rice varieties adapted to the Mekong Delta region are being developed using both conventional and modern approaches such as anther culture, mutation and marker-assisted breeding. Numerous short-maturing varieties such as Tam xoan-93, Tep Hanh, Mot Bui Do, OM4498, OM5900 and AS996 have been developed that can yield 4–5 t/ha under salt stress of 6.0–9.0 dS/m and are now being outscaled. Crop and nutrient management options for improved varieties are also being developed and new cropping patterns have been tested over the past few years. These involve the development of high-yielding, short-maturing varieties for less saline areas with ample fresh water, non-rice high-value crops such as soybean and groundnut for areas where freshwater resources are relatively scarce during the dry season and rice–aquaculture systems for areas where salinity is high during the dry season, as in some parts of Tra Vinh and Bac Lieu Provinces. Results generated from on-farm trials over the past 3 years in different areas and their initial impact are discussed.

Introduction

Vietnam is highly populated, with the current population exceeding 80 million, about 62% of which still live in rural areas. In the past two decades, Vietnam has made a leap in agricultural production at an average annual rate of 4.3%, out of which food production has increased by 5.8% per annum. As a result, Vietnam has moved from a country with chronic hunger to being one of the world's biggest rice exporters, with more than 5 million t of rice being exported annually (Table 16.1). Farmers' living standards have also improved considerably.

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Table 16.1. Population structure and rice production in Vietnam, 2004.

Item	Value
Total population (million)	80.0
Rural population (%)	61.9
Number of agricultural households (million)	10.9
Average rice yield (t/ha)	4.4
Annual rice production (million t)	33.0
Rice exports (million t)	5.0
GDP per capita (US$)	430.0
Agricultural GDP/ha (US$)	1010.0
Rate of increase in agricultural production (%)	5.23

Despite these developments, the majority of farmers living in coastal areas have not benefited much from such progress. In addition, because of the population increase and expansion of industrial production, agricultural land is decreasing rapidly at an annual rate of 1318 m^2 in 1980 to 1519 m^2 in 1990 and 914 m^2 in 2003. In the meantime, land and water resources in salt-affected coastal areas are progressively being exhausted as a consequence of land degradation and other factors. This means that the Vietnamese people, particularly those living in coastal delta areas, are under a potential threat of food shortage and effective measures should be taken urgently to cope with this serious situation.

In Vietnam, about 30 million people are living in coastal areas and, for various reasons, most of these people are very poor and hunger is not uncommon. This is because their farm production is not sufficient to provide enough food for the whole year. The immediate consequences of this are an overexploitation of natural resources and soil and environmental degradation. Moreover, the increasing incidences of natural hazards such as long droughts during the dry season and severe flash floods and longer-term floods in the rainy season are causing great losses of crops, infrastructure, property and people's lives. Furthermore, the coastal and Mekong Delta areas are progressively undergoing severe degradation because of excessive erosion and runoff. Most of the degraded soils have poor fertility, low pH, phosphorus and potassium deficiency and, in some cases, toxic amounts of available aluminium and iron. The high cropping intensity and very short fallow period also contribute to low soil fertility. Consequently, crop yields are low and are continuously decreasing with time; the average yield of rice in saline soils is 0.8–1.5 t/ha and that of maize 1.0–2.0 t/ha.

Apparently, and as indicated by our research over the past few years, there is great potential for increasing productivity and enhancing farmers' livelihoods in these areas. New conservation agriculture techniques can help rehabilitate degraded soils, contribute to the stabilization of crop yields and ensure resilience of the production system. However, this entails a pressing need for further research to develop effective technologies to revert and stabilize the current situation and benefit local farmers.

The Vietnamese government has a high priority to develop effective strategies for improving and stabilizing agriculture and food productivity in the Mekong Delta through the following means: (i) increase the area under cultivation by exploring less productive marginal lands; (ii) increase yields by developing high-yielding varieties tolerant of prevailing stresses, together with suitable management practices; and (iii) increase the value of agricultural products by introducing more adapted high-value crops.

Rice Production in the Mekong Delta

Rice in Vietnam is produced under different ecosystems, with the majority under the irrigated system, which currently constitutes about 80% of the total area, and the rest under rainfed ecosystems (Table 16.2). The increase in area under the irrigated system has occurred over the past few years because of the heavy investment in infrastructure and bolder systems to control water and salt ingress in coastal areas. The Mekong Delta has about 4 million ha of land with different soil types (Table 16.3), out of which 2.44 million ha are agricultural land, most of it under rice cultivation. However, most of these soils suffer from different abiotic stresses (Buu *et al*., 1995), particularly acid sulfate soils (41%) and soils with salt stress (19%), followed by high organic or peat soils (Table 16.4).

Table 16.2. Area under rice production in different ecosystems in Vietnam.

Rice ecotype	Area (000 ha)	Area (%)
Irrigated	3440	80.0
Rainfed	217	5.0
Deepwater	193	4.5
Upland	450	10.5

Buu and Lang (2004).

Table 16.3. Area of different soil types in the Mekong Delta, Vietnam.

Soil type	Area (ha)	% of total area
Acid sulfate	1,600,263	40.7
Alluvial	1,184,857	30.1
Saline	744,547	18.9
Soils near rivers, canals	190,257	4.8
Grey	134,656	3.4
Sandy	43,318	1.1
Peat	24,027	0.6
Laterite	8,787	0.2
Red yellow	2,420	0.1
Total	3,933,132	100.0

Buu *et al.* (1995).

Table 16.4. Percentages of different soil types under rice production in the Mekong Delta of Vietnam.

Soil type	Percentage (%)
Acid sulfate	40.8
Saline	18.9
Peat	10.0
Grey	3.4
Alluvial	26.9

Buu (1993); Buu *et al.* (1995).

As in other coastal areas, salinity in the Mekong Delta is normally high during the dry season and then decreases progressively with the onset of monsoon rains that wash the salt from the soil. For this reason, high salt stress is a problem for dry-season crops, as well as for wet-season rice during crop establishment. Salinity during the dry season can result from the capillary rise of salt from the shallow saline underground water as the soil surface dries. It also results from the ingress of salt water in inlands due to lower freshwater levels in the Mekong River and its tributaries at the mouth of the delta. This is particularly evident during February–May, with the peak during April–May, when salt intrusion can reach close to 60 km inland (Table 16.5).

In the Mekong Delta, rice is the major crop grown during both the wet and dry seasons, particularly in areas where salt stress is low to moderate during the dry season. In some areas, rice–aquaculture (shrimp and fish) is practised, particularly where salinity is high during the dry season. Rice is grown on 0.7 million ha in the coastal zones of the delta and most of this area is affected adversely by salt stress. As a consequence, vast areas remain fallow during the dry season (February–April). Rice varieties that are short maturing and salt tolerant during all developmental stages are needed for the dry season. However, for wet-season varieties, salinity tolerance at the early seedling stage is more important. This is because most of the rainfall is received during the wet season, with only about 10% of the annual rainfall occurring during the dry season in the delta region over a period of about 130 days.

The major constraints to agricultural production in the Mekong Delta involve multiple abiotic stresses, particularly salinity, flooding and other soil problems. Moreover, the delta is vulnerable to numerous natural hazards such as typhoons and floods. Because of these high risks and low productivity, farmers follow conservative strategies for risk aversion, with minimal or no use of agricultural inputs. Moreover, the small landholdings; lack of essential inputs such as good-quality seeds of high-yielding varieties, fertilizers and pesticides, and poor and inefficient extension systems together contribute to the lower productivity of the system. Proper water management is key to reducing the toxic effects of excess cations such as aluminium and iron, high acidity and the capillary rise of toxic sulfate compounds in acid sulfate soils.

Our research activities in the Mekong Delta focus on the development of proper technologies for enhancing and stabilizing farm productivity and improving farmers' livelihoods. This is being achieved through the development of rice varieties with tolerance of prevailing abiotic stresses; the adoption of proper soil, water, nutrient and crop management practices for

Table 16.5. Extent of salt intrusion (km) during the dry season (February–May) in four provinces at the mouth of the Mekong River. Data are averaged over 5 years during 1999–2003.

Mekong's	High (> 4 g/l)				Moderate (1–4 g/l)			
mouth	Feb	Mar	Apr	May	Feb	Mar	Apr	May
Cua Tieu	23	32	37	32	43	51	59	58
Ham Luong	23	30	34	26	46	51	57	54
Co Chien	22	31	35	27	44	58	55	51
Bassac	25	32	33	26	44	54	58	51

Buu and Lang (2004).

higher and more stable productivity; and the introduction of more profitable cropping systems. The latter involves the testing of rice–rice and rice–non-rice crops in low and moderately saline areas and rice–aquaculture in areas where salinity is high during the dry season. These efforts are being supported in part by funds provided by the Challenge Program on Water and Food through Project No 7 (PN7). The objectives of this paper are to provide a summary of the progress made in germplasm improvement and management options accomplished through this project over the past few years.

Progress in the Development of Salt-tolerant Rice Varieties

The development and use of salt-tolerant crop species and varieties have generally been considered the most economical and effective strategy to increase crop production in salt-affected areas. We approach this through different ways: collecting and evaluating indigenous material as potential donors for salinity tolerance and other adaptive traits; using conventional and modern breeding approaches to develop tolerant rice varieties; and exchanging and evaluating salt-tolerant elite materials with other countries through IRRI's International Network for Genetic Evaluation of Rice (INGER) and other international networks for local testing and release.

Collecting and evaluating local germplasm

In recent years, 167 traditional local landraces have been collected and 65 of them have been identified for further analysis of different adaptive and agronomic traits. Analysis of selected traits showed that the range of the coefficients of variation in this local material was high (data not shown). It varied from 2.1% for grain length to 34.0% for number of unfilled grains, showing that grain length was less variable than grain width (2.4%) and culm length (6.9%) when compared with other characteristics. These traits can be considered the most stable characteristics, as reflected by their coefficients of variability. The highest coefficient was that of unfilled grains (34%), indicating that this characteristic was more vulnerable to changes by the environment and cultural management practices. The variation in grain characteristics such as size, shape and colour is useful in distinguishing the different landraces or traditional varieties and in choosing proper parental lines for further improvement through breeding.

Analysis of variance of some agromorphological traits reflected significant differences among the 65 traditional rice varieties; however, correlation coefficients showed that all the traits were correlated significantly with each other, except with yield. The standardized Shannon–Weaver diversity index (H) for the quantitative morphological characters ranged from 0.68 to 0.95, with a mean of H = 0.88. Cluster analysis using UPGMA grouped the 65 traditional varieties into six major clusters, with varieties collected from the same collection site grouped together in the same cluster. On the other hand, molecular diversity analysis using 34 polymorphic SSR markers reflected significant genetic diversity among the 65 traditional varieties. These 65 varieties generated eight clusters at 0.61 similarity coefficient. Even some lines with the same common names were grouped into different clusters, though they belonged to the same cluster based on morphological markers. However, based on molecular analysis, most of the varieties (84%) belonged to the same cluster when using a less stringent threshold. This indicates that these genotypes are relatively closely related to each other, even though there are a number of subclusters (Buu and Lang, 2007)

Breeding strategies

Different approaches are being followed at the Cuu Long Delta Rice Research Institute (CLDRRI) to develop salt-tolerant varieties of rice. These approaches include conventional methods involving crosses with salt-tolerant donors and subsequent selection for agronomic and adaptive traits over several generations. Moreover, modern breeding tools such as mutation breeding, anther culture and molecular breeding are also being implemented to accelerate progress in breeding salt-tolerant varieties. Our phenotyping system follows the screening methods developed at IRRI using the Standard Evaluation System (SES) for rice (IRRI, 1996). This system uses visual scoring at different stages of plants grown hydroponically on Yoshida culture solution (Yoshida *et al.*, 1976). The system uses scores of 1 (highly tolerant) to 9 (highly sensitive). An example is shown in Table 16.6, where a set of modern rice varieties and checks are evaluated at 6 dS/m and 12 dS/m. All of these new varieties seem to have sufficient tolerance at 6 dS/m, with reasonably high yield in farmers' fields.

Table 16.6. Examples of rice lines developed for salt-affected areas and their responses under salt-stress conditions of 6 dS/m and 12 dS/m at vegetative stage in hydroponic culture solution. SES scores are mean values over five replications. The trial was conducted in Tra Vinh Province at two sites: Cau Ngang (6 dS/m) and Duyen Hai (9–12 dS/m). Yield data were from Cau Ngang.

Designation	Origin	Duration[b] (days)	Yield (t/ha)	SES[a] (6 dS/m)	SES (12 dS/m)
AS996	IR64/*Oryza rufipogon*	95–100	4.5	3	9
OM1490	OM606/IR44592-62-1-3-3	85–90	5.6	3	5
AS1007	IR64/*O. rufipogon*	95–100	3.2	5	7
OM1838	Samorang/Soc Nau	132	2.3	3	7
OM2031	TN1/OM 723-11	105–100	4.1	3	9
OM2041	IR69417-34-1/IR69191-99-2	105–100	2.4	3	9
OM1346	IR42/OM 739-7-2-2-1	140	3.1	3	7
OM1348	IR42/IR66	138	4.2	3	9
OM1849-5	OM723-11M/IR68	138	3.9	7	9
OM723-7	NN6A/A 69-1	115	4.5	3	7
Checks					
A69-1	Traditional from Vietnam	120	2.4	3	7
IR29 (sensitive)	IRRI	110	2.1	5	9
Pokkali (tolerant)	India	130	1.8	1	3
Doc Do (tolerant)	Traditional from Vietnam	150	2.5	1	1
Significance				**	**
$LSD_{0.05}$				0.37	0.68
CV%				8.50	7.60

[a]Standard evaluation system (IRRI, 1996) with a range of 1 (no injury) to 9 (severe injury and death); [b]depends on the season, being about 5 days longer for photo-insensitive lines during the wet season; **0.01 level of significance.

Mutation breeding

New breeding lines of known varieties were developed through radiation and chemical mutagenesis. An example is the development of Tam Xoan-93 from the Vietnamese variety Tam Xoan, which is a traditional variety from northern Vietnam that is tall, has low yield, but has good grain quality and reasonably high tolerance of acid sulfate soils. Seeds of Tam Xoan were gamma-irradiated and the generated plantlets were advanced to M_2 and screened for salinity tolerance at the seedling stage during both M_2 and M_3 generations. Putative salt-tolerant mutants were identified and further advanced and evaluated for agronomic and adaptive traits. Tam Xoan-93 subsequently was identified with superior agronomic and quality traits. The new variety matures earlier, is shorter, has more tillering capacity and higher harvest index and yields more than three times what the original variety yields (Table 16.7). This new variety also had high salt tolerance and was released to farmers during 2004/05. It has since been outscaled and had already covered over 500 ha by 2006.

Anther culture

Anther culture techniques have been studied for their use in rice breeding since the 1970s. This method provides a quicker means to obtain fixed homozygous lines in a short period of time and, if successful, new lines can be released as new varieties within 3–4 years, nearly half as long as conventional breeding methods would have taken. We are using this method to breed salt-tolerant varieties adapted to the salt-affected soils of the Mekong Delta. Six crosses were made and used for the selection of F_1 hybrids for anther culture (Table 16.8) to allow rapid fixation of homozygosity concurrent with the transfer of salt tolerance of donors to the desired parents having suitable plant type, yield and quality traits. The objective is to transfer the high salt tolerance from traditional cultivars into high-yielding modern varieties.

Anther culture was accomplished within one season following hybridization. About 156 anther culture-derived plants were obtained during 2004. Callus formation ranged from 0.56 to 1.67%; however, the

Table 16.7. Agronomic characters of Tam Xoan-93 developed through mutation breeding.

Variety	HD (days)	PH (cm)	TN	PL (cm)	SS (%)	1000-GW (g)	HI	Yield (t/ha)
Wild type	140	135	8	25.0	32	25.6	0.40	2.1
Mutant (Tam Xoan-93)	90	100	16	26.7	12	26.5	0.56	6.8

HD, heading date; PH, plant height; TN, tiller number; PL, panicle length; SS, spikelet sterility; GW, grain weight; HI, harvest index.

Table 16.8. Number of anther culture-derived lines and percentage of callus formation from crosses involving salt-tolerant parents. Crosses were made at CLDRRI in 2004.

Parentage	Anthers inoculated (number)	Calli produced (number)	Calli produced (%)	Calli transferred (number)	Green plantlets (number)	Green plantlets (%)	Number of lines produced
C41/MR 159	360	2	0.56	2	1	50	9
Tequing/ Giza 159	480	8	1.67	8	1	12	32
Tequing/ Madhukar	360	5	1.39	5	1	20	43
Tequing/ At 354	240	3	1.25	3	1	33	9
Tequing/Doc Phung	480	6	1.25	6	3	50	19
Tequing/ Pokkali	360	5	1.38	5	2	40	44

percentage of green plantlets was higher in the regeneration medium (Table 16.8). These anther culture-derived lines were transferred from test tubes to pots in clusters and then transplanted as individual seedlings in the greenhouse. Substantial variability was observed within and between the A_1 lines in growth habit, duration and yield attributes, as summarized in Table 16.9. Out of 1200 green plants derived from the six crosses, a total of 720 plants were spontaneous doubled haploids (DHs). Seeds of mature plants (A_2 generation) were harvested and their salinity tolerance was evaluated at the seedling stage under 6 dS/m and 15 dS/m. Survival ranged from 35% for Tequing/Madhukar cross to 74% for Tequing/Doc Phung cross under moderate salinity, and from 10% for Tequing/Doc Phung cross to 33% for Tequing/At 354 cross under high salinity (Table 16.9). About 26 derived lines were selected that were salt tolerant and they were being evaluated further in the greenhouse of CLDRRI for both seedling- and reproductive-stage salinity tolerance, as well as for other agronomic traits. The best selected lines will be entered into yield trials in subsequent years for field evaluation and potential release as varieties. The data demonstrate the effectiveness of anther culture in breeding for salinity tolerance. Through this technique, the characters of two parents can be made complementary in an early generation and a plant can be made homozygous immediately. Because the characters in anther-cultured rice are controlled by dominant and recessive genes and interallelic complementations, selecting parents with moderate traits based on a breeding target is important (Zhang, 1982). However, to broaden the genetic base, it is also necessary to use distant parents. We tried to explore both strategies in our selection of parental lines in these crosses.

Use of DNA markers to accelerate progress in breeding for salt tolerance

The identification of molecular markers associated with quantitative trait loci (QTLs) linked with useful agronomic or adaptive traits will help speed progress in breeding once developed because these DNA markers will become effective tools for selection. Moreover, positional cloning using DNA markers will make it possible to isolate agronomically useful genes, which can also be used in breeding across species via transgenic approaches. We developed several mapping populations using salt-tolerant and sensitive genotypes and used them for mapping QTLs associated with salinity tolerance during the seedling stage (Lang *et al.*, 2001). Two QTLs with relatively large effects were identified, one on chromosome 1 (linked to marker 18EC) and the second on chromosome 8 (linked to marker 12EC). Microsatellite markers closely linked to these loci were identified, such as RM215 associated

Table 16.9. Comparison of the major agronomic characters of anther culture-derived lines in A_1 generated from six different crosses and their survival under salt stress in hydroponics.

Parentage	Growth duration (days)	Plant height (cm)	Panicle length (cm)	Panicles per plant	Grains per panicle	Survival (%)	
						6 dS/m	15 dS/m
C41/MR 159	70–95	67–98	16.0–23.5	10–28	30–125	46.7	30.0
Tequing/Giza 159	67–117	67–117	16.6–23.4	9.0–42	32–145	37.5	15.6
Tequing/Madhukar	83–97	68–108	18.0–22.6	6.0–30.0	69–124	34.9	11.6
Tequing/At 354	95	57–107	21.6–24.4	11–21	91–176	66.7	33.3
Tequing/Doc Phung	85–98	72–127	15.6–23.0	5–34	47–169	73.7	10.5
Tequing/Pokkali	92–102	100–210	18.5–31.8	3–16	23–188	45.4	11.0
Pokkali						70.0	40.0
IR29						30.0	0

with the QTL on chromosome 1 and RM223 associated with the QTL on chromosome 8. These markers were further evaluated for their effectiveness in selection using a set of 24 improved varieties, including tolerant (Pokkali) and sensitive (IR28) checks. These cultivars were genotyped at these markers and then phenotyped for salinity tolerance at 12 dS/m in culture solution (Yoshida *et al.*, 1976) using visual SES scores. The results indicated an accuracy of more than 95% in identifying tolerant cultivars (Table 16.10), which indicated the usefulness of these markers in parental surveys and in identifying tolerant lines from segregating populations; however, further tests are needed to confirm their effectiveness in different genetic backgrounds. More efforts are needed to develop markers closely linked to these two QTLs to be used for their routine introgression into popular varieties and elite breeding lines.

Evaluation of rice breeding lines received from IRRI through INGER

Evaluation of breeding lines received from IRRI through INGER together with local check varieties such as AS996 is being conducted regularly during both the wet and dry seasons as part of the Challenge Program on Water and Food (CPWF) PN7 activities. These lines were evaluated in farmers' field trials, as well as at the CLDRRI station. Different traits were assessed: crop duration, plant height, grain setting and fertility, quality traits and salinity tolerance. Lines that were early maturing (90–110 days), semi-dwarf (90–110 cm), with a medium number of panicles/hill (8–10 panicles), a high number of grains/panicle (80–100 grains) and had high tolerance of salinity and duration similar to AS996 (approximately 98 days) were selected for further testing in rice–rice cropping patterns. Examples are IR73571-3B-9-3

Table 16.10. Comparison between the phenotype and genotype of 24 varieties under salt stress of 12 dS/m. Lines were genotyped using markers specific for the *Saltol* locus on chromosome 1 and a second QTL on chromosome 8, and phenotyped under salt stress in hydroponics.

Variety	RM315 Chr 1	RM223 Chr 8	Phenotype
IR28	S[a]	S	S
Pokkali	T	T	T
OM4059	S	T	S
OM85	S	S	S
OM4661[b]	S	T	S
OM5900[b]	T	T	T
OM5930[c]	T	S	T
OM4679	S	S	S
OM5641	S	S	S
OM6071	S	S	S
OM6036	T	S	T
OM6037	T	S	T
OM6040	S	S	S
OM6038	S	S	S
OM6043	T	S	T
OM6039	T	S	T
OM6041	T	S	T
OM6042	T	T	T
OM6044	S	S	S
AS996	T	T	T
OM3729	T	T	T
OM4151	S	S	S
OM4675	T	T	T
OM4245	T/S	T	T

[a]T, tolerant; S, sensitive; [b]OM5900 and OM4661 were tested in the field and seeds provided to farmers in several provinces for further testing; [c]OM5930 was developed as a somaclone and released as a regional variety in 2007.

and IR73571-3B-9-3, which will be suitable for salt-affected areas of Long Xuyen Square and Ca Mau Peninsula. However, some lines were also identified that have similarly high salinity tolerance but relatively longer duration, such as IR73571-3B-9-2 (114 days), IR73571-3B-5-1 and IR73055-8-3-1-3-1 (113 days), and these lines will be suitable for the rice–shrimp cropping pattern such as that in Ca Mau Peninsula and other salt-affected areas. Selected lines will be further tested in subsequent years. A few salt-tolerant breeding lines were being tested in farmers' fields in Tra Vinh and some short-maturing lines (< 100 days) were selected from IRRI breeding material, and their yield was reasonably higher than the check variety AS996 (Table 16.11). Lines such as OM6043, OM6036, OM6040 and OM6038 had significantly higher yields than the check variety and were being considered as candidates for release in areas where up to three crops could be considered each year.

Stability testing of salt-tolerant varieties in farmers' fields

Performance stability is one of the most important properties of a genotype to be released as a variety to ensure wide adoption. To ensure this, we tested eight indica rice varieties at nine different locations during the wet and dry seasons of 2004, using a randomized block design with three replications at each site. Duration, grain yield (t/ha) and stability index are presented in Table 16.12. The experiment was conducted in four provinces, Can Tho, Tra Vinh, Ben Tre and Bac Lieu. The highest grain yield across the nine sites was obtained from AS996 and Tam Xoan-93 during both seasons. The first genotype was bred by IRRI through wide hybridization for acid sulfate soils, whereas the latter was developed through mutation breeding, as discussed above. Most of the varieties showed a good stability index. An understanding of the environmental and genotypic causes of variation and G × E interaction is important at all stages of plant breeding for selection based on either specific traits or on yield (Yan and Hunt, 1998; IRRI, 1999).

Another set of eight rice genotypes was evaluated at nine different locations in Tra Vinh (five sites), Ben Tre (one), Bac Lieu (two) and Can Tho (one site at CLDRRI) during the dry seasons of 2006 and 2007, and at six sites in the same provinces during the 2005 and 2006 wet seasons (Table 16.13). The purpose of these experiments was to evaluate the performance of these genotypes over years under diverse stress conditions, and also to select varieties that were better adapted to one or both seasons at particular sites. Overall, the data showed that the performance of these selected varieties was fairly stable in these salt-affected areas. Some of these varieties have already been outscaled and are spreading over larger areas. An example is OM4498 during

Table 16.11. Agronomic traits, yield and yield components of some rice breeding lines selected at CLDRRI. Evaluation and selection were done in farmers' fields in Tra Vinh Province.

Variety	Duration (days)	Plant height (cm)	Panicles per m^2	Filled grains/ panicle (g)	1000-grain weight (g)	Yield (t/ha)
OM6036	110	94.2	315.8	122.0	14.2	5.8[a]
OM6037	109	95.6	482.5	131.1	15.2	5.9[a]
OM6038	110	94.3	382.8	120.5	14.6	6.0[a]
OM6039	112	96.5	443.6	100.2	12.0	5.3
OM6040	112	96.2	419.8	113.2	13.5	5.8[a]
OM6041	113	92.8	392.2	122.3	16.2	5.2
OM6042	109	96.3	443.6	132.6	14.2	5.1
OM6043	110	98.1	371.0	130.2	14.3	5.7[a]
OM6044	113	95.7	417.4	111.2	14.7	5.3
AS996	112	98.6	412.5	112.6	12.5	5.0
CV%	–	–	16.8	18.1	–	10.3
$LSD_{0.05}$	–	–	31.7	12.5	–	0.6

[a]Yield significantly higher than that of check variety AS996.

Table 16.12. Duration, grain yield and stability index of seven new salt-tolerant rice varieties evaluated at nine sites in farmers' fields in Tra Vinh during the wet and dry seasons of 2004. Data are means of three replications at each site.

Designation	Duration	Yield (t/ha) in 2004		Stability index[c]
		Dry season	Wet season	
AS996[a]	95	7.3	4.35	0.008
OM5900	95	6.8	3.80	0.062
OM4498[b]	97	6.5	3.85	0.290
Tam Xoan-93	100	7.3	4.12	0.1141
OM2665	115	6.3	3.81	0.099
Tep Hanh mutant	112	6.5	3.62	0.124
Motbui Do mutant	160	6.2	3.65	0.001
IR64 (check)	110	7.0	3.89	0.140
Significance		**	*	
$LSD_{0.05}$		0.165	0.644	
CV%		2.6	9.8	

[a]Released in October 2004 as a national variety; [b]released in May 2007 as a national variety; [c]stability index is a measure of the genotype × environment interaction with values in the range of 0 = stable to 1 = not stable; *0.05 level of significance; **0.01 level of significance.

Table 16.13. Average grain yield of eight new salt-tolerant rice varieties evaluated in farmers' fields in Tra Vinh Province at four sites during the wet seasons in 2005–2007 and at six sites during the dry seasons in 2006 and 2007. Data from each site are means of three replications.

Variety	Grain yield (t/ha)					Mean
	2005 wet season	2006 dry season	2006 wet season	2007 dry season	2007 wet season	
OM5239	2.93	5.97	3.12	5.46	4.23	4.342
OM5636	2.76	4.87	3.10	5.33	4.56	4.124
OM5651	3.96	3.79	2.36	5.41	4.22	3.948
OM4498	3.72	5.14	4.21	5.86	4.56	4.698
OM6035	3.25	5.01	3.11	5.45	3.26	4.016
OM5624	3.63	4.52	3.21	5.36	2.30	3.804
OM5637	2.93	5.39	2.36	5.26	3.20	3.828
AS996	3.49	4.35	3.21	5.75	4.12	4.184
Significance	*	*	**	*	*	
$LSD_{0.05}$	0.433	0.668	0.579	0.209	0.803	

* and ** = significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

both the wet and dry seasons from 2004 to 2006 (Table 16.14).

Apparently, good progress is being made in developing salt-tolerant varieties for the coastal Mekong Delta. A participatory approach involving mother trials on-station and in farmers' fields, together with baby trials using farmers' preferred varieties selected from mother trials and managed by farmers, seems very effective in Vietnam, as is the case in other countries involved in the CPWF PN7 project (Singh *et al.*, Chapter 13, this volume). The study showed that the released varieties were fairly stable across salt-affected areas in different provinces. AS996 was released as a national variety in 2004, OM4498 and OM5239 were released in 2007 as national and regional varieties, respectively, and OM5636 was being considered for release as a regional variety in 2008. Several promising breeding lines have also been selected and will be promoted for release as national varieties in subsequent years.

Table 16.14. Total area under the newly released variety OM4498 during 2004–2006.

Province	2004 wet season (ha)	2004/05 dry season (ha)	2005 wet season (ha)	2005/06 dry season (ha)	2006 wet season (ha)
Can Tho			2572	1939	1264
Kien Giang		645	500	1400	1400
Bac Lieu			500	200	1100
Vinh Long		150	650	500	3700
Ben Tre	50	300	700	325	700
Hau Giang					3533
Tien Giang					3000
Tra Vinh	5	20	100	250	500

Source: Lang *et al.* (2006).

Crop and Natural Resource Management Strategies for Salt-affected Areas in the Mekong Delta

Besides salt-tolerant varieties, proper rice crop and natural resource management have also contributed substantially to yield enhancement and stability in salt-affected areas. Management practices involve nursery management before transplanting, nutrient management in the field and water management during the dry season. Promising options that were developed before were being tested further in these coastal saline areas. Proper nursery management to develop robust seedlings was found to be effective in enhancing survival and reducing seedling mortality on transplanting in saline soils. These technologies involve using lower seed density in the nursery and a balanced nutrient supply, and transplanting seedlings that are older than those used under normal conditions. Nutrients such as calcium and phosphorus were also found to be beneficial when added in relatively larger quantities, in both the nursery and, when possible, the main field. Minimizing root damage during transplanting was also found to be beneficial as it minimized the extent of passive salt uptake early during seedling establishment and reduced the time required to recover from transplanting shock. Some of these technologies have also been tested in the Mekong Delta and are being extended over two seasons to farmers in affected areas in Tra Vinh Province (T.N. Lang, unpublished data).

Different nutrients added as chemical fertilizers or organic manures are also known to enhance the productivity of saline soils. We tested the effects of phosphorus and potassium together with nitrogen. The application of 60 kg N/ha seems sufficient for some soils in Tra Vinh and some genotypes, such as OM5930, are more responsive to N application than others (Table 16.15). The application of N alone or in combination with P and K

Table 16.15. Response of five rice genotypes to different amounts of nitrogen fertilizer during the wet season of 2004 in Tra Vinh Province. The experiment was conducted using a randomized complete block design with three replications. N was applied in three equal splits as basal, at 25 days after transplanting (DAT) and at 45 DAT. Yield in t/ha.

	Nitrogen					
Genotype	0	30	60	90	120	Mean
OM5796	2.40a[a]	2.53c	2.73d	2.37c	2.00d	2.41
OM5930	2.70a	3.47a	4.03a	3.40a	3.67a	3.45
OM4668	2.60a	2.70bc	3.00cd	2.73b	2.53c	2.71
OM4900	2.70a	3.00b	3.57b	2.87b	3.30b	3.09
OM5637	2.47a	3.00b	3.27bc	3.47a	3.10b	3.06
Mean	2.57	2.94	3.32	2.97	2.92	2.94

[a]Means within the same column followed by the same letter are statistically similar using Duncan's multiple range test.

enhanced N concentration in plant tissues significantly. The results also show that soils in Cau Ngang District (Tra Vinh Province) are more deficient in P than in Chau Thanh and Cau Ke Districts. Also, the best yield response to P application at Cau Ngang is observed when 60:60:40 NPK is applied during the dry season and 80:60:40 NPK during the wet season. Most of the coastal saline areas of the Mekong Delta also suffer from additional abiotic stresses, such as acidity and associated aluminium and iron toxicities and acid sulfate conditions. Proper cultural practices and water management strategies are essential for reducing the toxic effects of these soil constituents. For example, continuous flooding is important to avoid the capillary rise of sulfate compounds into dry soil.

The cropping sequence in these saline areas is also being adjusted, with the objectives of better use of resources, food security and better income for farmers. In most cases, rice was the only option during the wet season, and it was mostly the sole crop before the introduction of the high-yielding, short-maturing varieties. Additional options are currently being attempted for the dry season. Rice–rice fits well in areas where salinity is not too high during the dry season with the use of short-maturing varieties and availability of freshwater sources. Some farmers even grow three rice crops during the year. In areas where salinity is relatively high during the dry season and fresh water is scarce, non-rice crops such as groundnut, mungbean, maize, sesame, soybean and watermelon seem promising. However, when salinity is too high during the dry season and fresh water is not adequate, rice–aquaculture systems are being applied, with shrimp and fish during the dry season. The most successful systems in Tra Vinh so far are rice–shrimp, rice–fish, rice–groundnut intercropped with mungbean or maize, and rice–watermelon–sesame. In Bac Lieu, the most promising systems are again rice–shrimp or fish and rice–watermelon.

The adoption of non-rice crops during the dry season can help overcome food shortages and generate reasonable income for farmers in areas where water is too saline or not sufficient for rice production. Crops such as maize, soybean, mungbean, sesame and groundnut can be considered a good source of income for farmers and the selection of better varieties, together with the adjustment of sowing dates, water management and cultural practices, coupled with the proper training of farmers in growing these new crops, will help increase food production and improve farmers' conditions. For these reasons, the CLDRRI continues to develop and test new varieties of different crops in these areas and some examples of high-yielding soybean and groundnut varieties are now available (Table 16.16).

Training workshops involving several hundred farmers are also being organized by CLDRRI each year, besides regular site visits to help extend new knowledge to farmers and to learn of their challenges and needs. Short-term

Table 16.16. Yield (t/ha) of different varieties of soybean, mungbean and groundnut during the dry season of 2007 in Tra Vinh.

Soybean		Mungbean		Groundnut	
Genotype	Yield	Genotype	Yield	Genotype	Yield
OMDN110	2.75	OMDX8	2.32	OMDP1	2.13
OMDN29	2.74	OMDX1	2.22	OMDP13	2.52
OMDN111	2.71	OMDX5	2.20	OMDP5	1.97
OMDN1	2.68	OMDX10	2.20	OMDP7	1.79
OMDN112	2.62	OMDX11	2.19	OMDP12	1.82
OMDN14	2.61	OMDX3	2.19		
OMDN109	2.50	OMDX2	2.16		
OMDN72	2.46	V91-15	2.14		
OMDN87	2.39	OMDX12	2.13		
Mean	2.61		2.19		
$LSD_{0.05}$	0.08		0.05		0.79

training courses are being conducted regularly to cover the following areas: selection and management of suitable salt-tolerant varieties, proper handling and multiplication of certified seeds and effective nutrient and water management techniques for salt-affected coastal areas. Each year, about 500–600 farmers participate in these training workshops in Tra Vinh Province, where the courses are conducted in four different locations to ensure proximity and to maximize farmers' participation. It seems that farmers in this province are becoming extremely perceptive of these new interventions.

Conclusions and Future Prospects

Salt-affected soils of the Mekong Delta are highly degraded, with a complex of abiotic stresses including salinity, acid sulfate soils, toxic amounts of aluminium and iron and deficiency in nutrients such as P and K. To enhance and sustain the productivity of these soils, we adopt an integrated approach involving the development of adapted high-yielding and salt-tolerant varieties developed via novel breeding methods, proper management of resources and the introduction of effective cropping patterns that can meet farmers' needs and market demands. The development of salt-tolerant varieties is generally considered the most effective entry point for improving the productivity of salt-affected soils, and it is also the cheapest option for farmers. Through the use of innovative breeding strategies involving conventional and modern tools, together with effective phenotyping techniques, good progress has been made in developing salt-tolerant varieties with broad adaptation to the conditions of the Mekong Delta. Varieties such as Tam Xoan-93, Tep Hanh, Mot Bui Do, OM4498, OM5900 and AS996 have been developed that can yield 4–5 t/ha under salt stress of 6.0–9.0 dS/m, and they are being outscaled. The success of new varieties is assured through eventual testing and selection at target sites in partnership with farmers and under their own management, to guarantee relevance and subsequent adoption. Special emphasis is given to crop establishment because the early stages of rice seedling growth are extremely sensitive to salt stress (Moradi *et al*., 2003; Ismail *et al*., 2007). This is achieved through the combined use of salt-tolerant genotypes and proper nursery management and seedling handling, to ensure maximum survival of transplanted seedlings. Crop and nutrient management options have also been developed for these new varieties and alternative cropping sequences involving rice, non-rice crops and aquaculture have been developed and are being validated with farmers at target sites. Several non-rice crop varieties released by CLDRRI are being outscaled by district agronomists and other organizations and these seem to be well received by farmers, as witnessed by the swift adoption of some of these crops.

Future efforts should focus on the further collection and evaluation of local rice germplasm to identify landraces with greater tolerance of salt stress as sources of new genes or alleles for breeding. Additional breeding efforts such as mutation breeding and the identification of somaclonal variants should continue to develop better pre-breeding material. To benefit from the new and exciting developments in genomics, additional resources and efforts should be directed toward identifying new QTLs and genes underlying tolerance of the multiple stresses experienced in these problem soils of the Mekong Delta, for their subsequent integration into modern varieties and elite breeding lines. Special efforts should also be placed on alternative cropping patterns that are environmentally sound and more profitable, and on training young scientists to prepare a new generation that can tackle these problems effectively in a team approach, particularly with the unfavourably changing climate.

Acknowledgements

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References

Buu, B.C. (1993) Rice breeding for the problem soil areas in the Mekong Delta, Vietnam. In: *Report of an INGER Problem Soils Monitoring Visit to Thailand and Indonesia*, 20–27 June 1993. IRRI, Philippines, pp. 39–48.

Buu, B.C. and Lang, N.T. (2004) Improved varieties for the Mekong Delta through 2010. *Science and Technology* (*Vietnam*) 8, 1041–1043.

Buu, B.C. and Lang, N.T. (2007) Conservation and utilization of rice genetic resources in Mekong Delta. *Omon Rice* 15, 1–11.

Buu, B.C., Lang, N.T., Tao, P.B. and Bay, N.D. (1995) Rice breeding research strategy in the Mekong Delta. In: *Proceedings of the International Rice Research Conference: Fragile Lives in Fragile Ecosystems*, 13–17 February 1995. IRRI, Philippines, pp. 739–756.

IRRI (International Rice Research Institute) (1996) *Standard Evaluation System for Rice*. International Rice Research Institute, Los Baños, Philippines, 51 pp.

IRRI (International Rice Research Institute) (1999) *Experimental Design and Data Analysis for Agricultural Research*, Vol. 2. IRRI, Los Baños, Philippines, 277 pp.

Ismail, A.M., Heuer, S., Thomson, M.J. and Wissuwa, M. (2007) Genetic and genomic approaches to develop rice germplasm for problem soils. *Plant Molecular Biology* 65, 547–570.

Lang, N.T., Yanagihara, S. and Buu, B.C. (2001) A microsatellite marker for a gene conferring salt tolerance in rice at the vegetative and reproductive stages. *SABRAO Journal* 33, 1–10.

Lang, N.T., Tien, N.T.K. and Buu, B.C. (2006) Development of aromatic rice for Tra Vinh. *Final Technical Report*. Tra Vinh Province, Vietnam, 145 pp.

Moradi, F., Ismail, A.M., Gregorio, G. and Egdane, J. (2003) Salinity tolerance of rice during reproductive development and association with tolerance at seedling stage. *Indian Journal of Plant Physiology* 8, 105–116.

Yan, W. and Hunt, L.A. (1998) Genotype by environment interaction and crop yield. *Plant Breeding Review* 16, 135–178.

Yoshida, S., Forno, D.A., Cock, J.H. and Gomez, K.A. (1976) *Laboratory Manual for Physiological Studies of Rice*, 3rd edn. International Rice Research Institute, Manila.

Zhang, Z.H. (1982) Application of anther culture techniques to rice breeding. In: *Rice Tissue Culture Planning Conference*. International Rice Research Institute, Los Baños, Laguna, Philippines, pp. 55–61.

17 Diversified Cropping Systems in a Coastal Province of the Mekong Delta, Vietnam: from Testing to Outscaling

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Abstract

This study was carried out to test the hypothesis that diversification and polyculture (growing more than one crop/commodity at the same time in the same field) could contribute greatly to increased profitability and reduced risk for both rice-based and shrimp-based production systems in the coastal zone. Local authorities, community associations and farmers collectively selected study sites in seven land-use zones (LUZ). In each study site, farmer communities selected one demonstration farm (demo) and five nearby farms (controls) where farming activities were managed under current practices. The demos tested new diversified cropping systems and new or improved technologies. At the end of each cropping season, farmer-managed on-farm workshops – in which the participants were local authorities, community associations, the press, farmers – were conducted to compare the ease of implementation, yields, profits and the benefit–cost of the demos and the controls. At the end of the 3-year study, final on-farm workshops were arranged to give final ratings and recommendations for the tested systems and technologies, which were endorsed by local authorities for wide dissemination, with support from extension workers, village authorities, community organizations and the mass media. The rice–rice&fish[1] system was recommended for freshwater zones and the shrimp&crab–fish system for saltwater zones. For the intermediate water quality zone, the shrimp–rice&fish system was recommended only for areas near the freshwater zone. Component technologies recommended for outscaling included: new high-quality rice varieties; using a drum seeder for rice seeding; nitrogen fertilizer management using a leaf colour chart; appropriate stocking density of tilapia, anabas and silver carp for freshwater zones; and crab and elongated goby for saltwater zones. Extensive aquaculture techniques were recommended for shrimp in the shrimp–rice&fish system and semi-intensive for the shrimp&crab–fish system. After 3 years of study, approximately 8700 farmers adopted the recommended systems and technologies on 11,550 ha. The participatory approaches have been successful in outscaling diversified cropping systems and new technologies, generating more benefits to farmers.

Introduction

Millions of people living in the tidal ecosystems of South and South-east Asia are among the poorest and most food insecure. Because agricultural production is hindered by seawater intrusion during the dry season, one common strategy to address this is to construct

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

embankments and install sluice gates to keep out salt water. This strategy, however, fails to recognize the diversity of rural livelihoods in coastal zones and the potential environmental consequences for water quality and aquatic biodiversity. Farmers who rely on brackishwater resources resent the strategy, leading to conflict among different resource users, which is common in the deltaic coastal areas of Asia. The magnitude, the severity and the complexity of the conflict can be represented by examples from Bac Lieu Province, located in the Mekong River Delta (MRD) of Vietnam. The emphasis on rice in the 1990s created an imperative to control saline intrusion into the coastal zone, which was realized through the construction of major engineering works over an extended period (1994–2000). This, as shown by Tuong *et al.* (2003), increased rice production in the area to the east of the province, but at the cost of environmental degradation and livelihood deterioration for many poor people in the west of the province. Because of economic pressure (given the high demand for brackishwater shrimp on the world market) and to solve conflicts among rice and shrimp farmers, the provincial authorities had to adjust the land-use plans. With proper management of the salinity control sluices, the revised land-use plans accommodate both intensive rice cultivation in the freshwater environment to the east and shrimp culture in the brackish areas to the west of the province (Hoanh *et al.*, 2003).

Both rice and shrimp production systems have their own strengths and weaknesses (Gowing *et al.*, 2006). Economically, rice cultivation is a low-risk enterprise, but it brings low income. Shrimp cultivation, on the other hand, can be very profitable but is subject to market fluctuation and a very high risk of mass mortality because of diseases (Khiem and Hossain, Chapter 32, this volume and Can *et al.*, Chapter 23). The challenge is to find production systems and technologies that enhance economic profitability and reduce the risk. One risk aversion strategy in traditional farming systems is diversification. Farmers traditionally have grown various food and non-food crops and raised livestock mainly to meet domestic needs. In market-oriented agriculture, the development of diversified, highly productive systems that are well linked with the market provides an important pathway to exit from poverty. Diversification, which is suitable for different crops or commodities at different times of the year, is particularly important in the coastal zone because of the seasonal change in water salinity. We hypothesize that diversification and polyculture (i.e. growing more than one crop/commodity at the same time in the same field) with suitable technologies, can contribute greatly to increased profitability and reduced risk for both rice-based and shrimp-based production systems in the coastal zone.

The above hypothesis was tested by comparing selected diversified and polyculture production systems and improved technologies with farmers' traditional systems in the coastal Bac Lieu Province. A participatory approach was used to evaluate the new systems and improved technologies in the field and outscaling those which proved to generate more benefits to farmers.

Methodology

Study site and its land-use zones

The study focuses on Bac Lieu Province, which covers an area of 252,000 ha, of which about 208,000 ha are cultivated (GSO, 2004). It is located at the interface between saltwater sources from the surrounding seas and the fresh water of the Mekong River (Fig. 17.1). The natural conditions, including soil and water characteristics, are described by previous researchers (Hoanh *et al.*, 2003; Tuong *et al.*, 2003; Gowing *et al.*, 2006; Hossain *et al.*, 2006). Driven by economic conditions, the land-use policy of the province has gone through rapid changes during the past decade: from mono rice in the pre-2000 period to mixed land-use types (LUTs) ranging from intensive rice culture in the eastern part and shrimp culture in the western part of the province. Mixed LUTs were possible via proper management of the salinity control sluices surrounding the province, so that salinity of the canal water varied in different

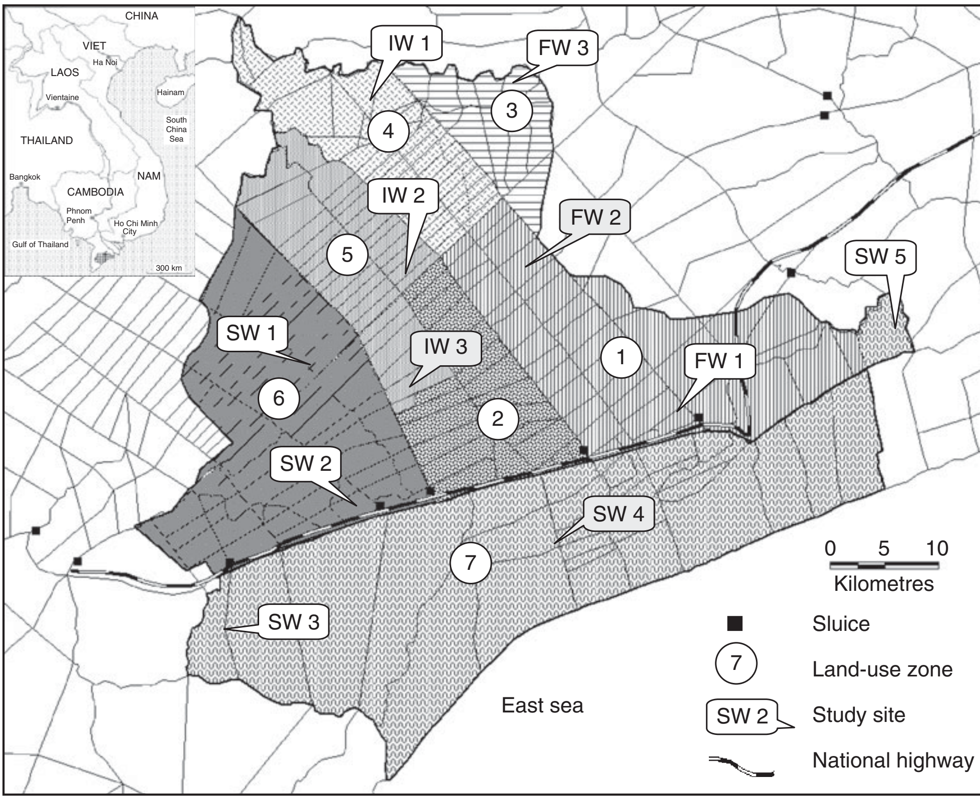


Fig. 17.1. Location of 11 study sites in the seven land-use zones.

areas, called land-use zones (LUZs), according to the water quality requirement of the LUTs. On the basis of water quality and soil characteristics, the study area can be divided into seven LUZs (after Hoanh *et al*., 2003), as indicated in Fig. 17.1.

LUZs 1–3 have freshwater ecologies, with canal water salinity < 7 dS/m all year-round. The soils are mainly alluvial. LUZ 3 has higher flood depth (about 50 cm during September–October) than LUZs 1 and 2; and water availability in LUZ 2 is less abundant than LUZs 1 and 3, especially at the end of the dry season (March–April).

LUZs 4 and 5 are intermediate types between fresh- and saltwater ecologies, with salinity > 10 dS/m during February–June and < 7 dS/m only during August–December. The freshwater period may be shortened, especially in LUZ 5, in years when the rainy season ends early. It is also sensitive to the management of the sluices. Soils comprise severe acid sulfate soil (ASS) in LUZ 5 and moderated ASS in LUZ 4.

LUZs 6 and 7 can be classified as having saltwater ecologies. The period with canal water salinity > 10 dS/m is January–June in LUZ 6 and year-round in LUZ 7. Salinity is < 7 dS/m only during August–December in LUZ 6. Soils are mainly severe ASS in LUZ 6 and saline in LUZ 7.

LUZ 7 includes a small area to the extreme east of LUZ 1 (Fig. 17.1). This area used to be protected from salinity intrusion and was similar to LUZ 1 but, since 2002, because of the high market value of shrimp, many farmers broke the salinity protection dykes to take in salt water year-round for intensive shrimp farming.

In consultation with provincial and district authorities, Hoanh *et al*. (2003) recommended the main LUTs for each of the LUZs, based on the water quality requirements for different crops:

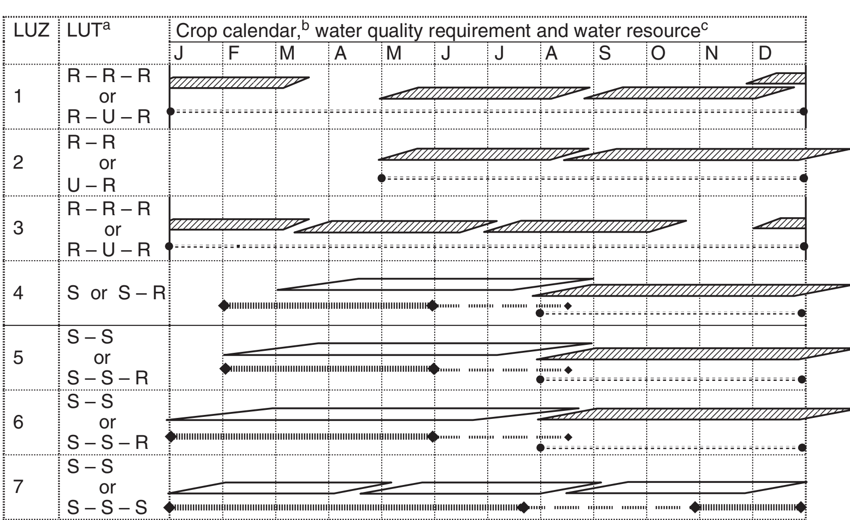
- Shrimp farming requires water salinity > 10 dS/m.
- Rice farming requires water salinity < 7 dS/m.
- Rice–shrimp farming requires water salinity of < 7 dS/m during the rice crop and >10 dS/m for shrimp. The transitional period between shrimp crop to rice crop requires fresh water for flushing salinity from the soils.

Figure 17.2 shows the main LUTs, together with their cropping calendars, in different LUZs. LUZs 1 and 3 were suitable for a cropping system of three agricultural crops (rice, R; or upland crop, U). Only two agricultural crops were recommended for LUZ 2 because of the difficulty in accessing fresh water during the latter part of the dry season. One dry-season shrimp culture (S) or shrimp (dry season)–rice (wet season) system was recommended for LUZ 4. In LUZs 5 and 6, because of the longer period of salt water available, the recommended system was two crops of shrimp from February (or January in LUZ 6) until the end of August. These can also be followed by a rice crop in the wet season. In these LUZs, during the last part of the second crop of shrimp, farmers had to store salt water in the shrimp ponds to ensure suitable salinity level (> 10 dS/m) for shrimp cultivation (Fig. 17.2). Two or three crops of shrimp were recommended for LUZs.

Testing new cropping systems and technologies

Participatory selection of testing sites

Since 2001, the provincial and district authorities have encouraged farmers to practise the LUTs shown in Fig. 17.2. Scientists from Can Tho University, local authorities and farmers have tested different new cropping systems with new or improved technologies, aiming at increasing income derived from individual crops and the year-round cropping systems in a sustainable manner. During 2004–2006, this study systematically compared the 'best bet' cropping systems and technologies with farmers' common practices in a series of test sites (1–3) per each LUZ. Each test site consisted of



[a]Land use type (LUT), [b]crop calendar (from March to April); [c]water quality type (salinity greater than 10 dS/m). S, shrimp; R, rice; U: upland crop; –, followed by. All cropping patterns begin with dry season crop.

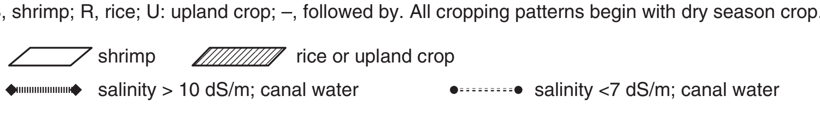


Fig. 17.2. Land-use zone (LUZ), land-use type (LUT), water requirement and water source.

a demonstration farm, which carried out new cropping systems and technologies, and five surrounding farms where farmers applied their own farming practices (control treatment).

The selection of the test sites was participatory, involving researchers, extension workers and local authorities, and consisting of several steps:

Step 1. Through the local authorities and extension workers, about 20–30 farmers in a village were invited to a meeting where researchers introduced the objectives of the study and described the new cropping systems and technologies to be tested. Farmers who were interested in participating were asked to register. If the number of registered farmers was less than six (one demonstration farm and five controls), the meeting was repeated in another village in the LUZ under study.

Step 2. Researchers and extension workers collected primary data and compiled secondary data to characterize the physical condition of the registered farms (soil types, locations, elevations, internal canal network and how it linked to the surrounding canal systems, salinity and pH of water in the canal). They also interviewed farmers to obtain their socio-economic profiles (landholding size, family size, available labour force, cropping systems and calendar, inputs, market channels, income and profit during the past 3 years).

Step 3. Researchers, local authorities and extension workers selected six participating farms. They should have the soil type, farm elevation and salinity profile typical of the pertinent LUZ. Their economic profiles represented the average conditions of the village. Furthermore, the selected farms should also have good access to water sources. Participating farmers were also selected on the basis of their enthusiasm and willingness to share their understanding with their neighbours.

Step 4. All of the previously registered farmers were invited to another meeting where the selected participating farmers were announced. Roles and functions of the demonstration and control farms were explained to all of those attended the meeting. The six selected participating farmers nominated the demonstration and five control farms on the basis that the profile of the demonstration farm was about the medium of the six selected farmers. The nomination was discussed and agreed on by all farmers who attended. The new cropping systems and technologies to be tested were again described in detail so that farmers could comment on their advantages and disadvantages over the existing land-use systems and technologies and on the implementation process.

Step 5. Researchers, local authorities and extension workers visited the selected demonstration farm and discussed with the farmer's family – including children – details of the new cropping system and technologies to be applied to their farm, together with their desires, experiences and perceived difficulties. The whole family made a final decision on the testing of the new cropping systems and technologies. This was to ensure the buy-in and participation of the whole family, instead of only the 'head of the family' who went to the meeting, but was not necessarily the person who implemented the demonstration or made other decisions in the family.

Figure 17.1 shows the locations of 11 testing sites: three (FW 1–3; FW stands for fresh water) were in the freshwater ecology zones (LUZ 1 and 3); three (IW 1–3; IW stands for intermediate water quality) in the intermediate water ecology zones (LUZ 3 and 4); and five (SW 1–5; SW stands for salt water) were in the saltwater ecology zones (LUZ 6 and 7). Among the sites in the saltwater zones, SW 2 was on a relatively high elevation. There were no sites in LUZ 2 because this zone was very similar to LUZ 1, except that there was no water available during the latter part of the dry season. The tested cropping systems, new technologies (those which had not been used by famers previously) and improved technologies (where some modifications were made to the technologies used by farmers to improve their performance) tested on the demonstration farm of each test site are described in Table 17.1.

Sites FW 2, IW 3 and SW 4 were discarded after 1 year of study. Compared with the controls, the tested cropping system in FW 1 had an additional upland crop after the DS rice crop. A new element in the cropping systems at sites FW 2, 3 and IW 1, 2 and 3 was the stocking of genetically improved farm

Table 17.1. Cropping systems, new and improved technologies in 11 demonstration sites.

LUZ	Site	Cropping systems[a]	Code[b]	New cropping system elements and technologies[c]	Improved technologies[d]
1	FW 1	DS rice, DS upland crop, WS rice	R–U–R	Additional crop of bitter cucumber (variety TW10) after DS rice Rice: sowing by drum seeder, N management using a leaf colour chart (LCC)	Rice: high-quality, improved varieties of Jasmine, OM3242
	FW 2[d]	DS rice, WS rice and fish	R–R&F	Stocking genetically improved farm tilapia (GIFT), common carp, climbing perch in wet-season rice field Rice: sowing by drum seeder, N management using LCC	Rice: high-quality, improved varieties OM4495, VND95–20, OM2517
3	FW 3	DS rice, WS rice and fish	R–R&F		Rice: high-quality, improved varieties ST3;
4	IW 1	DS shrimp, WS rice and fish	S–R&F	Stocking GIFT in wet-season rice field Rice: sowing by drum seeder, N management using LCC	Rice: high-quality, salinity-tolerant varieties Shrimp: extensive farming, stocking density 2.5 postlarvae (PL)/m^2
5	IW 2	DS shrimp, WS rice and fish	S–R&F		
	IW 3[d]	DS shrimp, WS rice and fish	S–R&F		
6	SW 1	DS shrimp and crab, WS fish	S&C–F	Stocking crab together with shrimp Stocking GIFT or elongated goby	Shrimp: semi-intensive farming, stocking density: 4–5 PL/m^2
	SW 2	DS shrimp and crab, WS fish	S&C–F	(*Pseudapocryptes elongates*) after shrimp harvest	
7	SW 3	DS shrimp and crab, WS fish	S&C–F		
	SW 4[d]	DS shrimp and crab, WS fish with upland on the bunds	S&C–F*U	Stocking crab together with shrimp Stocking GIFT or elongated goby after shrimp harvest growing onion, cucumber on the bunds during wet season	
	SW 5	DS shrimp, WS rice and fish	S–R&F	Stocking GIFT in wet-season rice field Rice: sowing by drum seeder, N management using LCC	Rice: high-quality, salinity-tolerant varieties Shrimp: semi-intensive farming, stocking density: 4–5 PL/m^2

[a]DS, dry season; WS, wet season; [b]R, rice, U, upland crop; F, fish; C, crab; S, shrimp; – followed by; &, together with (i.e. mixed, polyculture); *, secondary crops, grown on embankment/bunds; all cropping patterns begin with dry-season crop; [c]the technologies which had not been used by farmers previously; [d]some modifications (e.g. new varieties, stocking rates) were made to the technologies used by farmers to improve the crop performance.

tilapia (GIFT) in the rice field, i.e. polyculture of rice and fish (R&F), in the wet season. Some surrounding farmers also caught fish in the rice field, but the fish were mainly wild rather than intentionally stocked.

The new elements in the cropping systems at the saline sites SW 1 to SW 4 were polyculture of shrimp and crab (S&C – by stocking crabs during the shrimp-raising periods) and an additional GIFT season during the wet season, after the S&C harvest. The polyculture of S&C had been practised by some surrounding farmers before this study, but this was not common. In addition, this study introduced brackishwater fish culture, using GIFT and elongated goby (*Pseudapocryptes elongates*), in the shrimp ponds after the harvest of S&C, when the water salinity became less optimal for shrimp at the end of the wet season. GIFT is known to be able to adapt to salinity 5–10 dS/m (Alam *et al*., 2008). Elongated goby is a brackishwater fish species with a high market price.

Though site SW 5 was located in the saltwater zone, the cropping system tested (shrimp–rice&fish) was similar to that in the intermediate water quality zone. This reflected the local authorities' plan to reinforce the salinity protection scheme and to discourage farmers from intensive shrimp farming that may endanger the nearby freshwater zone, i.e. LUZ 1.

The new agriculture technologies tested by farmers included sowing rice seeds with drum seeders (see IRRI, n.d.a) and site-specific management of nitrogen fertilizer using a leaf colour chart (see IRRI, n.d.b). The improved rice technologies used mainly high-quality yet high-yielding varieties of rice (for freshwater zones), or varieties that had better tolerance of salinity (for intermediate water quality zones). For shrimp culture (Table 17.1), researchers and extension workers advised farmers to have a proper dyke (1.5 m wide and 0.8 m high) and trench (2.5 m wide and 0.8 m depth) dimension and to adjust the postlarvae (PL) stocking density to 2.5 PL/m^2 in the intermediate water zone and to 4.5 PL/m^2 in the saltwater zone.

After 1 year, three demonstration farms, FW 1, IW 3 and SW 4, were dropped from the study. At FW 1, there was a lack of labour resources because of a family member migrating to the city. Demonstration farms IW 3 and SW 4 shifted to mono-intensive shrimp farming. These farms are not included in the following discussion on results.

Farmer participatory testing of new or improved technologies

At the beginning of each cropping/farming season, technical staff from Can Tho University and extension workers gave technical training to all members of the family participating in the farming demonstration. Simple flip charts, leaflets and posters were used to illustrate all steps from seed (or fingerlings, PL) selection, seeding (or fingerling and PL stocking) to pest and disease management, water pH and salinity monitoring, to harvest. Cropping calendars were also discussed. The training materials for rice were based on the Rice Knowledge Bank materials (http://www.knowledgebank.irri.org/) and rice production programme 'Three Reductions, Three Gains' in Vietnam (http://www.irri.org/irrc/). The Research Institute of Aquaculture 2, Vietnam, supplied training materials for fish and shrimp culture.

A 'farming diary' was given to each of the participating farmers who were trained to record the information. The diary consisted of four parts. Part 1 recorded the physical condition and family profile of the farm. Part 2 recorded daily activities, pest and disease incidents, labour, amount and expenses of inputs, amount and value (including home consumption) of harvest and visits of extension workers or technical staff from Can Tho University. Part 3 was reserved for suggestions and comments of the technical staff after their visit. Part 4 was for community evaluation of the tested cropping systems and technologies.

Farmers on the demonstration farms carried out farming activities with the guidance of technical staff and extension workers. Farmers on the control farms carried out farming practices of their own without interference from the technical staff. However, they also recorded the requested information in their farming diaries. Technical staff and extension workers visited the sites weekly during the first month of each crop and every half-month after. They checked the recorded data in the diary and, for clarification, interviewed the person who recorded the data. They also measured pH, EC of water and made necessary suggestions to the demonstration farm family. Any changes to the agreed schedule of the demonstration farms were recorded. Technical staff also input all information from diaries to a common data set for ease of computation and cross-site comparison and analyses.

Assessing new and improved technologies

At the end of each crop, technical staff and extension workers, together with participating farmers, analysed yield and economic performance of the demonstration and control farms. Yield of rice (kg/ha; at 14% moisture) was calculated from the final harvest of the whole field area, which was often dried and weighed by farmers before the rice was stored or sold. Farmers often harvested cucumber, shrimp, crabs and fish periodically during the crop season. The total yields were calculated using a summation of all recorded harvest. All yields were computed on the basis of the whole field (i.e. including trenches, embankments, etc.).

The production cost was computed from the recorded labour (including family labour) and inputs multiplied by their market prices. These were checked against the recorded amount that farmers actually paid out. Farm income was calculated from all farm harvests/outputs (including for home consumption) multiplied by their market prices. The computed farm income was checked against the recorded sales that farmers actually received and recorded in the diaries. The profit of each crop and of the whole cropping system was the difference between income and production cost. Benefit–cost ratio (B/C) was computed from benefit and production costs. Technical staff and extension workers also helped farmers prepare simple posters illustrating the pertinent points of the production systems and their yields and cost–benefit analyses.

An on-farm workshop was organized at the end of each cropping cycle (i.e. at the harvest of the wet-season crop) at each test site. The workshop invited village leaders, leaders of farmers' associations and women's union, extension workers, 15–20 farmers living in the same LUZ, district and provincial reporters from print and broadcast media and television crews.

All workshop participants made field visits to the demonstration and control farms. Farming technologies and cropping patterns were explained by the participating (host) farmers. In the workshop, participants examined yield, cost–benefit analyses of demonstration and control farms as explained by participating farmers and displayed on posters. Discussion focused on soil and water suitability, crop management, cost and labour investment, profitability and potential market. The workshop also suggested modifications to improve the technologies.

Final workshops were held at all sites after 3 years of testing. Participants were asked to rate the whole system as good, medium or fair, based on their assessment of the ease to apply, cost of production, profitability and environment friendliness. They also recommended suitable component technologies (such as rice varieties, fish fingerling stocking rate, etc.) for wider dissemination.

Dissemination of new and improved technologies

Researchers from Can Tho University and extension workers assessed and compiled recommendations from the on-farm workshops, especially the final ones, with assessments written in the diaries by visitors who had visited the sites during the cropping seasons. The compilation resulted in a list of technologies that could be disseminated in different LUZs. The lists were endorsed by district and provincial authorities, who directed village leaders, leaders of farmers' associations, women's unions and extension workers at village level to disseminate the technologies in the villages widely throughout the whole LUZ. They also requested village authorities and district statistics offices to report the adoption rate of the technologies annually. In addition, 40 courses (about 40 trainees each) were organized at village level to train farmers on technologies recommended by the on-farm workshops. Journalists and reporters who attended on-farm workshops gave good coverage of the recommended cropping systems and technologies in local newspapers and on radio and television.

Results and Discussion

Performance of cropping systems in the freshwater area

Cropping system rice–upland crop–rice at site FW 1

On the demonstration farm, Jasmine rice was affected by stem borer (*Chilo suppressalis*) and leaf folder (*Cnaphalocrocis medinalis*) and was replaced by OM3242 after two seasons. Low yield of Jasmine rice resulted in lower average yields on the demonstration farm compared with those on control farms (Table 17.2). Profits from rice on the demonstration farm were, however, higher than those on the control farms. This was because of the higher market prices for new rice varieties (Jasmine and OM3242, at US$0.24/kg) compared to those on the control farms (US$0.22/kg). The use of LCC (http://www.irri.org/irrc/ssnm/index.asp) in nutrient management reduced nitrogen fertilizer by 80 kg/ha and drum seeder technology reduced the amount of seed by 17 kg/ha. These contributed to the higher B/C ratio of the demonstration farm (Table 17.2).

The upland crop (bitter cucumber, variety TW10) grown after the DS rice was also unsuccessful. It was the only crop in the field that attracted pests and diseases. Lack of irrigation water at the end of the DS rice also contributed to the failure of the upland crop. Cultivation of cucumber resulted in a loss to the demonstration farmer.

Over the whole year, the new cropping system and technologies increased the profit by US$30/ha, but slightly reduced the B/C ratio of the demonstration farm. The failure of bitter cucumber, the lower rice yield (Jasmine) and lower B/C were the reasons behind the community's evaluation of the demonstration farm as only 'fair' (Table 17.3).

Cropping system rice–rice&fish at site FW 3

The rice yield on the demonstration farm was lower than that on the control farms (Table 17.2). This was because of a loss of 40% of the cultivated area resulting from the construction of trenches and embankments needed for fish culture. This led to a lower profit from rice on the demonstration farm compared with that on the control farms. However, rice had a higher B/C ratio on the demonstration farm than on the control farms. This was because of a combination of: a lower seeding rate (drum seeder technology); lower nitrogen input (LCC technology); better market price of the high-quality varieties tested; and fewer inputs because of the smaller area. In addition, good embankments reduced the amount of seepage loss of water on the demonstration farm, hence reducing irrigation costs by about US$10/ha annually.

Despite 40% loss of the cultivated area because of the construction of trenches and embankments, the demonstration farm had a much higher profit from fish production than the control farms (Table 17.2). This was because of the demonstration farm's much higher yield. The B/C ratio of the demonstration farm was slightly less than that of the control farms. Farmers on the control farms collected wild fish from their rice fields, thus there was no fish production cost.

Overall, the rice–rice&fish cropping system on the demonstration farm produced a much higher profit and higher B/C ratio than the control farms (Table 17.2).

Farmers also reported that the new technologies reduced the number of labour days required for weeding and reduced pest and disease incidences; hence, less pesticide was needed for the rice crops. This also benefited the fish culture. The final evaluation by the community of this demonstration farm was 'good' (Table 17.3).

Performance of cropping systems in the intermediate water area

Cropping system shrimp–rice&fish at site IW 1

With improved technologies, shrimp culture on the demonstration farm had higher yields and higher profits and B/C ratio than the control farms (Table 17.2). New varieties (ST3 in 2004

Table 17.2. Yield and profitability of demonstration (demo) and farmers' common practices (control).

LUZ	Site	Cropping system[a]	Components	Seasons × farms		Yield[b] (kg/ha)		Profit[b] (US$/ha)		B/C ratio[b]	
				Demo	Control	Demo	Control	Demo	Control	Demo	Control
1	FW 1	R–U–R	Rice[c]	6 × 1	6 × 5	4600 ± 310	5290 ± 100	416 ± 24	399 ± 17	1.47 ± 0.19	1.07 ± 0.1
			Upland	3 × 1	0	Negligible		–50.3			
			Whole year	3 × 1	3 × 5			829 ± 194	799 ± 45	1.03 ± 0.47	1.05 ± 0.13
3	FW 3	R–R&F	Rice[c]	6 × 1	6 × 5	3160 ± 290	4740 ± 130	346 ± 70	388 ± 31	2.06 ± 036	1.27 ± 0.11
			Fish	3 × 1	3 × 3	475 ± 66	122 ± 27	335 ± 34	79 ± 17	4.29 ± 0.3	4.9 ± 0.3
			Whole year	3 × 1	3 × 5			1026 ± 218	854 ± 79	2.47 ± 10.42	1.31 ± 0.13
4	IW 1	S–R&F	Shrimp	3 × 1	3 × 3	324 ± 57	1 93 ± 28	1398 ± 40	311 ± 155	4.98 ± 192	3.17 ± 0.8
			Rice	3 × 1	3 × 5	4141 ± 210	3960 ± 160	513 ± 27	483 ± 17	3.27 ± 0.63	4.41 ± 0.43
			Fish	3 × 1	3 × 5	365 ± 73	92 ± 25	225 ± 35	37 ± 5	4.54 ± 0.9	10.20 ± 0.9
			Whole year	3 × 1	3 × 5			2136 ± 479	1332 ± 133	3.55 ± 0.41	4.18 ± 0.54
5	IW 2	S–R&F	Shrimp	3 × 1	3 × 3	88 ± 22	110 ± 13	290 ± 96	230 ± 10	2.22 ± 0.68	0.84 ± 0.2
			Rice	3 × 1	2 × 3	0	600 ± 250	–327 ± 146	–3 ± 20	–	–
			Fish	3 × 1	3 × 3	906 ± 45	138 ± 32	30 ± 9	39 ± 16	1.66 ± 0.54	5.26 ± 1.08
			Whole year	3 × 1	3 × 5			–7 ± 241	267 ± 61	–	–
6	SW 1	S&C–F	Shrimp	3 × 1	3 × 3	133 ± 73	213 ± 25	651 ± 603	985 ± 149	2.27 ± 2.02	4.37 ± 0.75
			Crab	3 × 1	3 × 5	94 ± 1	27 ± 4	327 ± 83	134 ± 33	6 ± 1	3.8 ± 3.6
			Fish	3 × 1	3 × 5	172 ± 53	124 ± 30	96 ± 17	47 ± 9	2.49 ± 0.6	7.1 ± 1.4
			Whole year	3 × 1	3 × 5			1075 ± 528	1166 ± 186	2.53 ± 0.91	4.53 ± 0.63
	SW 2	S&C–F	Shrimp	3 × 1	3 × 5	98 ± 2	84 ± 21	258 ± 66	235 ± 121	1.3 ± 0.6	0.9 ± 0.5
			Crab	3 × 1	3 × 4	32 ± 6	9 ± 3	84 ± 12	13 ± 20	33 ± 0.8	0.7 ± 0.6
			Fish	3 × 1	3 × 5	76 ± 36	122 ± 55	74 ± 66	78 ± 17	0.9 ± 0.6	10 ± 2.3
			Whole year	3 × 1	3 × 5			416 ± 149	326 ± 129	1.09 ± 0.46	1.02 ± 0.44
7	SW 3	S&C–F	Shrimp	3 × 1	3 × 3	322 ± 15	154 ± 31	848 ± 39	394 ± 123	2.7 ± 1	0.7 ± 0.2
			Crab	3 × 1	3 × 5	92 ± 57	35 ± 7	260 ± 131	94 ± 42	3.9 ± 1.1	1.9 ± 0.5
			Fish	3 × 1	3 × 4	155 ± 39	148 ± 31	194 ± 81	42 ± 10	2.8 ± 1	8.2 ± 1.2
			Whole year	3 × 1	3 × 5			1352 ± 478	531 ± 122	2.44 ± 0.65	1.82 ± 0.60
	SW 5	S–R&F	Shrimp	3 × 1	3 × 4	479 ± 98	550 ± 172	1260 ± 421	866 ± 367	1.6 ± 0.2	0.3 ± 0.2
			Rice	3 × 1	3 × 1	0	170 ± 40	–7	–9 ± 19	–	0.3 ± 0.5
			Fish	3 × 1	3 × 1	920 ± 66	96 ± 19	59 ± 30	30 ± 13	7.7 ± 1.6	4.2 ± 1.8
			Whole year	3 × 1	3 × 5			1314 ± 505	887 ± 348	1.83 ± 0.20	0.25 ± 0.20

[a]R, rice; U, upland crop; F, fish; C, crab; S, shrimp; –, followed by; &, together with (i.e. polyculture); [b]means ± SD computed over number of seasons × sites; [c]for both dry and wet seasons.

Table 17.3. Community rating of the tested cropping systems and recommendations.

LUZ	Site	Cropping system[a]	Community rating of the cropping system: Good	Medium	Fair	General recommendations	Component technologies recommended for outscaling
1	FW 1	R–U–R	4	7	18	The upland crop is impossible without canal excavation to increase water availability during dry season	Rice variety OM3242; drum seeder; LCC
3	FW 3	R–R&F	18	10	3	Recommended for outscaling in whole LUZ 3 and the part of LUZ 1 adjacent to LUZ 3	Rice varieties OM4495, VND95–20, OM2517; drum seeder; LCC Fish: GIFT + anabas + silver carp at ratio 0.3 + 0.2 + 0.1 ind/m^2
4	IW 1	S–R&F	22	5	3	Recommended for outscaling in whole LUZ 4	Rice varieties ST3, ST5; drum seeder Shrimp: extensive, stocking density ~ 2 PL/m^2 with two times of stocking Fish: GIFT + anabas + silver carp at ratio 0.2 + 0.07 + 0.05 ind/m^2
5	IW 2	S–R&F	0	3	14	Water too saline for rice and GIFT. S&C–F system more suitable for present conditions. S–R&F is possible only if the sluices are managed so that water is fresh until mid-January	Shrimp: extensive, stocking density ~ 2 PL/m^2 with two times of stocking Fish: elongated goby 1 ind/m^2
6	SW 1	S&C–F	2	10	12	The cropping system is good but trench excavation has to be done properly to avoid acid water, then the system can be outscaled	Shrimp: semi-intensive, density ~ 4 PL/m^2 with two times of stocking Crab: density 0.05 ind/m^2 Fish: elongated goby 1 ind/m^2
	SW 2	S&C–F	6	9	5	Recommended for outscaling in whole LUZ 6	As for SW1
7	SW 3		17	11	0	Recommended for outscaling in whole LUZ 7	As for SW1
	SW 5	S–R&F	16	11	2	Not suitable, water too saline for rice. System S&C–F may be more suitable	Shrimp: semi-intensive, density ~ 4 PL/m^2 with two times of stocking Fish: elongated goby 1 ind/m^2

[a]R, rice; U, upland crop; F, fish; C, crab; S, shrimp; –, followed by; &, together with (i.e. polyculture).

and ST5 in later years) on the demonstration farm yielded more and had higher profits than the local variety, Mot Bui Do, grown on the control farms. New varieties and technologies had lower B/C ratio; farmers often did not invest in fertilizer and pest and disease control for the local variety.

New technologies on the demonstration farm increased the yield of fish and its associated profits compared with the control farms. The B/C ratio on the control farms, however, was higher than on the demonstration farm (Table 17.2) because farmers on the control farms merely captured wild fish that happened to be in the ponds. They did not invest in fish stocking, labour or feed.

Overall, the shrimp–rice&fish cropping system on the demonstration farm had a much higher total profit than did the control farms (US$2136 versus US$1332/ha annually). With higher profit, even with a B/C ratio smaller than the control farms, the community rated the demonstration farm cropping system and technologies as ‘good’ (Table 17.3).

Cropping system shrimp–rice&fish at site IW 2

The yield of shrimp on the demonstration farm at site IW 2 was nearly as high as that on the control farms (Table 17.2), despite its much lower PL stocking density (2 versus 5 PL/m^2). Lower stocking density resulted in bigger shrimp size, which commanded a higher price. The lower investment on PL cost and higher shrimp market value resulted in a higher profit and much higher B/C ratio on the demonstration farm than on the control farms.

Rice cultivation at site IW 2 did not perform well and resulted in financial loss, on the demonstration farm as well as on the control farms. This was because of high salinity at the end of the rainy season when rice was in its reproductive stage. Even the local rice variety, Mot Bui Do, known for its high salinity tolerance, yielded on average only 600 kg/ha. Loss because of rice cultivation on the demonstration farm was higher than that on the control farms, because the demonstration farm required higher inputs (Table 17.2).

High salinity in rice fields also resulted in a low yield of GIFT and financial loss in 2004. Farmers on the demonstration farm replaced GIFT with elongated goby (*P. elongates)* in 2005 and 2006 and this resulted in higher profits compared with the natural fish on the control farms. Because of the loss in 2004, the average profit from fish on the demonstration farm was lower than on the control farms (Table 17.2). Overall, the tested cropping system shrimp–rice&fish at site IW 2 ran a loss of US$274/ha annually compared with the control farms and was rated by the community as ‘fair’ (Table 17.2). Farmers living around the demonstration farm accepted only two component technologies: low shrimp stocking density and raising elongated goby but not GIFT.

Performance of cropping systems in the salt water area

Cropping system shrimp&crab–fish at site SW 1

Yield, profit and B/C ratio from shrimp culture on the demonstration farm were lower than those on the control farms. This could be explained in part by the oxidation of potential acidic materials after the trenches had been excavated for storing more salt water. This was supported by lower pH values of water on the demonstration farm (7.2) compared with those on the control farms (8.0). Lower profit and B/C ratio on the demonstration farm could also be explained by higher PL stocking rate, compared to the control farms (4.5 versus 3.5 PL/m^2).

Yield, profit and B/C ratio from crab were higher on the demonstration farm than those on the control farms. Acidic pollution because of trench excavation did not affect the growth of crab. Deep trenches provided a better habitat for crab.

Raising GIFT was not successful in 2004. Farmers on the demonstration farm replaced GIFT by elongated goby and this resulted in excellent profits in 2005 and 2006 and a higher average profit compared to the control farms (Table 17.2). The B/C ratio of fish culture on the demonstration farm, however, was much lower than that of the control farms. Farmers on the control farms did not invest in fish stocking, labour or feed.

Overall, the demonstration farm at site SW 1 had similar profits as the control farms, but much lower B/C ratio (Table 17.2). The community rating was from ‘fair’ to ‘medium’ (Table 17.3). Farmers, however, rated the culture of elongated goby highly. Their evaluation was that deeper and wider trenches were good for crab and elongated goby, but recommended that care had to be taken during excavation to avoid acidic pollution of the water. They believed that if this were achieved, shrimp would also give a high yield and profit.

Cropping system shrimp& crab–fish at site SW 2

Because of its relatively high elevation, site SW 2 had high water loss from shrimp ponds, and therefore high pumping costs during the dry season. Only shallow water depth (< 30 cm) could be maintained in the ponds, affecting the yields of shrimp, crab and fish, which were lower than those at site SW 1.

Shrimp yield and associated profit on the demonstration farm were slightly higher than those on the control farms, but the B/C ratio on the demonstration farm was substantially higher than that on the control farms (Table 17.2). This was because of less money spent on PL, of which the stocking density on the demonstration farm (4 PL/m^2) was only about half of that on the control farms. Crab performed much better on the demonstration farm than on the control farms in terms of yield, profit and B/C ratios. On the demonstration farm, fish yields were less than those of the control farms but had higher profit because elongated goby raised on the demonstration farm had higher market value than the natural fish that farmers harvested on the control farms. Similar to other sites, the control farms had a higher B/C ratio for fish than the demonstration farm, since farmers did not have to invest in capturing the natural fish in the ponds.

In total, the demonstration farm at SW 2 gave an additional profit of US$90/ha over the control farms, with similar B/C ratios. Because of relatively low additional profit, the community rated the demonstration farm at SW 2 as ‘medium’ (Table 17.3). However, farmers highly assessed the low stocking density of shrimp PL and the raising of elongated goby after the harvest of shrimp.

Cropping system shrimp& crab–fish at site SW 3

Shrimp and crab culture on the demonstration farm of site SW 3 performed better than on the control farms in terms of yield, benefit and B/C ratio (Table 17.2). The better performance of the demonstration farm was attributed to a proper PL stocking density for shrimp and a monthly harvest of shrimp rather than several times a month. Frequent harvest of shrimp also trapped crabs, which had to be released back to the field. The frequent disturbances might have resulted in lower crab yields on the control farms.

The average fish yield of the demonstration farm was lower than that of the control farms. It included very low yield of GIFT in 2004, so this was replaced by elongated goby, which gave excellent yield and profits in 2005 and 2006. Despite the higher profit, similar to other sites, the B/C ratio of fish on the demonstration farm was much lower than on the control farms, where farmers merely caught the wild fish in the ponds.

In general, the cropping system shrimp&crab–fish (elongated goby) resulted in a higher total profit when compared to the control farms at US$821/ha/year (US$1352 versus US$821/ha/year), which the community rated as ‘good’ (Table 17.3).

Cropping system shrimp–rice&fish at site SW 5

Shrimp on the demonstration farm yielded slightly less, but gave a much higher profit and B/C ratio than the control farms. Low PL stocking reduced input cost and resulted in large-sized individuals, with higher market price than those from the control farms (Table 17.2).

Rice failed on the demonstration farm as well as on the control farms. The cropping system shrimp–rice&fish was tested in SW 5, while many surrounding farmers were practising intensive shrimp farming that requires intake of salt water all year-round. High salinity in the area must have caused the failure of the rice crops.

Overall, despite the failure of rice, the profit and B/C ratio of the demonstration farm was much higher than the control farms. Since there are many farmers practising intensive shrimp farming in the area, it is not advisable to practice shrimp–rice&fish. Farmers proposed to change the cropping system to shrimp–fish, with low shrimp PL stocking and elongated goby as the fish of choice.

The community's overall assessment and recommendation

The community ratings of the cropping systems and tested technologies for each site are presented in the previous sections and are summarized in Table 17.3. In most cases, the community rated the new cropping systems and technologies favourably. The three cases that received a low rating related to the lack of freshwater sources to cultivate upland crops (site FW 1); the water became saline before the rice harvest (site IW 2); and there was acidic pollution because of the excavation of trenches (site SW 1). Farmers' ratings were guided more by the yield and profit brought about by the systems or the technologies than the B/C ratio. Farmers were willing to invest in fish culture to gain extra profit rather than rely on natural fish captured from the pond, which had a much higher B/C ratio than having to stock fingerlings and raising high-value fish. The tested cropping system at site SW 5 failed (rice could not be grown because of high salinity), but farmers still rated the demonstration farm favourably (Table 17.3) because other component technologies (shrimp and fish) brought more profit to the farmers than common practices. The extra income from new aquaculture technologies for shrimp and fish outweighed the loss of rice.

Table 17.3 includes a compilation of recommendations made by farmers and extension workers. It was recommended that most of the tested cropping systems be widely disseminated in their respective relevant LUZs. In three cropping systems that were not recommended for dissemination (R–U–R at site FW 1; S–R&F at site IW 2; and S–R&F at site SW 5), the community suggested alternative cropping systems or conditions needed to ensure the success of the tested systems (Table 17.3).

Farmers also highly assessed the component technologies that were tested and recommended them to be disseminated. New rice varieties and seeding with drum seeders were recommended at all sites in the freshwater and the intermediate water quality zones where rice was a component of the cropping system. Raising GIFT in freshwater and intermediate water quality zones was recommended with elongated goby recommended for saltwater zones. Appropriate stocking densities of shrimp PL were recommended according to the salinity zones (Table 17.3).

Outscaling

The continuing programme of training and field visits organized for surrounding farmers exposed the tested cropping systems and technologies to the wider community. The on-farm workshops organized at the end of each cropping season gave participating farmers platforms to convince local authorities and community organizations such as farmers' associations and women's unions of the importance of adapting the new systems and technologies. Local newspapers, radio and television, with their first-hand experiences at the on-farm workshops, continued to give wide coverage to the tested technologies. Surrounding farmers gradually started trying out the demonstrated systems or the component technologies, even before the end of the study.

Having attended the on-farm workshops and listened to the farmers' debates there, local authorities were ready to endorse the recommendations by farmers, extension workers and scientists. Public funds were made available for extension workers to outscale the technologies. From May 2004 to the end of 2006, 4300 farmers adopted the shrimp&crab–fish systems, with the recommended component technologies. Approximately 3200 farmers applied the rice–rice&fish system in the freshwater zone. A further 1200 farmers adopted new rice varieties, seeding by drum seeders in other cropping systems where rice was a component. These farmers cultivated a total area of 11,500 ha.

The provincial government also took into account the study's findings and participatory recommendations in revising land-use planning for the province (McDonald, 2008).

Conclusions

The study used participatory evaluation rather than rigid statistical designs and analysed it to compare the tested systems and technologies and the controls. The endorsement and support of local authorities for outscaling the recommended technologies and the widespread adoption of the study results and recommendations support the choice of the approaches used. Using vigorous statistical designs and analyses for complex systems at regional scale, in which many parameters varied in space and time, as illustrated in this study, would be prohibitively complicated and expensive.

The method used in this study required participation from different stakeholders (from farmers to local authorities) in every step, from testing site selection to outscaling. Involving the whole family of the participating farmers in decision making and then training them on the technologies tested were important steps to avoid the often cited mistake that 'the ones who go to meetings and get trained (usually men) are not the ones who actually make decisions and carry out farming activities at home'. Farmer-managed on-farm workshops, with presentations from farmers rather than researchers or extension workers, were very effective in creating lively debates and a conducive atmosphere for the farmer participants to contribute ideas and inputs. Publicity given by the media (press), reporting their first-hand experiences with the technologies via the on-farm workshops, was important in technology dissemination. The endorsements from local authorities, who were also involved in every step from site selection to community evaluation, were crucial in the formulation of a cohesive programme from the provincial to district and village levels to disseminate the new cropping systems and technologies. The results of the study confirmed that diversification and polyculture, with the appropriate technologies, could contribute greatly to an increased profitability and improved livelihood of the farmers living in the coastal zones.

Acknowledgement

This study was carried out under the framework of the Challenge Program on Water and Food Project No 10 (CPWF PN10). We thank the local authorities for their support. Special thanks are due to all the farmers who participated in the demonstration and also to the control farms.

Notes

[1] In all cropping systems, the first crop refers to the dry-season crop, followed by (–) wet-season crops; & refers to 'together with', i.e. polyculture.

References

Alam, M.J., Islam, M.L., Tuong, T.P. and Joffre, O. (2008) Improved rice–aquaculture integration in coastal rice–shrimp systems in Bangladesh. In: Humphreys, E., Bayot, R.S., van Brakel, M., Gichuki, F., Svendsen, M., Wester, P., Huber-Lee, A., Cook, S., Douthwaite, B., Hoanh, C.T., Johnson, N., Nguyen-Khoa, S., Vidal, A., MacIntyre, I. and MacIntyre, R. (eds) *Fighting Poverty Through Sustainable Water Use: Volume 3, Proceedings of the CGIAR Challenge Program on Water and Food 2nd International Forum on Water and Food, Addis Ababa, Ethiopia, 10–14 November 2008*. The CGIAR Challenge Program on Water and Food, Colombo, pp. 103–106.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing*

Agriculture–Fishery–Aquaculture Conflicts. Comprehensive Assessment of Water Management in Agriculture Series, No 2. CAB International, Wallingford, UK, pp. 48–60.

GSO (General Statistics Office) (2004) *Statistical Yearbook 2004*. Statistical Publishing House, Hanoi.

Hoanh, C.T., Tuong, T.P., Gallop, K.M., Gowing, J.W., Kam, S.P., Khiem, N.T. and Phong, N.D. (2003) Livelihood impacts of water policy changes: evidence from a coastal area of the Mekong River Delta. *Journal of Water Policy* 5(5), 475–488.

Hossain, M., Ut, T.T. and Bose, M.L. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts. Comprehensive Assessment of Water Management in Agriculture Series, No 2*. CAB International, Wallingford, UK, pp. 30–47.

IRRI (International Rice Research Institute) (n.d.a) Planting Machines (http://www.knowledgebank.irri.org/PlantEstablish/WebHelp/Plant_lesson06.htm, accessed 8 August 2009).

IRRI (International Rice Research Institute) (n.d.b) Site Specific Nutrient Management: Leaf Color Chart for Fertilizer N Management in Rice (http://www.irri.org/irrc/ssnm/lcc/orderlcc.asp, accessed 8 August 2009).

McDonald, B. (2008) Managing Water and Land Resources for Sustainable Livelihoods at the Interface between Fresh and Saline Water Environments in Vietnam and Bangladesh – A Project Funded by the Challenge Program on Water and Food – Impact Evaluation of the Vietnam Component. CPWF, Sri Lanka.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Barr, J. and Ben, D.C. (2003) Impact of seawater intrusion control on the environment, land use and household incomes in a coastal area. *Journal of Paddy and Water Environment* 1(2), 65–73.

18 Improving Rice Productivity in the Coastal Saline Soils of the Mahanadi Delta of India through Integrated Nutrient Management

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Abstract
The coastal saline belt of the Mahanadi Delta in Orissa, India, is mostly monocropped with rainfed rice during the wet season (WS). In the dry season (DS), a small area is planted to rice using harvested rainwater. Currently, yields are low; however, integrated nutrient management combined with improved salt-tolerant rice varieties could increase system productivity substantially. On-farm trials were conducted in the Ersama block of Jagatsinghpur district (Orissa) using rice varieties Pankaj (shallow lowland) and Lunishree (intermediate lowland) in the wet season and Annapurna and Canning 7 in the dry season. Selected nutrient management practices were evaluated during 2004–2006 and the most promising options were validated in participatory farmer-managed trials in 2006–2007 conducted at six to eight locations. In the shallow lowlands, *Sesbania* green manuring (GM) + prilled urea (PU; 20 kg/ha N), *Azolla* + PU (30 kg/ha N) and *Sesbania* + *Azolla* were as effective as PU at 60 kg/ha N, in both the 2004 and 2005 WS, with a yield advantage of 30–40%. In the intermediate lowlands, the grain yields with *Sesbania* in 2004 and farmyard manure (FYM; 5.0 t/ha) + PU (20 kg/ha N) in 2005 were comparable with the yield achieved with urea supergranules (USG; 45 kg/ha N), which had limited scope because of unavailability and placement problems. The yield advantage of these treatments was 23–68%. During the DS of 2005 and 2006, *Azolla* + PU (50 kg/ha N) resulted in significantly higher yields (15%) than the application of PU at 80 kg/ha N. In demonstration trials at six on-farm sites in the 2006 WS, *Sesbania* and *Sesbania* + *Azolla* increased rice yields in the shallow lowlands by 12–40% (mean 23%) and 19–77% (mean 41%), respectively. In the same season, the yield advantage due to *Sesbania* was 8–50% (mean 29%) for eight on-farm sites in intermediate lowlands. In the 2007 DS, *Azolla* increased rice yield by 16–35% (mean 24%) over a control treatment at eight on-farm sites. These findings suggest that, under both the shallow and intermediate lowlands, *Sesbania* for the WS and *Azolla* biofertilizer for the DS are promising organic nutrient sources that can improve soil quality and contribute to enhancing and sustaining crop productivity in coastal areas.

Introduction

Out of the 8.1 million ha of salt-affected area in India, nearly 5.0 million ha are inland and 3.1 million ha occur along the east and west coasts (Yadav *et al.*, 1983). The east coast accounts for more than 60% of the total coastal salt-affected land and consists predominantly of deltas, including the Mahanadi Delta. The entire area is mostly rainfed and monocropped with rice during the wet season (WS). In the dry season (DS), only a limited area is planted to rice using harvested rainwater, while more than 90% of these lands remain fallow due to a lack of irrigation water. Rice in the WS suffers from several abiotic stresses (salinity, drought and submergence) and natural hazards (storms and cyclones), resulting in low productivity and occasional crop failure. The majority of farmers in this region are resource-poor with marginal to small landholdings. Their economic conditions worsened after the 1999 super cyclone that ravaged the entire area, causing irreparable asset losses and further deteriorating their livelihood.

In the WS, the rice crop is often subjected to drought and salinity stress at seedling and reproductive stages and submergence at the vegetative stage due to erratic high rainfall. Farmers generally grow traditional varieties with few inputs. The application of chemical fertilizers is difficult and, if applied, their efficiency is low under waterlogged conditions, particularly in intermediate lowlands (Ladha, 2005) where the excess water (0.3–0.5 m depth) causes fertilizer dilution and overflow to neighbouring fields. In the DS, salinity is more severe and farmers grow rice in less saline areas using short-duration varieties to escape salinity damage at later stages. Soils are loamy sand to clay loam in texture, with large variability in salinity and fertility status (Sahu and Dash, 1993; Maji and Bandyopadhyay, 1996). In order to cope with the stresses and to enhance productivity to ensure food security, improved salt-tolerant rice varieties have been introduced for the WS and DS (Sen *et al.*, 2006), but improved nutrient management options are necessary to make use of the higher yield potential of these varieties. Integrated nutrient management (INM), combining chemical with organic fertilizers, was shown to improve nutrient-use efficiency and increase crop productivity (Panda *et al.*, 2004; Bajpai *et al.*, 2006). Organic amendments are also known to improve physico-chemical and microbiological soil properties and to maintain soil productivity lastingly (Elfstrand *et al.*, 2007; Tirol-Padre *et al.*, 2007). However, studies on INM for rice in saline coastal ecosystems under farmers' field conditions are scanty. Therefore, this paper summarizes results from a number of on-farm site-specific INM trials and their implications for productivity are further discussed.

Materials and Methods

Site-specific on-farm trials were conducted in the Ersama block of Jagatsinghpur district, Orissa, India, during 2004–2006, to evaluate selected INM practices. The most promising options were demonstrated subsequently for dissemination during 2006–2007 through farmer-managed participatory trials. Three separate trials were conducted: two in the WS under shallow (0–0.3 m) and intermediate (0–0.5 m) water depths of lowland conditions and one in the DS under irrigated conditions, using a randomized complete block design with four, five and three replications, respectively. The treatments for different trials were selected based on their suitability to a particular situation, and treatment details are given in Table 18.1. In the WS, rice varieties Pankaj (shallow lowlands) and Lunishree (intermediate lowlands) were used, whereas Canning 7 and Annapurna were used in the DS. In shallow lowlands, the soil (0–0.15 m depth) at the trial site had a sandy loam texture with 0.47% organic C, 0.05% total N and 8 kg/ha available P (Olsen P; Jackson, 1973); the soil at the trial site for intermediate lowlands had a clay loam texture with 1.1% organic C, 0.10% total N and 12 kg/ha available P; and the DS site had a soil with sandy clay loam texture, 0.74% organic C, 0.07% total N and 10 kg/ha available P. In the WS, the crop was transplanted at 0.2 × 0.15 m spacing using 40-day-old seedlings in the shallow lowlands and 50-day-old seedlings in the intermediate lowlands. In the DS, 30-day-old seedlings were planted at 0.15 × 0.15 m spacing.

A uniform dose of 40 kg/ha P_2O_5 and K_2O as single superphosphate and muriate of potash, respectively, was used in all treatments and in both seasons. *Sesbania aculeata* was grown *in situ* with a basal application of 30 kg/ha P_2O_5 and 45-day-old plants were incorporated into the soil during puddling. Fresh *Azolla caroliniana* was applied at a rate of 1.0 t/ha 1 week after transplanting and grown with rice as dual cropping (intercropping). Phosphorus at 10 kg/ha P_2O_5 was applied in three equal splits at 7-day intervals to improve *Azolla* growth. The

Table 18.1. Treatment details for different trials during the wet and dry seasons.

Season/land situation	Treatments
Wet season	
Shallow lowland	T_1 (no N) – control
	T_2 (PU) – prilled urea (PU) at 60 kg/ha N applied in three splits (30 + 15 + 15) as basal and at tillering and panicle initiation (PI)
	T_3 (Sesb + PU) – *Sesbania* green manure (GM) + PU at 20 kg/ha N applied at PI
	T_4 (Az + PU) – *Azolla* dual cropping + PU at 30 kg/ha N (20 kg as basal and 10 kg at tillering)
	T_5 (Sesb + Az) – *Sesbania* GM + *Azolla* dual cropping
Intermediate lowland	T_1 (no N) – control
	T_2 (USG) – urea super granule (USG) at 45 kg/ha N applied 10 days after transplanting
	T_3 (Sesb) – *Sesbania* GM
	T_4 (FYM + PU) – farmyard manure at 5.0 t/ha + PU at 20 kg/ha N applied as basal
Dry season	T_1 (no N) – control
	T_2 (PU) – PU at 80 kg/ha N applied in three splits (40 + 20 + 20) as basal and at tillering and PI
	T_3 (Az + PU) – *Azolla* dual cropping + PU at 50 kg/ha N (30 kg as basal and 20 kg at tillering)

P applied for *Sesbania* and *Azolla* was part of the recommended P rate for rice and only the remaining P along with the entire K was applied before transplanting, except in the *Sesbania* GM + *Azolla* treatment, in which all P was applied to the *Sesbania* and *Azolla*. In the remaining treatments, the entire P and K dose was applied just before transplanting. Urea supergranules (USG) were placed with a simple device in the reduced zone between four hills 10 days after transplanting. The device was made of a PVC pipe (inner diameter 2.0 cm) fitted at the lower end to a wooden piece having a neck with a slanting face to deflect the urea granules outward through a semi-circular opening on the pipe, and a cone-shaped body to facilitate their penetration into the soil. The diameter of the cone at the neck joint was greater than the outer diameter of the pipe to prevent entry of mud and blocking of the passage of fertilizer granules. The FYM was spread uniformly and ploughed into the soil during the initial land preparation after the onset of seasonal rains. Soil samples (0–0.15 m depth) were collected periodically in both seasons and composite samples were used for electrical conductivity analysis in a saturation extract (ECe) with a Cyberscan-510 conductivity meter (Jackson, 1973). In the DS trial, a piezometer (1.3 m depth) was installed and the groundwater table depth and groundwater EC were recorded periodically. During 2006–2007, the most promising INM practices – (i) *Sesbania* (shallow and intermediate lowlands, WS), (ii) *Sesbania* + *Azolla* (shallow lowlands, WS) and (iii) *Azolla* + prilled urea (DS) – were disseminated through demonstration trials conducted at six (shallow lowland) and eight (intermediate lowland and during DS) farmers' locations. A no-N control for the WS trials and a no-*Azolla* control for the DS trials were included for comparison.

Results and Discussion

Soil, surface-water and groundwater salinity

During the WS, soil (saturation extract) and field-water EC for most of the crop growth period in the shallow lowland trial ranged between 0.4–3.9 and 0.1–0.5 dS/m in 2004 and between 2.0–7.3 and 0.4–2.8 dS/m in 2005, respectively. The corresponding EC ranges in the intermediate lowland trial were 0.4–4.6 and 0.5–1.6 dS/m in 2004 and 2.7–8.0 and 0.3–2.4 dS/m in 2005. The water table in the WS remained near or above the soil surface during most of the cropping period. Soil and field-water salinity was higher in 2005 than in 2004 because of lower rainfall during August–September. In the DS trial, soil and field-water

EC were 3.9–11.0 and 2.5–5.5 dS/m in 2005 and 1.4–4.9 and 1.2–5.3 dS/m in 2006, respectively. Depths to the groundwater table in this trial were 0.67–0.95 m and 0.46–1.04 m, and groundwater EC ranged between 3.6–10.5 and 2.0–9.9 dS/m in 2005 and 2006, respectively. Salinity in the DS was higher in 2005 than in 2006. A terminal drought during October–November in the 2004 WS was responsible for the greater salinity build-up in the 2005 DS, whereas high rainfall during October 2005 led to lower salinity in the 2006 DS. Apparently, salinity during the WS varied, based mainly on the rainfall pattern and land situation, whereas salinity during the DS depended on the depth of the groundwater table, groundwater EC, atmospheric evaporative demand and rainfall pattern in the preceding wet season.

Rice grain yield

In shallow lowlands, *Sesbania* GM + PU (20 kg/ha N), *Azolla* dual cropping + PU (30 kg/ha N) and *Sesbania* GM + *Azolla* were as effective as PU at 60 kg/ha N in increasing grain yield of rice in the 2004 and 2005 WS (Fig. 18.1). The yield advantage due to these treatments over the no-N control was 30–40%. The *Sesbania* + *Azolla* treatment is of special interest because it does not need any inorganic N fertilizer. In intermediate lowlands, the rice grain yields obtained under *Sesbania* GM and USG (45 kg/ha N) treatments were comparable in 2004 but not in 2005 (Fig. 18.2), because *Sesbania* growth was poor due to the initial drought coupled with high soil salinity (8–11 dS/m). The FYM + PU (20 kg/ha N) treatment was not effective in 2004, possibly because of slower decomposition of FYM under the excess soil moisture conditions (Senapati and Behera, 2000). However, in 2005, it increased grain yield significantly (57%) over the no-N control and was on a par with the other treatments, possibly because of favourable soil moisture conditions during initial decomposition and the residual effects of FYM applied in 2004 (Prasad *et al.*, 2005; Bajpai *et al.*, 2006). The yield advantage due to USG and *Sesbania* over the no-N control was similar for both (52%) in 2004 and was 68 and 27%, respectively, in 2005. In the shallow lowland trial, yields were higher in 2004, probably because the crop suffered from prolonged waterlogging at the late vegetative stage in 2005. A similar effect was not observed in intermediate lowlands, where a taller variety with better tolerance of submergence/waterlogging was used.

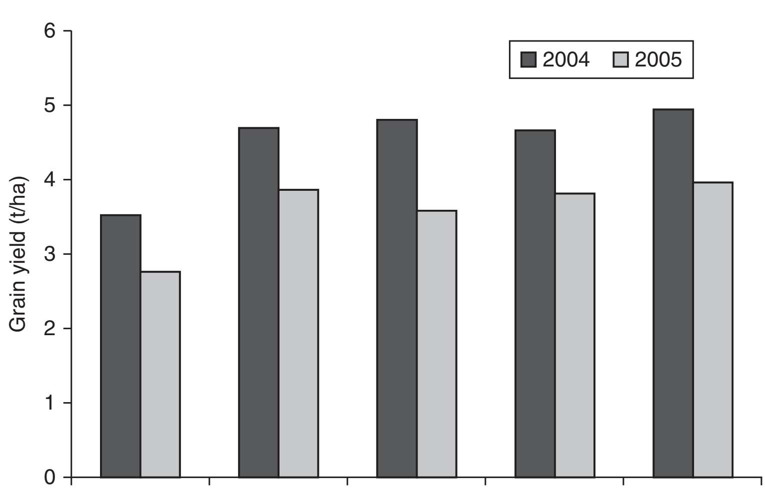

Fig. 18.1. Effect of different integrated nutrient management treatments on grain yield of rice (variety Pankaj) under shallow lowland conditions in Ersama Jagatsinghpur district (Orissa, India) during the wet season of 2004 and 2005. Treatment details are given in Table 18.1. $LSD_{0.05}$, 0.79 in 2004 and 0.62 in 2005.

In the DS, *Azolla* + PU (50 kg/ha N) resulted in significantly higher yields than the application of PU at 80 kg/ha N, with about 15% higher grain yields in both years (Fig. 18.3). This finding suggests that *Azolla* saved 30 kg/ha N of chemical fertilizer, besides improving rice yield. The yield advantage of the *Azolla* + PU treatment over the no-N treatment was 114% in 2005 and 91% in 2006. Possible reasons for the higher rice yields with *Azolla* include its suppressing effect on weed growth (Satapathy and Singh, 1985), reduced

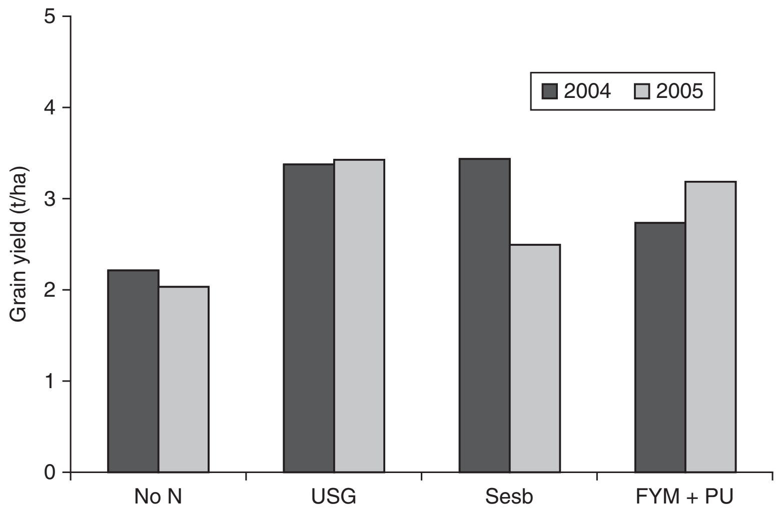

Fig. 18.2. Effect of different integrated nutrient management treatments on grain yield of rice (variety Lunishree) under intermediate lowland conditions in Ersama Jagatsinghpur district (Orissa, India) during the wet season of 2004 and 2005. Treatment details are given in Table 18.1. $LSD_{0.05}$, 0.53 in 2004 and 0.40 in 2005.

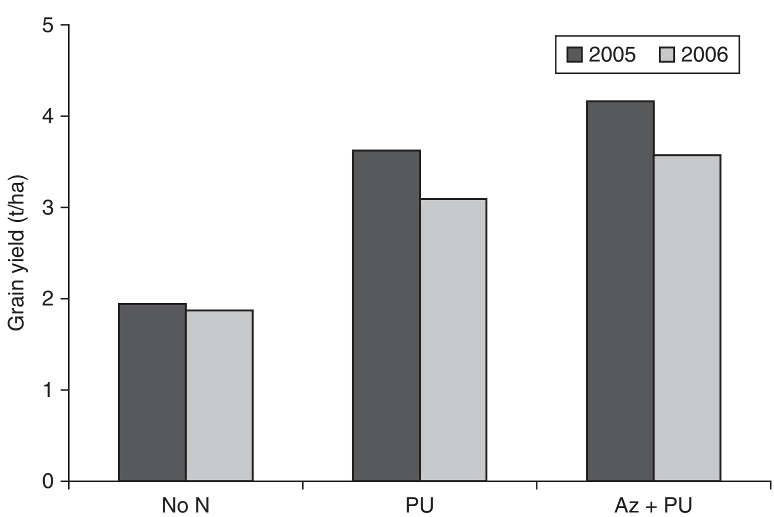

Fig. 18.3. Effect of different integrated nutrient management treatments on grain yield of rice (mean of varieties Annapurna and Canning 7) in Ersama Jagatsinghpur district (Orissa, India) during the dry season of 2005 and 2006. Treatment details are given in Table 18.1. $LSD_{0.05}$, 0.35 in 2005 and 0.45 in 2006.

volatilization losses of applied chemical N (Kroeck *et al.*, 1988) and the effect of the *Azolla* mat on water temperature. The grain yield in all treatments was higher in 2005 than in 2006, possibly due to lower ambient temperatures during the grain-filling period (GFP). The mean daily temperature during GFP was 27.6–29.6°C (average of 28.6°C) in 2005 and 29.1–30.3°C (average of 29.7°C) in 2006. Higher temperature during GFP decreases rice yield by lowering the percentage of filled grains as a consequence of a shortened grain-filling period and reduced assimilate supply (Yoshida, 1981; Kobata and Uemuki, 2004). However, grain weight is not affected significantly. In 2005, soil salinity was high towards maturity but remained below 6 dS/m during most of the crop growth duration and may not have affected grain yield adversely. Yield enhancement under different nutrient management practices in both years was associated with a higher panicle number per unit area and more grains per panicle (data not shown).

In demonstration trials during the 2006 WS, *Sesbania* GM and *Sesbania* GM + *Azolla* increased the grain yield of rice over the control at all shallow lowland sites by 12–40% (mean 23%) and 19–77% (mean 41%), respectively (Fig. 18.4). In intermediate lowlands (Fig. 18.5), the yield advantage due to *Sesbania* GM over the control was 8–50% (mean 29%). In the 2007 DS, *Azolla* increased rice yields by 16–35% (mean 24%) over the no-*Azolla* treatment (Fig. 18.6). The considerable variability of the observed yield advantages in different demonstration trials could probably be attributed to differences in soil texture, soil fertility and salinity status, depth of groundwater table (DS), hydrological situation (WS) and farmers' management. For example, *Sesbania* grew poorly in sandy loam soils with low fertility, whereas it grew well and produced more biomass in sandy clay loam soils with a better fertility and moisture status. The higher yields obtained under favourable conditions and better management are comparable with those reported for non-saline conditions (Singh and Singh, 2001; Panda *et al.*, 2004).

Sesbania green manure and *Azolla* biofertilizer technologies have been tested extensively in the past but, so far, there has been limited adoption by farmers. In the irrigated ecosystem, farmers are reluctant to grow *Sesbania* and, instead, prefer growing another commercially important crop. In rainfed environments, poor adoption of green manure is due mainly to the problems encountered during its establishment and subsequent incorporation when

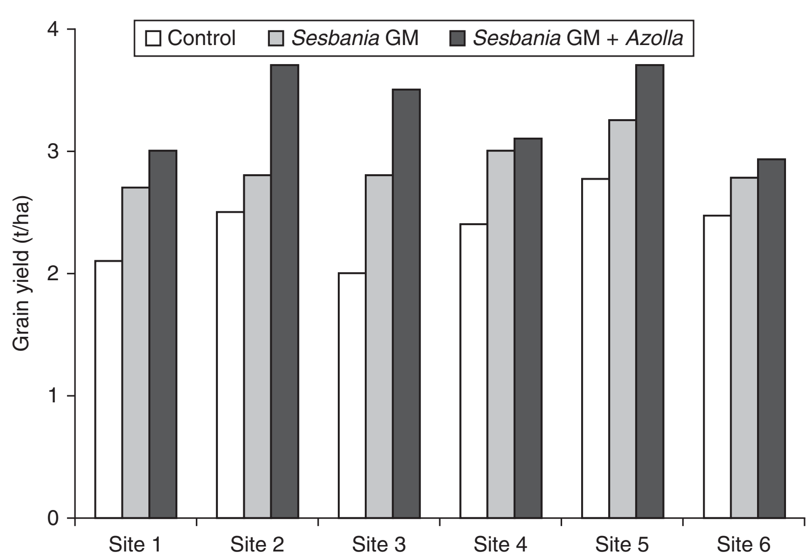

Fig. 18.4. Grain yield of rice (variety Pankaj) in demonstration trials at six sites in shallow lowlands in Ersama Jagatsinghpur district (Orissa, India) during the 2006 wet season. $LSD_{0.05}$, 0.27.

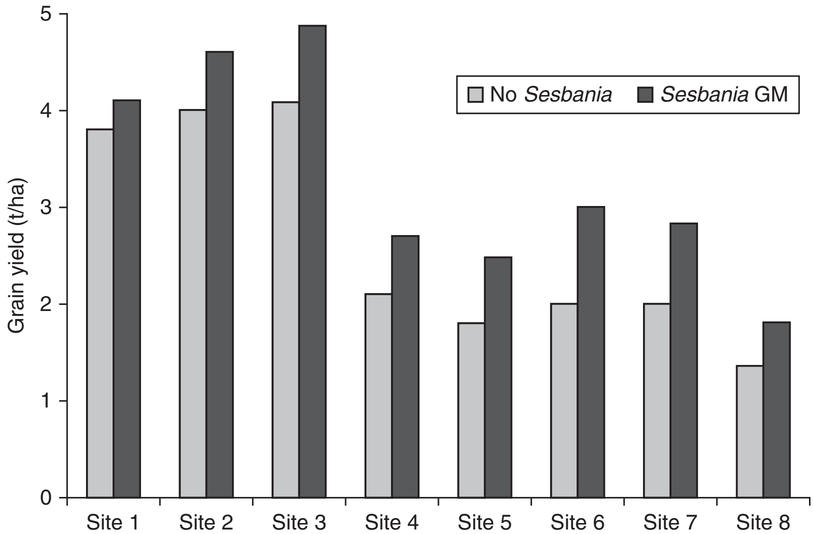

Fig. 18.5. Grain yield of rice (variety Lunishree) in demonstration trials at eight sites in intermediate lowlands in Ersama Jagatsinghpur district (Orissa, India) during the 2006 wet season. $LSD_{0.05}$, 0.28.

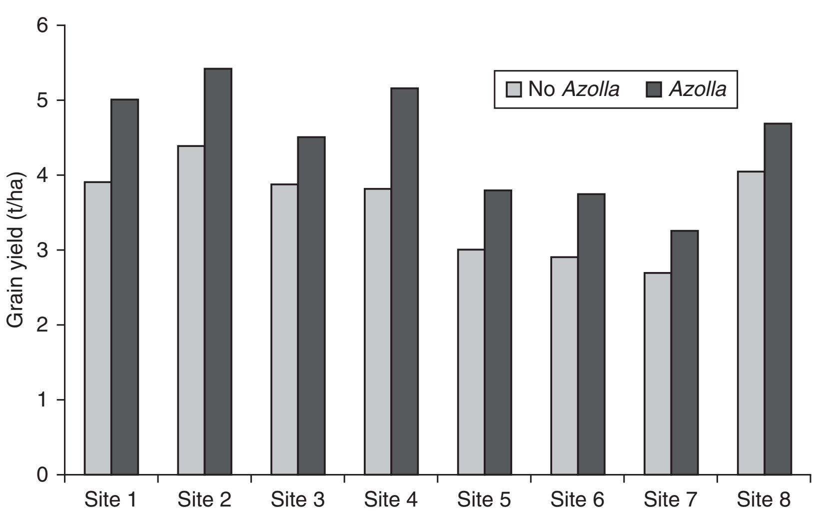

Fig. 18.6. Grain yield of rice (mean of varieties Annapurna and Canning 7) in eight demonstration trials conducted during the 2007 dry season in Ersama Jagatsinghpur district (Orissa, India). $LSD_{0.05}$, 0.23.

rainfall is low. However, in certain rainfed areas such as shallow lowlands, it is possible to meet the N requirement of the rice crop with chemical fertilizers, but in predominantly intermediate (semi-deep) lowlands (including those in coastal saline areas), the application of chemical N fertilizer is less feasible and less efficient under waterlogged conditions. In such situations, *Sesbania* green manure is a viable option, despite its limitations.

We analysed rainfall data for the past 30 years for the period during which *Sesbania* was normally established (23–27 meteorological weeks) to find out the probability of its success in this area (Table 18.2). There was severe drought (40% less rainfall than the average) for

Table 18.2. Analysis of the past 30 years' rainfall data during establishment of *Sesbania* green manure (23–27 meteorological weeks).

Meteorological week	Average rainfall (mm)	Occurrence of drought (rainfall 40% less than the average) during 23–27 meteorological weeks					
		1-week drought	No. of years	2-weeks' drought	No. of years	3-weeks' drought	No. of years
23	51.5	23	20	23–24	11	23–25	4
24	40.0	24	17	24–25	6	24–26	2
25	54.1	25	11	25–26	2	25–27	0
26	58.7	26	10	26–27	3		
27	59.1	27	11				
Total	263.4						

three consecutive weeks during 23–25 and 24–26 meteorological weeks in 4 and 2 years, respectively. Since 1 year was common in both cases, the frequency of severe drought for 3 weeks was 17%. In such drought years, the *Sesbania* crop could be affected severely. A severe drought for 2 consecutive weeks during 23–24, 24–25, 25–26 and 26–27 meteorological weeks occurred in 11, 6, 2 and 3 years, respectively. In the years with drought during 23–24 weeks, there could be a delay in *Sesbania* sowing but crop establishment would not be affected much because rainfall would be adequate in the following weeks. Also, in the years with drought during 24–25 and 26–27 weeks, the *Sesbania* crop would not suffer because enough rainfall would be received in both preceding and succeeding weeks. Drought for 1 week would not have any effect and the green manure crop could be well established with rain during the previous or following weeks. Rainfall data during the period of green manure incorporation (28–31 meteorological weeks) indicate that, at best, incorporation may be delayed due to deficit rainfall in 3 out of the 25 years (12%; excluding those 5 years when *Sesbania* establishment could be difficult due to low rainfall).

Based on this analysis, it is concluded that green manures could be used successfully in most years. It is worthwhile to mention that the coastal saline ecosystem in India is fragile, with highly erratic rainfall, and some risk is always involved, even with the rice crop. In view of the increasing cost of chemical fertilizers and declining trend of rice productivity, the use of organic manures is becoming more important for improving soil fertility and achieving good yield. Since *Sesbania* suffers occasionally from drought and salinity, we are evaluating two salt-tolerant varieties identified by the Central Soil Salinity Research Institute, Karnal, India.

Azolla biofertilizer is recommended for irrigated and rainfed favourable shallow lowland ecologies which do not have severe drought or flooding problems. Its poor adoption in these areas is mainly because of the lack of inoculum. The coastal areas have plenty of water bodies where *Azolla* can easily be multiplied with little additional cost and then applied in neighbouring rice fields. We have demonstrated the successful production of *Azolla* inoculum in village ponds.

A benchmark survey conducted in this area in 2004 revealed that the majority of farmers were not fully aware of the use of *Sesbania* green manure and *Azolla* biofertilizer. After the farmers' participatory on-farm demonstrations, there was a positive response and many progressive farmers started adopting these technologies. They are now producing *Sesbania* seed on their homestead land and on field bunds, and *Azolla* inoculum in small ponds and ditches. This was confirmed in a qualitative impact assessment made in November 2006 (Zolvinski, 2006). The local government is now providing *Sesbania* seed. Large-scale adoption will require serious, constant and concerted efforts by all the concerned agencies.

The results of this study clearly suggest that *Sesbania* GM is promising during the WS in both shallow and intermediate lowlands. In intermediate lowlands, where application of PU is not very effective due to the frequently waterlogged conditions, *Sesbania* appears to be the only option to improve the crop N supply. Although USG is equally effective, it is not readily available and there are practical problems for its application. Similarly, FYM is often available in small quantities only and is used mostly for vegetable cultivation in homestead gardens. *Azolla* is a promising biofertilizer for the DS. It can also be used successfully in shallow lowlands during the WS, provided that there is no drought or flood. Farmers can produce their own *Azolla* inoculums at low cost in ponds and ditches, which are common in coastal areas. Therefore, we conclude that, despite certain limitations, *Sesbania* green manure and *Azolla* biofertilizer offer considerable opportunities to improve soil quality and enhance and sustain rice crop productivity in coastal saline soils and need to be further promoted. These findings may also be useful for other areas with similar environmental conditions and constraints.

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References

Bajpai, R.K., Chitale, S., Upadhyay, S.K. and Urkurkar, J.S. (2006) Long-term studies on soil physico-chemical properties and productivity of rice–wheat system as influenced by integrated nutrient management in Inceptisol of Chhattisgarh. *Journal of the Indian Society of Soil Science* 54, 24–29.

Elfstrand, S., Hedlund, K. and Martensson, A. (2007) Soil enzyme activities, microbial community composition and function after 47 years of continuous green manuring. *Applied Soil Ecology* 35, 610–621.

Jackson, M.L. (1973) *Soil Chemical Analysis*. Prentice Hall of India, New Delhi.

Kobata, T. and Uemuki, N. (2004) High temperatures during the grain-filling period do not reduce the potential grain dry matter increase of rice. *Agronomy Journal* 96, 406–414.

Kroeck, T., Alkamper, J. and Watanabe, I. (1988) Effect of an *Azolla* cover on the conditions in floodwater. *Journal of Agronomy and Crop Science* 161, 185–189.

Ladha, J.K. (2005) Improving the recovery efficiency of fertilizer nitrogen in cereals. *Journal of the Indian Society of Soil Science* 53, 472–483.

Maji, B. and Bandyopadhyay, B.K. (1996) Characterization and classification of coastal soils of Balasore, Orissa. *Journal of the Indian Society of Soil Science* 44, 722–726.

Panda, D., Panda, N., Sarkar, A.K. and Rath, A.K. (2004) Integrated nutrient management in rice-based cropping system of different agro-ecologies. In: Panda, D., Sasmal, S., Nayak, S.K., Singh, D.P. and Saha, S. (eds) *Recent Advances in Rice-Based Farming Systems*. Proceedings of the National Symposium, 17–19 November 2004, Cuttack, India. Central Rice Research Institute, Cuttack, India, pp. 114–134.

Prasad, P.R.K., Radha, K.Y., Uma, M.N.V.A., Rao, V.S. and Bandyopadhyay, B.K. (2005) Effect of integrated nutrient management in rice (*Oryza sativa*)-blackgram (*Vigna mungo*) cropping system in salt-affected soils of coastal Andhra Pradesh. *Journal of the Indian Society of Coastal Agricultural Research* 23, 110–112.

Sahu, G.C. and Dash, S.S. (1993) Characterization and classification of salt-affected coastal soils of Astaranga, Orissa. *Journal of the Indian Society of Soil Science* 41, 138–144.

Satapathy, K.B. and Singh, P.K. (1985) Control of weeds by *Azolla pinnata* in rice fields. *Journal of Aquatic and Plant Management* 23, 40–42.

Sen, P., Mahata, K.R., Singh, D.P. and Singh, R.K. (2006) Identification of suitable salt-tolerant rice genotypes for coastal saline areas of Eastern India. *Abstract, Proceedings of the 2nd International Rice Congress*, 9–13 October 2006, New Delhi, India, pp. 222–223.

Senapati, H.K. and Behera, B. (2000) Effect of moisture on evolution of carbon dioxide and microbial activity in soil amended with organic substrates. *Journal of the Indian Society of Soil Science* 48, 384–386.

Singh, P.K. and Singh, D.P. (2001) Prospects of *Azolla* biofertilizer for rice in India. In: Yadav, A.K., Motsara, M.R. and Rai Chauduri, S. (eds) *Recent Advances in Biofertilizer Technology*. Society for Promotion and Utilization of Resources and Technology, New Delhi, pp. 257–271.

Tirol-Padre, A., Ladha, J.K., Regmi, A.P., Bhandari, A.L. and Inubushi, K. (2007) Organic amendments affect soil parameters in two long-term rice-wheat experiments. *Soil Science Society of America Journal* 71, 442–452.

Yadav, J.S.P., Bandyopadhyay, A.K. and Bandyopadhyay, B.K. (1983) Extent of coastal saline soils in India. *Journal of the Indian Society of Coastal Agricultural Research* 1, 1–6.

Yoshida, S. (1981) *Fundamentals of Rice Crop Science*. International Rice Research Institute, Los Baños, Philippines, 59 pp.

Zolvinski, S. (2006) Qualitative impact assessment for coastal saline-affected villages in Orissa, India. Unpublished report. Social Sciences Division, International Rice Research Institute, Manila, December 2006.

19 Crop Diversification for Improving Water Productivity and Rural Livelihoods in Coastal Saline Soils of the Mahanadi Delta, India

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Abstract
Coastal saline areas are normally monocropped with rice grown during the wet season. On-farm trials were conducted in Ersama block of Jagatsinghpur district, Orissa, India, during 2005–2006 to evaluate the performance of selected non-rice crops in the coastal saline ecosystem during the dry season. In 2005, sunflower, *Basella*, watermelon, chilli, pumpkin, groundnut, tomato, bitter gourd and okra were evaluated under medium salinity (topsoil ECe 4–7 dS/m) and high salinity (ECe of 10–15 dS/m) in sandy loam soils. In 2006, watermelon, chilli, sunflower, pumpkin, *Basella,* okra and groundnut were grown under medium salinity (excluding *Basella*; ECe 2–6 dS/m, except during the latter part of the season) and high salinity (excluding okra and groundnut; ECe 4–8 dS/m, increasing to 16–26 dS/m towards the end of the season) at two locations with sandy loam and clay loam soils. In 2005, all crops performed well under medium salinity, whereas only sunflower and *Basella* produced reasonable yields under high salinity. The other crops failed because of high soil and groundwater/irrigation water salinity during the early crop growth stages due to prolonged terminal drought in the preceding wet season. In 2006, all crops performed well, but with variable yield, except for sunflower and chilli. The yields of watermelon and pumpkin were especially dependent on irrigation water quality. Across seasons and salinity levels, watermelon, chilli, pumpkin and sunflower were the best-performing dry-season crops based on rice yield equivalent, net return, benefit–cost ratio and water productivity. Okra was the most remunerative crop under medium salinity, although its water productivity was lower than that of watermelon and pumpkin in some cases. The crops tested in this study offer considerable opportunities for the diversification of rice-based systems in saline coastal areas.

Introduction

India is bounded by the sea on three sides and it has 8129 km of coastline. Of the total of 10.78 million ha of coastal area, about 3.09 million ha along the east and west coast are saline (Yadav, 2001). The Mahanadi Delta is located on the east coast, which accounts for more than 60% of the total salt-affected coastal land. Most of these salt-affected coastal lands are monocropped with rice during the wet season. The farmers are generally resource-poor, with marginal to small landholdings (< 2 ha). Agricultural productivity is low and unstable due to the frequent occurrence of abiotic stresses (salinity, drought, submergence) and natural hazards (storms, cyclones). In the dry season, lands remain largely fallow due to the lack of good-quality irrigation water and high soil salinity. However, this salinity problem is complex and dynamic, with large spatial and temporal variability. In

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general, soil salinity is low during the wet season (June–November) and increases gradually during the post-monsoon period, reaching its maximum in May (Bandyopadhyay *et al.*, 2003).

In spite of its high water requirement, rice is grown by some farmers on a small area during the dry season using very limited freshwater resources, often because the low yields in the wet season are not sufficient to provide their consumption needs. However, recent research showed that wet-season rice yields could be enhanced and stabilized through the introduction of high-yielding, salt-tolerant varieties and improved management practices (Mahata *et al.*, Chapter 18, this volume). These technologies could ease the pressure to grow dry-season rice and provide opportunities for the introduction of less water-consuming non-rice crops. The shift from rice to non-rice crops could also help enhance land and water productivity, crop diversification and farmers' income, and reduce the risk of yield losses due to a shortage of irrigation water during the grain filling of rice. This may also create employment opportunities and improve the livelihoods of poor rural communities. However, the choice of suitable non-rice crops depends strongly on their salinity tolerance, site- and season-specific salinity and agroclimatic conditions. This study evaluates the performance of selected non-rice crops in farmers' fields at different locations in the Mahanadi Delta to identify suitable cropping options for the dry season in saline coastal environments.

Materials and Methods

On-farm trials were conducted during the 2005/6 cropping seasons in Ersama block of Jagatsinghpur district, Orissa, India, to evaluate the performance of selected non-rice crops in the dry season after the harvest of wet-season rice. The crops were selected based on their suitability to the agroclimatic conditions, farmers' choices and market value. In 2005, sunflower (*Helianthus annuus* L., cv. KBSH 1), *Basella* (*Basella alba* L., local), watermelon (*Citrullus vulgaris* Schrad., Sugarbaby), chilli (*Capsicum annuum* L., Utkal Abha), pumpkin (*Cucurbita moschata* Duch. ex Poir., local), groundnut (*Arachis hypogaea* L., AK 12-24), tomato (*Lycopersicum esculentum* Mill., BT 2), bitter gourd (*Momordica charantia* L., local) and okra (*Hibiscus esculentus* L., Mahyco Hybrid 10) were evaluated in separate experiments under high and medium salinity conditions in sandy loam soils. The experimental sites were within 1 km of the river. In 2006, five crops (watermelon, chilli, sunflower, pumpkin and *Basella*) for high-saline areas and six crops (watermelon, chilli, okra, sunflower, pumpkin and groundnut) for medium-saline areas were grown at two locations in sandy loam (site I) and clay loam (site II) soils. For both medium and high salinity in 2006, site I was the same as in 2005. Site II was also within 1 km of the river, but was located before a sluice gate which was constructed to prevent the entry of salt water during high tides. For all the trials, medium- and high-salinity fields were selected based on farmers' experience and rating. The pH, organic C, total N and available P (Olsen P) were 5.2–6.9, 0.64–0.87%, 0.06–0.08% and 5–10 ppm, respectively, in the sandy loam soil and 6.4–6.9, 0.82–1.05%, 0.08–0.11% and 6–11 ppm, respectively, in the clay loam soil (0.0–0.15 m depth). A randomized complete block design with three replications for the 2005 trials and four replications for the 2006 trials was used. The plot size in each trial was 50 m^2. Watermelon, pumpkin and bitter gourd were sown in pits (diameter of 0.4 m and depth of 0.3 m) refilled with dugout soil, whereas sunflower, groundnut, okra and *Basella* were sown in rows on flat beds. For chilli and tomato, seedlings were raised in separate beds and 25-day-old seedlings were transplanted. The date of sowing/planting and harvesting for different crops is presented in Table 19.1. Furrows were made between the rows after seedling establishment to facilitate irrigation. The recommended agronomic practices and need-based plant protection measures for each crop were followed. Irrigation was applied in pits with a pitcher for watermelon, pumpkin and bitter gourd, whereas the other crops were established initially through the application of water along the rows using a pitcher and then with furrow irrigation using a 1.5-HP pump with regulated discharge. The crops were

Table 19.1. Crops evaluated under high- and medium-salinity fields; sowing, transplanting and harvesting dates in the dry seasons of 2005 and 2006.

		2005			2006		
Salinity	Site	Crop	Date of sowing/ planting[a]	Date of harvest	Crop	Date of sowing/ planting[a]	Date of harvest
High	I	Sunflower	27 Dec 04 (S)	6 Apr 05	Sunflower	3 Jan 06 (S)	13 Apr 06
		Chilli	14 Jan 05 (P)	–	Chilli	3 Jan 06 (S)	25 Mar–20 Apr 06
		Watermelon	27 Dec 04 (S)	–	Watermelon	9 Jan 06 (S)	26 Mar–8 Apr 06
		Groundnut	27 Dec 04 (S)	–	*Basella*	3 Jan 06 (S)	12 Mar–4 May 06
		Okra	27 Dec 04 (S)	–	Pumpkin	9 Jan 06 (S)	30 Mar–15 Apr 06
		Tomato	14 Jan 05 (P)	–			
		Bitter gourd	27 Dec 04 (S)	–			
		Basella	27 Dec 04 (S)	3 Mar–29 Apr 05			
		Pumpkin	27 Dec 04 (S)	–			
	II	–	–	–	Sunflower	12 Jan 06 (S)	20 Apr 06
					Chilli	14 Jan 06 (P)	7–29 Apr 06
					Watermelon	12 Jan 06 (S)	26 Mar–7 Apr 06
					Basella	12 Jan 06 (S)	17 Mar–10 May 06
					Pumpkin	12 Jan 06 (P)	4–19 Apr 06
Medium	I	Sunflower	5 Jan 05 (S)	11 Apr 05	Sunflower	5 Jan 06 (S)	12 Apr 06
		Chilli	14 Jan 05 (P)	4–30 Apr 05	Chilli	5 Jan 06 (P)	27 Mar–21 Apr 06
		Watermelon	5 Jan 05 (S)	21–31 Mar 05	Watermelon	10 Jan 06 (S)	25 Mar–4 Apr 06
		Groundnut	5 Jan 05 (S)	15 Apr 05	Groundnut	5 Jan 06 (S)	13 Apr 06
		Okra	5 Jan 05 (S)	24 Feb–25 Apr 05	Okra	5 Jan 06 (S)	25 Feb–28 Apr 06
		Tomato	14 Jan 05 (P)	30 Mar–18 Apr 05	Pumpkin	10 Jan 06 (S)	2–18 Apr 06
		Bitter gourd	5 Jan 05 (S)	14 Mar–18 Apr 05			
		Basella	5 Jan 05 (S)	11 Mar–11 May 05			
		Pumpkin	5 Jan 05 (S)	1–16 April 05			
	II	–	–	–	Sunflower	6 Jan 06 (S)	16 Apr 06
					Chilli	12 Jan 06 (P)	7 Apr–1 May 06
					Watermelon	12 Jan 06 (S)	28 Mar–9 Apr 06
					Groundnut	6 Jan 06 (S)	18 Apr 06
					Okra	6 Jan 06 (S)	25 Feb–26 Apr 06
					Pumpkin	12 Jan 06 (S)	–

[a]Crop establishment was via transplanting (P) of 25-day-old seedlings for chilli and tomato and direct seeding (S) for the remaining crops.

irrigated as and when required to avoid water-deficit stress. The source of irrigation was pond-water for both trials in 2005 and the trials at site I in 2006. In 2006 at site II, water was used from a nearby river, provided through a sluice gate. Irrigation water applied for each crop was quantified by using a pitcher of known volume and by measuring the volume of water discharged by the pump per minute. The time of irrigation for each crop was monitored using a stopwatch. Piezometers were installed (1.3 m depth) at each site and depth to the groundwater table was recorded periodically. Soil samples (three from each plot) were collected periodically throughout the season for each trial from 0.0–0.15 m depth and composite samples were used for salinity measurement. Electrical conductivity (EC) of the soil saturation extract, groundwater and irrigation water was also measured periodically with a hand-held EC meter (Orion 118 conductivity-2). In 2006, the fields under high and medium salinity at site II were adjacent but with a different elevation, and a common piezometer was installed between the two fields.

Since the produce from various crops and its market value differed widely, yields were converted to rice yield equivalent for meaningful comparisons. This was done by dividing the product of crop yield (t/ha) and its market value (Rs/t) by the price of paddy (Rs/t). The cost of cultivation, which included all field operations starting from land preparation to harvesting, threshing and cleaning wherever necessary (including the cost of family labour), and inputs such as seed, fertilizer and pesticide (excluding the cost of the land), net return and benefit–cost (B:C) ratio for each crop were also calculated. Irrigation water productivity was computed from data on the net return and the quantity of irrigation water used and expressed as net return in US$/m^3 water applied.

Results and Discussion

Soil, groundwater and irrigation water salinity

In 2005, the EC of soil (saturation extract, Fig. 19.1a) and groundwater (Fig. 19.1b) during the cropping season ranged between 9.3–14.3 and 10.0–14.1 dS/m in high-salinity fields and between 3.9–7.0 and 2.9–4.7 dS/m in medium-salinity fields. Depth to the groundwater table declined from 0.75 m to more than 1.20 m in high-salinity fields and ranged from 0.62 to 0.90 m in medium-salinity fields (Fig. 19.1c). The EC of the irrigation water ranged from 4.1 to 7.0 dS/m in high-salinity fields and from 0.8 to 1.3 dS/m in medium-salinity fields. The EC of the soil in high-salinity fields was initially high (10 dS/m), increased further after 6 February, because of the increasing salinity of the irrigation water, and remained stable at around 15 dS/m towards the end of the season. An early cessation of rain in the preceding wet season (last significant rain on 7 October) contributed to the high soil salinity at the start of the experiment. The initial EC of the soil in medium-salinity fields was 6 dS/m and it fluctuated between about 4 and 7 dS/m, with a small decline to about 3 dS/m at the end of the season, most likely because of the use of irrigation water with lower EC. The EC of the groundwater in high-salinity fields was initially high but subsequently declined with the application of irrigation water with much lower EC than the groundwater. The increasing EC of the irrigation water and the increasing atmospheric evaporative demand might then have caused a gradual increase in groundwater EC from the end of February onward. In medium-salinity fields, the initial groundwater EC was much lower than in the high-salinity fields, with little variation during the season. At both sites, the groundwater table fell rapidly from mid-season onward, was always lower at the high salinity site and fell below the piezometer range after 10 March.

In 2006, the EC of the soil (Fig. 19.2a) and groundwater (Fig. 19.2b) in high-salinity fields was initially similar to that in medium-salinity fields (6–7 dS/m) and remained below 8 dS/m until the latter part of the season, when it peaked at 16 and 25 dS/m at sites I and II, respectively. Depth to the groundwater table (Fig. 19.2c) at sites I and II varied between 0.72–1.10 and 0.60–1.00 m, and the respective irrigation water EC ranged between 1.9–5.9 and 0.6–1.8 dS/m. Soil EC at both sites remained below 8 dS/m, with negligible fluctuations during the early part of

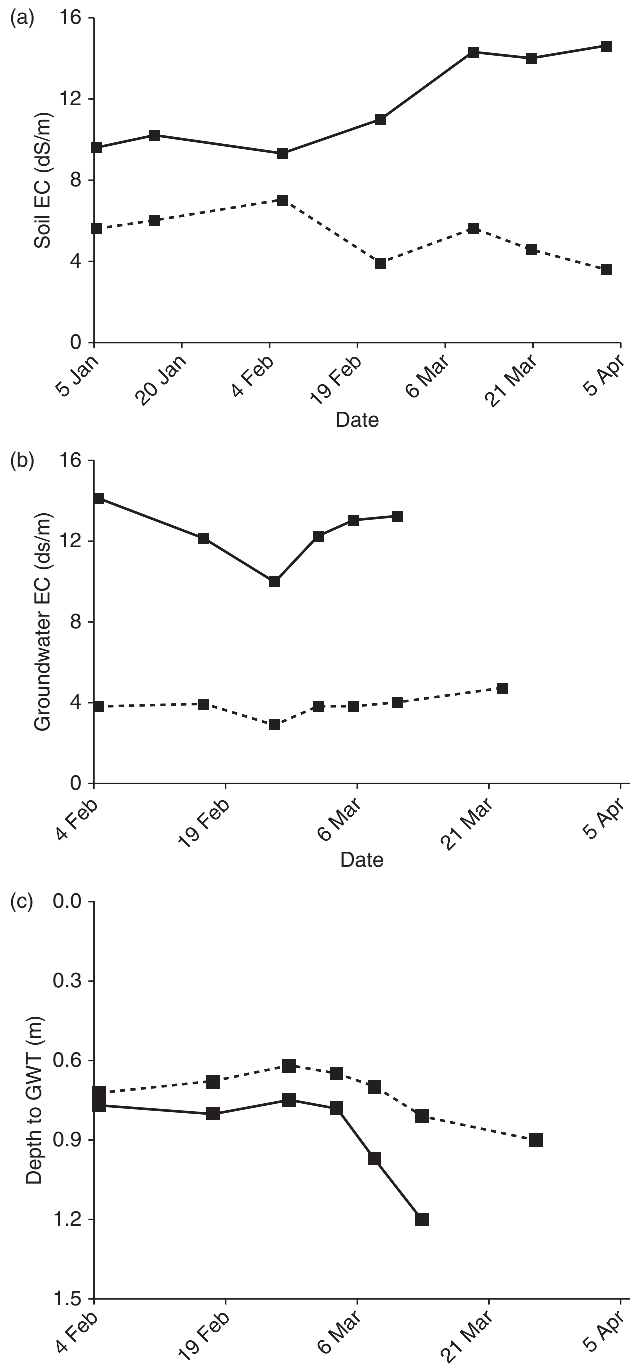

Fig. 19.1. Electrical conductivity (EC) of (a) soil saturation extract, (b) groundwater and (c) depth to groundwater table (GWT) in high-salinity (solid line) and medium-salinity (dotted line) fields during the dry season of 2005.

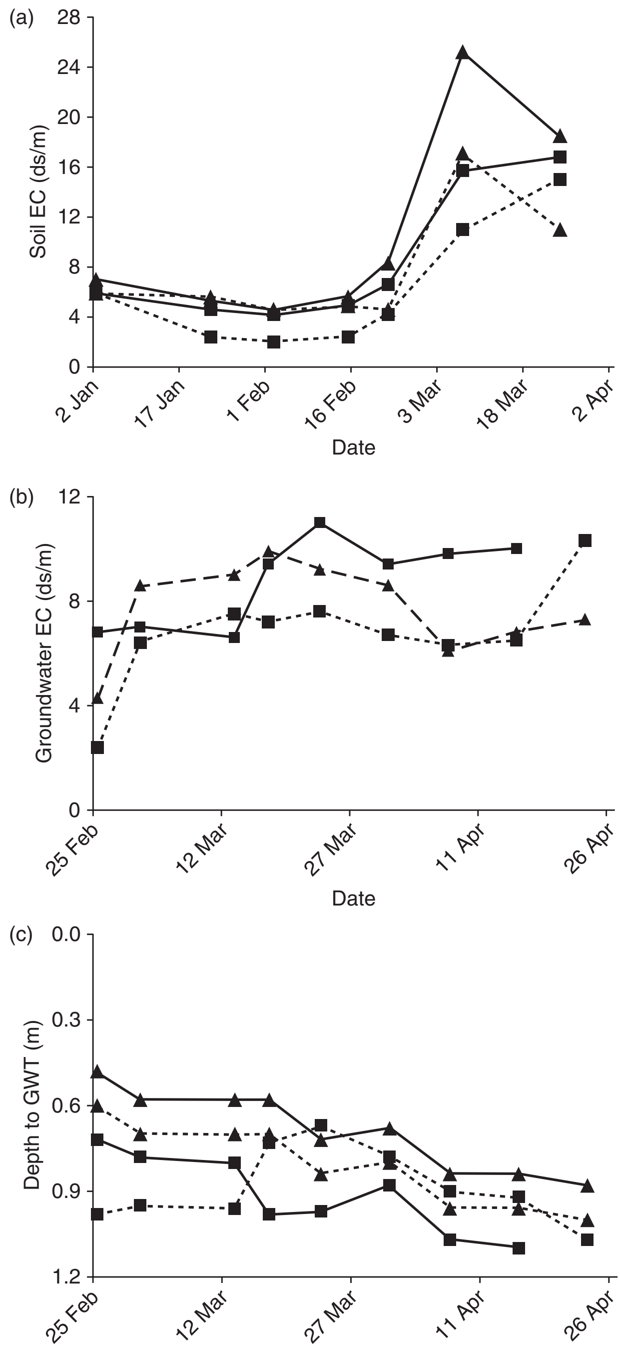

Fig. 19.2. Electrical conductivity (EC) of (a) soil saturation extract, (b) groundwater and (c) depth to groundwater table (GWT) in high-salinity (solid line) and medium-salinity (dotted line) fields at site I (■) in all the figures, site II (▲) in Fig. 19.2a and c and site II of both high and medium salinity (broken solid line) with a common piezometer in Fig. 19.2b during the dry season of 2006.

the season, probably due to the dilution effects of excess rainfall at the end of the preceding wet season (478 mm rain during 18 October to 1 November; Fig. 19.3a) and the use of low-EC irrigation water. However, soil EC increased rapidly at both sites towards the end of February because of the combined effect of increasing irrigation and groundwater salinity and the increasing atmospheric evaporative demand. At site II, rainfall in the week before soil sampling caused a decline in the soil EC at the end of the season, which was not observed at site I. The groundwater table was lower throughout the season at site I and decreased progressively with time at both sites (Fig. 19.2c).

The ranges of the EC of soil and groundwater in medium-salinity fields were between

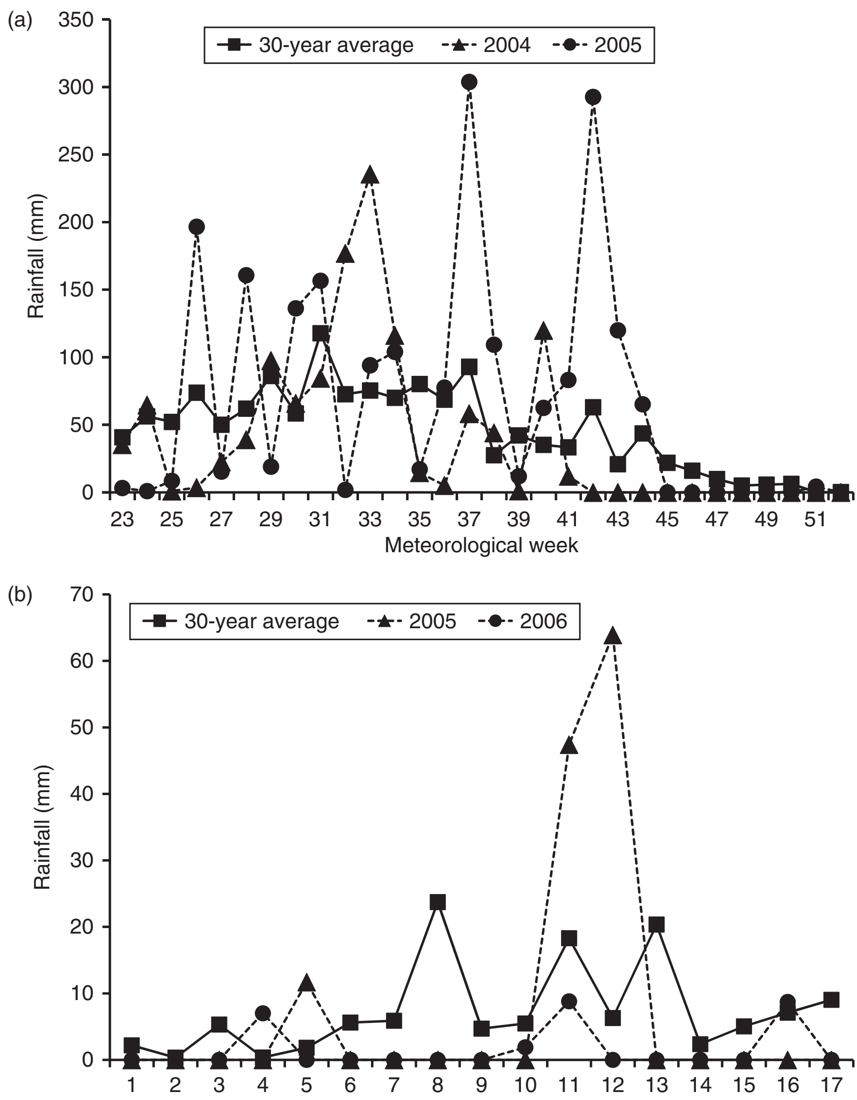

Fig. 19.3. Rainfall pattern in (a) preceding wet season and (b) during the cropping season compared with 30-year average.

2.0–15.0 and 2.4–10.3 dS/m at site I and between 4.6–17.1 and 4.3–9.9 dS/m at site II (Fig. 19.2a and b). Groundwater table depth at site I varied between 0.67 and 1.07 and between 0.60 and 1.00 m at site II (Fig. 19.2c). Irrigation water EC ranged from 0.8 to 5.8 dS/m at site I and from 0.6 to 1.8 dS/m at site II. Soil EC in medium-salinity fields was similar to that in the high-salinity fields at both sites, but the differences in soil salinity between sites I and II were more pronounced throughout the whole season. During the early part of the season, higher soil and groundwater EC at site II were related to a shallower groundwater table.

These results indicate that soil salinity in coastal areas is determined by complex interactions of groundwater and irrigation water salinity, irrigation water quantity, groundwater depth, soil texture, rainfall pattern and atmospheric evaporative demand. The resulting soil salinity is highly variable in space and time, which makes the categorization of soils with respect to salinity very difficult. Therefore, the selection of medium-salinity and high-salinity fields in this study was based on farmers' experience, and this may not always conform to the conventional salinity classification. For example, the high-salinity field at site I in 2006 was the same as the high-salinity field in 2005, but the observed soil salinity in the 2 years differed considerably, due mostly to different rainfall patterns in the preceding wet season, which caused differences in the initial soil salinity, and groundwater and irrigation water salinity. However, although salinity differences between high-salinity and medium-salinity fields were much clearer in 2005, farmers' ratings of soil salinity were apparently proper in both experimental years.

Crop yield and economic analysis

In 2005, most crops grew well and produced good yields in the medium-salinity fields (Table 19.2). However, in high-salinity fields, only sunflower and *Basella* could be harvested (yields of 1.25 and 5.28 t/ha, respectively; data not shown), whereas all other crops succumbed at later growth stages to high soil and groundwater salinity, as well as the use of increasingly saline irrigation water. This indicates that sunflower and *Basella* are more tolerant of salinity stress than the other crops. This agrees with an earlier classification that sunflower is moderately salt tolerant, whereas watermelon, okra and pumpkin are grouped as moderately sensitive (Maas, 1993). Katerji *et al*. (2000) have even included sunflower in the salt-tolerant group, along with sugarbeet and durum wheat, using a water-stress-day index for classifying salt tolerance. In the 2005 cropping season, the

Table 19.2. Yield, rice yield equivalent and economic characteristics of non-rice crops evaluated in medium-salinity fields during the dry season of 2005.

Crop	Yield (t/ha)	Rice yield equivalent (t/ha)[a]	Net return (Rs/ha)	Benefit–cost ratio
Sunflower	1.79	7.16	17,706 (402)[b]	2.62
Chilli	3.78	14.16	47,172 (1,072)	5.96
Watermelon	35.92	17.96	63,423 (1,441)	8.53
Groundnut	1.18	4.80	8,930 (203)	2.02
Okra	6.00	9.00	28,092 (638)	4.55
Tomato	1.58	1.98	(–)1,508 (34)	0.84
Bitter gourd	1.71	3.41	4,932 (112)	1.56
Basella	10.18	3.06	5,308 (121)	1.77
Pumpkin	8.18	8.18	25,181 (572)	4.34
$LSD_{0.05}$		2.29		

[a]Rice yield equivalent was calculated based on yield and current produce prices of the different crops (price of paddy was Indian Rs 4/kg); [b]numbers in parentheses are the net return in US$ based on an exchange rate of US$1 = 44 Indian rupees.

yield of sunflower in high-salinity fields declined by 30% compared with that of medium-salinity fields. According to Francois (1996), the threshold of soil EC for sunflower hybrids is 4.8 dS/m, and each unit increase in soil EC above this causes a yield reduction of 5%. This is close to the observation in this experiment in which the average seasonal soil EC is 11.8 dS/m, corresponding to an estimated yield loss, according to Francois (1996), of 35%. However, a threshold value of 7.1 dS/m was reported from India under farmers' field conditions (Hebbara *et al.*, 1992). Even at this low yield, sunflower will be profitable, but not *Basella*. Under medium salinity, watermelon produced the highest rice yield equivalent, net return and B:C ratio, followed by chilli, okra, pumpkin and sunflower (Table 19.2). The rice yield equivalent of okra, pumpkin and sunflower was comparable, but the B:C ratio was lower for sunflower because of the higher cultivation costs.

In 2006, all crops established well and even produced good yields in the high-salinity fields at site I, in contrast to 2005. This was because of the lower soil, groundwater and irrigation water salinity, particularly during the early part of the season (Fig. 19.2). At this site, the rice yield equivalent and net return were the highest for chilli, followed by sunflower and watermelon (Table 19.3). At site II, all crops, with the exception of sunflower and chilli, achieved much higher rice yield equivalents than at site I, and net returns were highest for watermelon, followed by pumpkin and chilli. The poorer performance of watermelon, *Basella* and pumpkin at site I was probably caused by the use of saline irrigation water. The lower yield of sunflower at site II might have been caused by excess soil moisture because of the lower plots, higher water table and the finer soil texture (clay loam). The adverse effects of excess soil moisture on growth and yield of sunflower have been reported before (Oad *et al.*, 2001; Padmavathi, 2004) and the negative effects of finer textured soils and poor aeration on seed yields have been described by Katerji *et al.* (2000) for clay versus loam soils. Similar yields of chilli at both sites are consistent with its better tolerance of excess soil moisture (Bandyopadhyay and Sen, 1992). The B:C ratio of all crops in the high-salinity fields ranged between 2.0 and 4.1 at site I and between 2.0 and 6.9 at site II, with the highest value for chilli at site I and watermelon at site II (Table 19.3).

In the medium-salinity fields, okra produced the highest rice yield equivalent and net return at both sites, followed by pumpkin, sunflower and watermelon at site I and

Table 19.3. Yield, rice yield equivalent and economic characteristics of non-rice crops evaluated in high-salinity fields at two sites (site I and site II) during the dry season of 2006.

	Yield (t/ha)		Rice yield equivalent (t/ha)[a]		Net return (Rs/ha)		Benefit–cost ratio	
Crop	Site I	Site II	Site I	Site II	Site I	Site II	Site I	Site II
Sunflower	1.81	1.38	6.43	4.89	17,936 (408)[b]	11,056 (251)	2.63	2.00
Chilli	2.59	2.50	8.63	8.34	29,272 (665)	27,922 (634)	4.06	3.92
Watermelon	7.22	23.33	4.01	12.96	9,590 (218)	49,865 (1,133)	2.13	6.89
Basella	13.11	21.73	3.50	5.80	8,804 (200)	19,148 (435)	2.27	3.76
Pumpkin	3.72	12.76	3.31	11.35	7,320 (166)	43,480 (988)	1.97	6.75
$LSD_{0.05}$			1.96	2.21				

[a]Rice yield equivalent was calculated based on yield and current produce prices of the different crops (price of paddy was Indian Rs 4.50/kg); [b]numbers in parentheses are the net return in US$ based on an exchange rate of US$1 = 44 Indian rupees.

Table 19.4. Yield, rice yield equivalent and economic characteristics of non-rice crops evaluated in medium-salinity fields at two sites (site I and site II) during the dry season of 2006.

	Yield (t/ha)		Rice yield equivalent (t/ha)[a]		Net return (Rs/ha)		Benefit–cost ratio	
Crop	Site I	Site II	Site I	Site II	Site I	Site II	Site I	Site II
Sunflower	1.73	1.83	6.15	6.51	16,656 (378)[b]	18,256 (415)	2.51	2.66
Chilli	1.50	2.24	5.00	7.45	12,922 (294)	24,022 (546)	2.35	3.51
Watermelon	9.83	21.42	5.46	11.89	16,115 (366)	45,090 (1,025)	2.90	6.33
Groundnut	1.63	1.07	5.44	3.56	15,570 (354)	7170 (163)	2.75	1.81
Okra	10.80	8.09	16.79	12.59	67,642 (1,537)	48,672 (1,106)	9.50	7.12
Pumpkin	8.07	–	7.18	–	24,720 (562)	–	4.27	–
$LSD_{0.05}$			1.81	2.79				

[a]Rice yield equivalent was calculated based on yield and current produce prices of the different crops (price of paddy was Rs 4.50/kg); [b]numbers in parentheses are the net return in US$ based on an exchange rate of US$1 = 44 Indian rupees.

watermelon, chilli and sunflower at site II (Table 19.4). The pumpkin crop at site II grew well, but was severely damaged by fruit fly (*Bractocera cucurbitae*), which could not be controlled effectively. The rice yield equivalent for watermelon was comparable with that of okra at site II but not at site I, where the irrigation water became increasingly saline at later crop growth stages. The point placement of salt water in pits for watermelon, versus furrow irrigation for okra, may also have contributed to a greater salinity in the root zone of watermelon. The B:C ratio across crops under medium salinity was 2.5–9.5 at site I and 2.7–7.1 at site II, with the highest B:C value for okra at both sites (Table 19.4).

The net return and B:C ratios achieved by several crops in our experiments were comparable with or even higher than those reported from non-saline sites (Muralidharudu *et al.*, 2003; Selvi *et al.*, 2004; Yadav and Luthra, 2004). Similarly, the observed sunflower yields under various salinity levels were comparable with those reported from non-saline conditions (Reddy *et al.*, 2002; Upadhyay *et al.*, 2004; Saha *et al.*, 2006). In contrast, watermelon performance clearly depended on good-quality irrigation water. Encouraged by the crop performance and farmers' response, seeds of sunflower and watermelon were provided to more than 100 farmers from 11 villages in 2007 and the yields recorded ranged between 0.5 and 1.9 and 8.7 and 24.7 t/ha, respectively (data not shown).

The promising non-rice crops now have good market potential because of limited supply and greater demand. However, assuming that 10% or more of the cultivated lands are devoted to these crops, sunflower may resist the supply-dependent price fluctuation because it provides much-needed cooking oil for daily consumption and can be stored for longer periods. The price of chilli also may not fall much as it can be stored and transported to distant markets having greater demand. Being perishable commodities, the prices of watermelon and okra might fall with the increase in total production. However, if prices fall by up to 25%, these crops will remain profitable, with average net returns of Rs25,450 (US$636)/ha and Rs30,416 (US$770)/ha, respectively. In the event of prices falling by 50%, farmers will still gain reasonable profits from these two crops. They can also make some adjustments in planting time to regulate supply and avoid any drastic fall in prices during the peak season. Furthermore, cultivation of non-rice crops over the years will reduce soil salinity gradually, which in turn should lead to higher crop productivity and profitability.

Water productivity

Water scarcity and quality are the main constraints for dry-season cropping in the coastal saline belt of the Mahanadi Delta; hence, water productivity is an important parameter in determining the suitability of a specific crop. We calculated the irrigation water productivity of each crop, expressed as net return in US$/m^3 water applied. Data on total rainfall during the cropping season (January–April) and irrigation applied for each crop are presented in Table 19.5. In 2005, water productivity in medium-saline fields was highest for watermelon, followed by chilli, pumpkin and bitter gourd (Fig. 19.4). The very high water productivity of watermelon was due to its high yield, which was comparable with yields reported from non-saline conditions (Yadav and Luthra, 2004). Obviously, rather low water productivity values were achieved in high-salinity fields during 2005, when only sunflower and *Basella* produced any yield (data not shown). In 2006, water productivity in high-salinity fields was highest for chilli, followed by watermelon, sunflower and pumpkin at site I; whereas at site II, it was highest for watermelon, followed by pumpkin, chilli and *Basella* (Fig. 19.5). However, the differences between chilli and watermelon or sunflower and pumpkin at site I and chilli and *Basella* at site II were not significant. Water productivity in 2006 in medium-salinity fields was highest for pumpkin, followed by okra and watermelon at site I, and for watermelon, followed by okra, chilli and sunflower at site II (Fig. 19.6). The differences between watermelon and okra at site I and okra and chilli or chilli and sunflower at site II were not significant. The higher water productivity for watermelon and pumpkin could be attributed to irrigation point placement. Excluding the high-salinity fields in 2005, water productivity was considerably higher in 2005 than in 2006, most likely because of higher rainfall during the cropping season in 2005 (136 mm in 2005 versus 26 mm in 2006). The water productivity calculated on a yield basis for several crops in this study was higher than what was reported before (Oad *et al.*, 2001; Cueto-Wong *et al.*, 2003; Tingwu *et al.*, 2003), possibly because of the water contributed from the shallow groundwater table (Kahlown *et al.*, 2005) and rainfall.

The performance of non-rice crops is influenced by rainfall pattern in the preceding

Table 19.5. Total rainfall and irrigation applied for different crops during the cropping season (January–April) in 2005 and 2006.

				Number of irrigations		Total irrigation water applied (m^3)	
Salinity	Year	Rainfall (cm)	Crop	Site I	Site II	Site I	Site II
Medium	2005	13.6	Sunflower	3	–	640	–
			Chilli	4	–	608	–
			Watermelon	4	–	216	–
			Groundnut	3	–	348	–
			Okra	5	–	948	–
			Tomato	3	–	412	–
			Bitter gourd	3	–	156	–
			Basella	5	–	508	–
			Pumpkin	5	–	340	–
	2006	2.6	Sunflower	4	3	832	533
			Chilli	5	4	730	536
			Watermelon	6	4	304	200
			Groundnut	4	3	576	370
			Okra	7	6	1016	881
			Pumpkin	7	5	352	222
High	2006	2.6	Sunflower	4	3	832	533
			Chilli	5	4	730	536
			Watermelon	6	4	304	200
			Basella	7	6	744	533
			Pumpkin	7	5	352	222

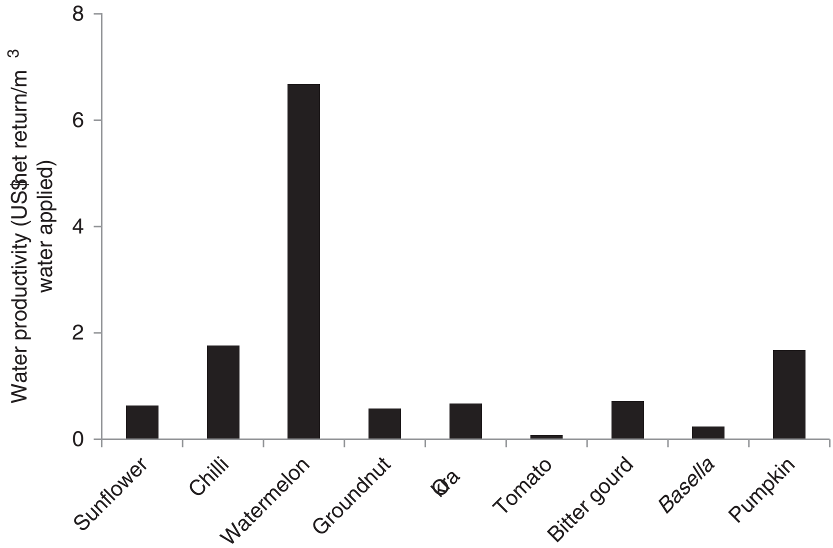

Fig. 19.4. Water productivity, expressed as net return (US$)/m³ of applied irrigation water, for non-rice crops evaluated in medium-salinity fields during the dry season of 2005 ($LSD_{0.05}$ = 0.46).

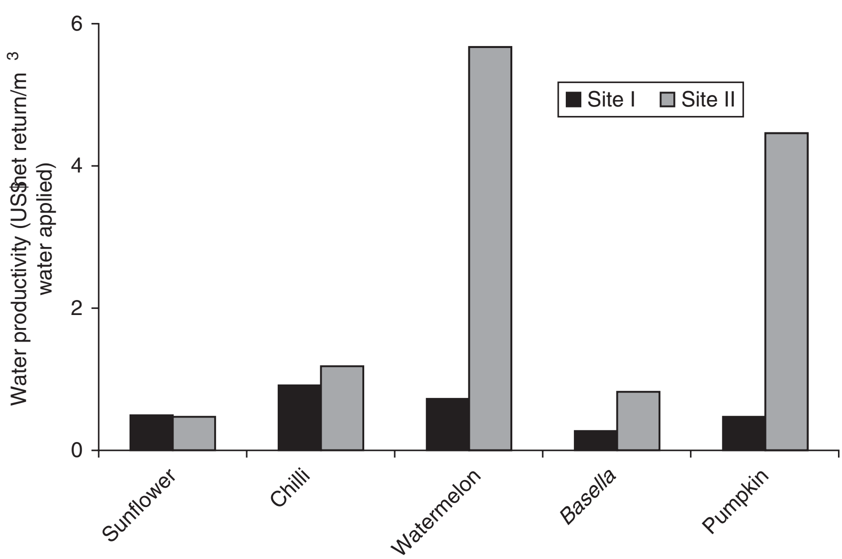

Fig. 19.5. Water productivity, expressed as net return (US$)/m³ of applied irrigation water, for non-rice crops evaluated at site I (black bars) and site II (grey bars) in high-salinity fields during the dry season of 2006 ($LSD_{0.05}$ = 0.20 for site I and 0.42 for site II).

wet season, as well as during the cropping season (January–April). The occurrence of drought towards the end of the preceding wet season leads to increased soil and groundwater/irrigation water salinity in the beginning of the following dry season. This was observed in 2005 (Fig. 19.3a), when only sunflower produced good yield under high salinity. Analysis of the

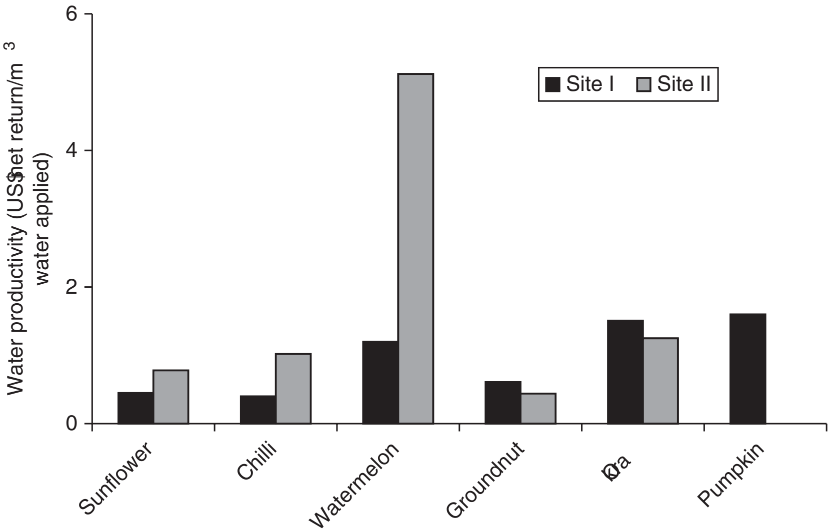

Fig. 19.6. Water productivity, expressed as net return (US$)/m^3 of applied irrigation water, for non-rice crops evaluated at site I (black bars) and site II (grey bars) in medium-salinity fields during the dry season of 2006 ($LSD_{0.05}$ = 0.32 for site I and 0.34 for site II).

past 30 years' rainfall data showed that the frequency of severe terminal drought (less than 40% of the average rainfall during the 2nd week of October to December; 41–52 meteorological week) was 27%. In such years, farmers have the option of growing sunflower in high-salinity fields and watermelon, okra, chilli and pumpkin in medium-salinity fields. When rainfall in the preceding wet season is normal, all these crops, except okra, can be grown even under high salinity. Rainfall during the cropping season will determine the frequency and amount of irrigation. All the crops needed more irrigation water in 2005, which received only 20% of the average rainfall, than in 2006, when rainfall was more than 100% of the average (Fig. 19.3b). Crop performance will be affected when there is unusually high rainfall, particularly during crop establishment. The frequency of unusually high rainfall (more than 40% of the average rainfall during January–April; 1–17 meteorological week) during the cropping season is as low as 13%. In such an exceptional situation, most of the crops may not survive, particularly in poorly-drained lowlands. This analysis suggests that non-rice crops are likely to perform well in most years.

Conclusions

The extent of soil salinity varied widely between seasons and sites, depending on the complex interactions of groundwater and irrigation water salinity, irrigation quantity, groundwater table depth, soil texture, rainfall pattern and atmospheric evaporative demand. The farmers' perceptions about soil salinity rating were close to our assessment based on the EC measurements. With the exception of sunflower and chilli, the performance of most crops evaluated varied considerably between fields and sites. Watermelon, chilli, pumpkin and sunflower were promising for medium- and high-salinity conditions, occurring at the experimental sites and in seasons, based on rice yield equivalent, B:C ratio and water productivity. Under high-salinity conditions, watermelon and pumpkin performed better when good-quality irrigation water was used. Okra was the most remunerative crop under medium-salinity conditions, although its water productivity was in some cases lower than that of watermelon and pumpkin. Sunflower and chilli produced relatively consistent yields across the locations and were preferred by farmers for their own consumption needs and for their better storage characteristics. Farmers' response to adoption of these non-rice crops is encouraging and demand for their seed is increasing rapidly in this area. This could contribute greatly to crop diversification as well as livelihood improvement of these poor farming communities. Results of this study could be extended to other salt-affected coastal areas with similar conditions.

Acknowledgement

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References

Bandyopadhyay, B.K. and Sen, H.S. (1992) Effect of excess soil water conditions for a short period on growth and nutrition of crops on coastal saline soils. *Journal of the Indian Society of Soil Science* 40, 823–827.

Bandyopadhyay, B.K., Maji, B., Sen, H.S. and Tyagi, N.K. (2003) Coastal soils of West Bengal: their nature, distribution and characteristics. CSSRIRRS (Central Soil Salinity Research Institute Regional Research Station) Bulletin No 1/2003, 18 pp.

Cueto-Wong, J.A., Sanchez-Cohen, I., Perez-Gonzalez, J.L., Mendoza-Morino, F.S. and Inzunza-Ibarra, N.A. (2003) Productivity and yield of watermelon by effect of water in different management conditions. *Revista Chapingo Serie Horticultura* 9, 209–223.

Francois, L.E. (1996) Salinity effects on four sunflower hybrids. *Agronomy Journal* 88, 215–219.

Hebbara, M., Viswanath, D.P., Naganagoud, A. and Basavaraj, B. (1992) Interrelationship between soil salinity and crop yields on Vertisols. *Journal of the Indian Society of Soil Science* 40, 888–889.

Kahlown, M.A., Ashraf, M. and Zia-ul-Haq (2005) Effect of shallow groundwater table on crop water requirements and crop yields. *Agricultural Water Management* 76, 24–35.

Katerji, N., van Hoorn, J.W., Hamdy, A. and Mastrorilli, M. (2000) Salt tolerance classification of crops according to soil salinity and to water stress day index. *Agricultural Water Management* 43, 99–109.

Maas, E.V. (1993) Testing crops for salinity tolerance. In: Maranville, J.W., Baligar, B.V., Duncan, R.R. and Yohe, J.M. (eds) *Proceedings of the Workshop on Adaptation of Plants to Soil Stresses*, 1–4 August 1993, Lincoln, Nebraska. INTSORMIL Pub. No 94-2, University of Nebraska, Lincoln, Nebraska, pp. 234–247.

Muralidharudu, Y., Reddy, B.N., Chandranath, H.T. and Lokesha, K.R. (2003) Effect of nutrients and moisture conservation practices on growth, yield and economics of rabi sunflower under rainfed vertisols. *Journal of Oilseeds Research* 20, 244–248.

Oad, F.C., Soomro, A., Oad, N.L., Abro, Z.A., Issani, M.A. and Gandahi, A.W. (2001) Yield and water use efficiency of sunflower crop under moisture depletion and bed shapes in saline soil. *On-line Journal of Biological Sciences* 1, 361–362.

Padmavathi, P. (2004) Effect of water logging on growth and yield of sunflower, *Helianthus annuus* L. *Journal of Oilseeds Research* 21, 359–360.

Reddy, S.S., Yadahalli, Y.H., Kumar, V.K.K., Kumara, O. and Boraiah, B. (2002) Effect of fertilizer, gypsum and boron application on growth, yield and nutrient uptake in sunflower hybrids. *Research on Crops* 3, 353–358.

Saha, S., Moorthy, B.T.S. and Poonam, A. (2006) Cultivation of sunflower in rice fallows: a viable technology option for coastal Orissa farmers. *Indian Farming* 56, 33–35.

Selvi, D., Santhy, P., Rajkannan, B. and Thiageshwari, S. (2004) Effect of integrated nutrient management on yield and economics in okra in an Inceptisol. *Journal of Maharashtra Agricultural University* 29, 122–124.

Tingwu, L., Jaun, X., Guangyong, L., Jianhua, M., Jianping, W., Zhizhong, L. and Jianguo, Z. (2003) Effect of drip irrigation with saline water on water use efficiency and quality of watermelons. *Water Resources Management* 17, 395–408.

Upadhyay, S.K., Joshi, B.S., Bajpai, R.K. and Shrikant, C. (2004) Effect of higher fertility levels combined with farmyard manure and row spacing on seed yield, oil yield and economics of sunflower. *Journal of Oilseeds Research* 21, 189–191.

Yadav, J.S.P. (2001) Resource management for coastal ecosystem. *Journal of the Indian Society of Agricultural Research* 19, 10–29.

Yadav, V.S. and Luthra, J.P. (2004) Effect of NICAST (organic manure) on growth, yield and economics of watermelon. *Haryana Journal of Horticultural Sciences* 33, 263–264.

20 Water Supply and Demand for Dry-season Rice in the Coastal Polders of Bangladesh

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Abstract

In Bangladesh, about 1.0 million ha of land, most of which remain fallow in the dry season, are affected by varying degrees of salinity. Studies show that utilization of river water is a feasible technology for dry-season rice (locally known as *boro* rice) cultivation, but reservoir volume limits the irrigated area in the dry season. Therefore, alternatives should be developed to increase the rice area and the productivity of the coastal region of Bangladesh, not only to meet future food demand, but also to improve farmers' livelihoods. One option is to maximize river water utilization before it becomes saline and minimize dependency on the reservoir water for *boro* rice cultivation. Experiments were therefore conducted in polder 30 at Batiaghata Subdistrict in Khulna District during the dry seasons of 2005/06 and 2006/07 to test the hypothesis that early crop establishment can reduce the reservoir water-use period, thereby increasing the irrigated area and productivity. The results showed that seeding on 7 November produced 4–5 t/ha rice yield by utilizing about 50% of the required water directly from the river and the remaining 50% from the reservoir. Seeding on 15 November produced a rice yield on par with that of 7 November, but more reservoir water was used for the later seeding date, which would then reduce the dry season irrigation coverage. The rice yield was reduced drastically when seeding was carried out before 7 November because of cold stress at the critical reproductive period of rice. This study determined that about 260 mm water was required from the reservoir for successful cultivation of *boro* rice in the coastal area and about 14% of net cultivable area (NCA) could be brought under irrigation with the existing hydraulic system of polder 30. With moderate excavation, the irrigation coverage could be increased to about 35% of NCA. Therefore, both productivity and irrigated area in the dry season could be increased by advancing the rice cultivation season to the second week of November through to the first week of April.

Introduction

More than 30% of the cultivable land in Bangladesh is in the coastal area, about 1.0 million ha of which are affected by varying degrees of salinity. The cropping intensity and productivity in this region is very low and the farmers grow mostly low-yielding (2–3 t/ha)

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traditional rice in the monsoon/wet season, typically transplanting in July/August and harvesting in November/December. Most of the lands remain fallow in the post-monsoon dry season (January–May) because of high soil salinity and lack of good-quality irrigation water; some farmers grow shrimp by using salt water during this period.

In most areas of Bangladesh, groundwater is used intensively for dry season (locally termed *boro*) rice cultivation, typically transplanted in December/January and harvested in April/May. But, access to fresh groundwater is limited in the coastal regions; thus, many farmers there cannot grow *boro* rice. Excessive pumping would result in saltwater intrusion into the coastal aquifers (ICZMP, 2004). Mondal *et al.* (2006) showed that *boro* rice could be cultivated using river water directly during November to mid-February, and then conserving it in reservoir canals for irrigation from mid-February to the end of March. This new practice was tested successfully in a limited area. Outscaling the technology, i.e. promoting its adoption over larger areas, has not been investigated systematically. How large the area and where the technology can be applied depends on several factors: (i) the water requirement of *boro* rice; (ii) determination of optimum planting time for better yield of crop; and (iii) the storage capacity of the internal canal networks during the second phase of irrigation for the *boro* rice.

Irrigation coverage in the dry season could be increased either by increasing reservoir volume and/or by advancing the cropping period. Reservoir storage volume can be increased by digging new canals/ponds and widening and deepening existing ones, but this needs a huge investment. Early crop establishment might expose the crop to cold stress during the panicle initiation (PI) stage if it is planted too early. It may also have a lower yield potential because of low radiation during November–January.

We hypothesize that proper timing of *boro* rice cultivation can reduce its irrigation requirement from reservoir-stored water while attaining optimal rice yields, thereby enabling more farmers to increase their rice productivity with minimal investment in irrigation infrastructure development in the coastal region of Bangladesh. This chapter describes the experimental procedures and outcomes of on-farm research to test this hypothesis at a typical site in the target region.

Objectives

The general objective of the study was to develop crop and water management techniques for increasing water productivity with the existing hydraulic storage facilities (old rivers/canals) in the coastal region of Bangladesh. The specific objectives were:

1. To quantify the water requirement and yield of the dry-season rice (*boro* rice) for different planting dates;
2. To determine trade-offs between conserving the reservoir irrigation water requirement and attaining yield, as affected by planting dates; and
3. To estimate the potential area and production of fully irrigated *boro* rice that could be achieved in a representative coastal polder by maximizing the use of the potential storage of the polder river channels.

Methodology

Experimental design

Field experiments were carried out during the dry seasons of 2005/6 and 2006/7 in polder 30 at Kismat Fultola village under Batiaghata Subdistrict in Khulna District, located in the south-west region of Bangladesh (Fig. 20.1). The experiment was set up in a split-plot design with four replications.

The treatments were:

Main plots with four sowing dates
D_1 = 22 October;
D_2 = 01 November;
D_3 = 07 November;
D_4 = 15 November.

Subplots with two rice varieties
V_1 = BRRI dhan28;
V_2 = PVS B8.

BRRI dhan28 is a short-duration rice variety popularly grown in the dry season, whereas

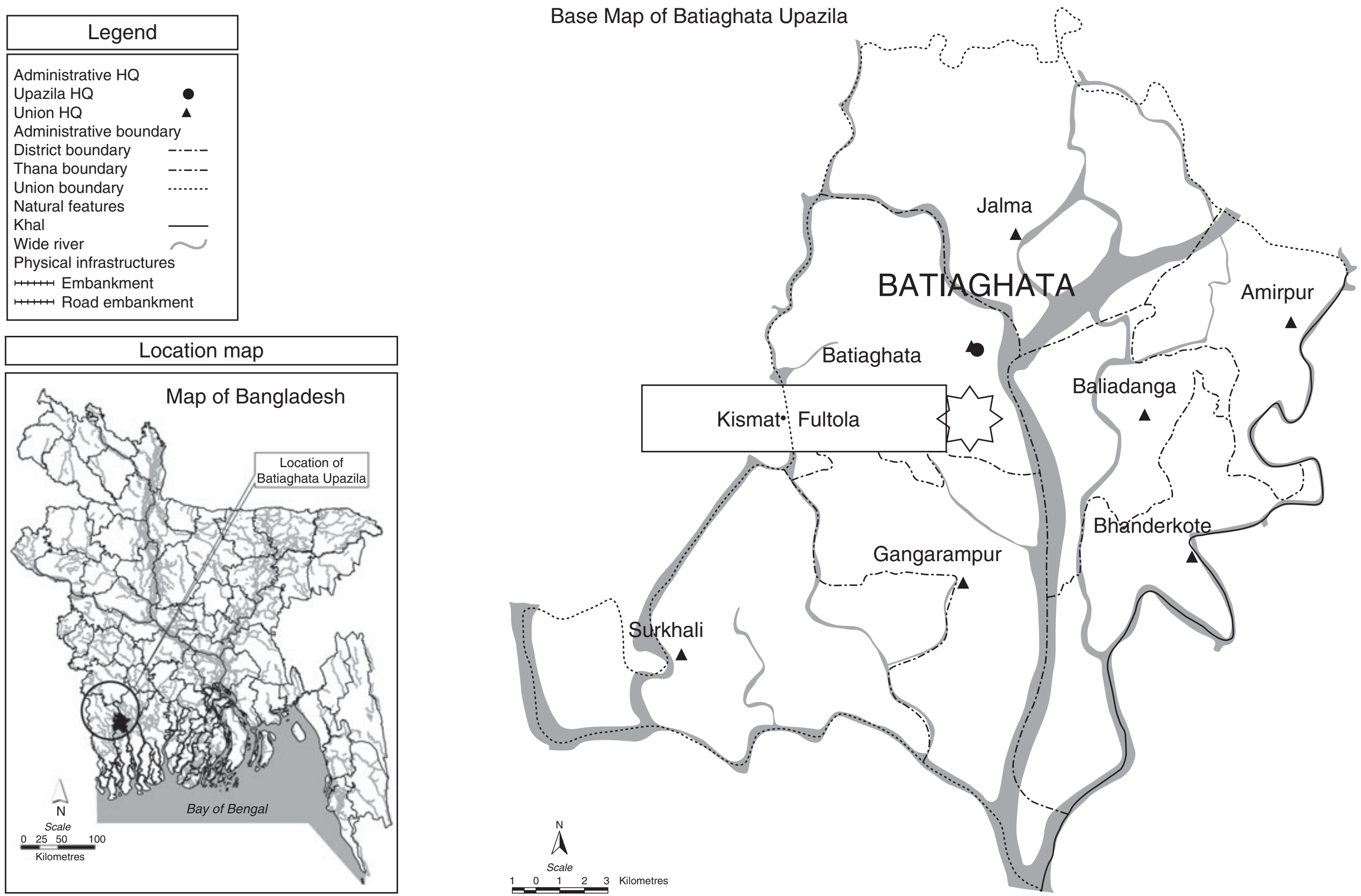

Fig. 20.1. Map of Batiaghata Subdistrict showing the study site, Kismat Fultola village.

PVS B8, which has similar growth duration as BRRI dhan28, reportedly has some salt-tolerant ability, as assessed by farmers (BRRI, 2004).

Experimental layout

Field layout of the 6 × 8 m plots and bund construction was performed prior to land preparation. The bunds – 20 cm high and 50 and 20 cm wide for the main and secondary bunds, respectively – were compacted to prevent seepage to and from adjacent plots. In addition, plastic linings were installed at a depth of 30 cm into the soil around the perimeter of the main plots.

Seedling raising and crop establishment

Sprouted seeds were sown at the rate of about 2800 seeds/m^2 in a 0.5 m × 1.0 m box having 40 mm deep soil and cow dung mixture (soil:cow dung = 80:20). The seedlings were raised with regular watering. In 2005/6, transplanting was carried out on 9, 21 and 30 November and 11 December for the D_1, D_2, D_3 and D_4 treatments with 18-, 21-, 23- and 27-day-old seedlings, respectively. The transplanting dates were the same in 2006/7, except for D_4, which was transplanted 3 days earlier, on 8 December 2006.

Irrigation water measurement

Irrigation water was measured by a V-notch weir. Water was sourced directly from the river Kazibacha during high/flood tide from November to January, and after that from water stored in a natural canal. The canal was filled with river water in the first week of February, when river water salinity was < 4.0 dS/m. After transplanting, the plots were irrigated to 2–3 cm depth of standing water, depending on the height of the seedlings. After establishment, the water depth was increased to a maximum of 5 cm and the plots were irrigated whenever the water depth went below 1 cm. Irrigation was stopped 10–15 days before harvest. The temporarily fallow plots (because of different planting dates) were also irrigated in a similar way to avoid seepage loss from the crop field.

Evapotranspiration, seepage and percolation

A water subsidence technique, i.e. the fall in water depth, was used to determine evapotranspiration (ET), seepage (S) and percolation (P) over the period that the plots were continuously flooded until shortly before harvest. Two 1 m × 1 m galvanized iron (GI) tanks (40 cm height and 22 gauge thickness), one with a sealed bottom and one bottomless, were installed in the subplots of four main plots for ET and ET + P measurement, respectively. The tanks were painted green to match the rice environment (i.e. to reduce reflection) and were covered with polyethylene sheets to avoid/reduce any potential toxic effects of the GI. The open-bottom tank was inserted up to 30 cm deep by uniform hammering in the undisturbed soil profile. For the closed-bottom tank, a 30 cm-deep soil volume was removed before inserting the tank. The excavated soil was replaced layer by layer to maintain the original soil condition inside and outside the tank. Three vertical gauges in each subplot were installed, two outside and one inside each GI tank to measure the water subsidence and also to check water depth during irrigation both inside and outside the tank. Subsidence of water level in the rice field and inside the tank was measured daily at 09.00 a.m. ET was determined by subtracting the water level of two consecutive days from the sealed tank with proper adjustment of rainfall and irrigation water, if any. The same procedure was followed to determine ET + P from the bottomless tank; P was calculated by subtracting ET values obtained from the sealed tank. The difference between water subsidence from the rice field outside of the tank and from the bottomless tank was taken as the value of S.

Climatic data

A US Weather Bureau (USWB) Class A evaporation pan and a standard rain gauge were installed in the vicinity of the experimental field to measure daily evaporation and rainfall at the site. Maximum and minimum temperature data during the study period were collected from the Khulna meteorological station, about 10 km from the experimental site. Long-term daily rainfall, relative humidity and maximum and minimum temperature data were also collected from the meteorological office.

Fertilizer and pesticide application

Fertilizer was applied at 120 kg N, 60 kg P_2O_5, 40 kg K_2O, 60 kg $CaSO_4$ and 10 kg $ZnSO_4$ per hectare. All the P, K, S, Zn and one-fourth of the urea were applied at the time of the final land preparation. The remaining urea was top-dressed in three equal splits at 25 days after transplanting (DAT), 5–7 days before PI and at heading. Weeding was carried out three times, synchronizing with the urea top-dressing. In 2005/6, there was a serious attack of stem borer and insecticides were applied nine times to control insect pest infestation. The damage resulted in an estimated 20–40% yield loss. The yield loss was assessed by counting total productive tillers and white-head tillers from 20 randomly selected hills from the harvest area (Fig. 20.2). In 2006/7, preventative measures were taken (weekly and alternate application of systemic and contact pesticides) to prevent crop loss as a result of pest and disease attacks so as to determine yield loss due to cold stress more accurately.

Phenology dates

Panicle initiation (PI), flowering (FL) and physiological maturity (PM) dates were recorded for both rice varieties. Daily monitoring of 12 plants at the designated sampling area (Fig. 20.2) from each replication for 10 days was carried out 5 days before the expected onset of PI and FL. Plants were dissected to measure panicle primordia to determine PI date. The FL date was determined by counting the tillers on the selected ten hills when 50% of them had flowered and the PM date was taken when 80% of the grain had turned a golden colour (visual estimate).

Assessment of yield components and crop yield

Grain yield was estimated from a 4 m × 2 m harvest area in the middle of each plot (8 m × 6 m). The exact number of hills harvested, including missing and dead hills, was also recorded. The samples were threshed, cleaned and sun dried properly to determine the yield per hectare at 14% moisture content. Yield components (number of panicles/m^2, total spikelets/panicle, per cent filled spikelets/panicle and 1000-grain weight on oven dry weight basis) were determined at PM from four hills at each corner of the harvest area.

Storage capacity of the internal hydraulic system

There are 53 major and minor old river sections (locally referred to as canals) inside polder 30, of which the Bangladesh Water Development Board (BWDB) has measured the length and cross-sectional area at 150 m intervals along the length of 15 major canals. The length of the canals varies from 1 km to 4.4 km. In 2007, the lengths of the remaining 38 canals (the longest was 7 km) and their cross-sectional areas were measured at intervals of 150–450 m, depending on the uniformity of the canal section. The total volume of the canal was determined by multiplying the cross-sectional area with the length of the canal. The total storage volume of polder 30 was determined by summing up the volumes of all the 53 canals inside polder 30.

Results and Discussion

Phenological development of rice

Table 20.1 summarizes the onset of the key phenological stages for the 2005/6 and 2006/7 rice crops. The key phenological characteristics emerged later in PVS B8 compared with BRRI dhan28 for all the sowing dates and in both years. Although PI and FL occurred much earlier in BRRI dhan28, both varieties reached PM

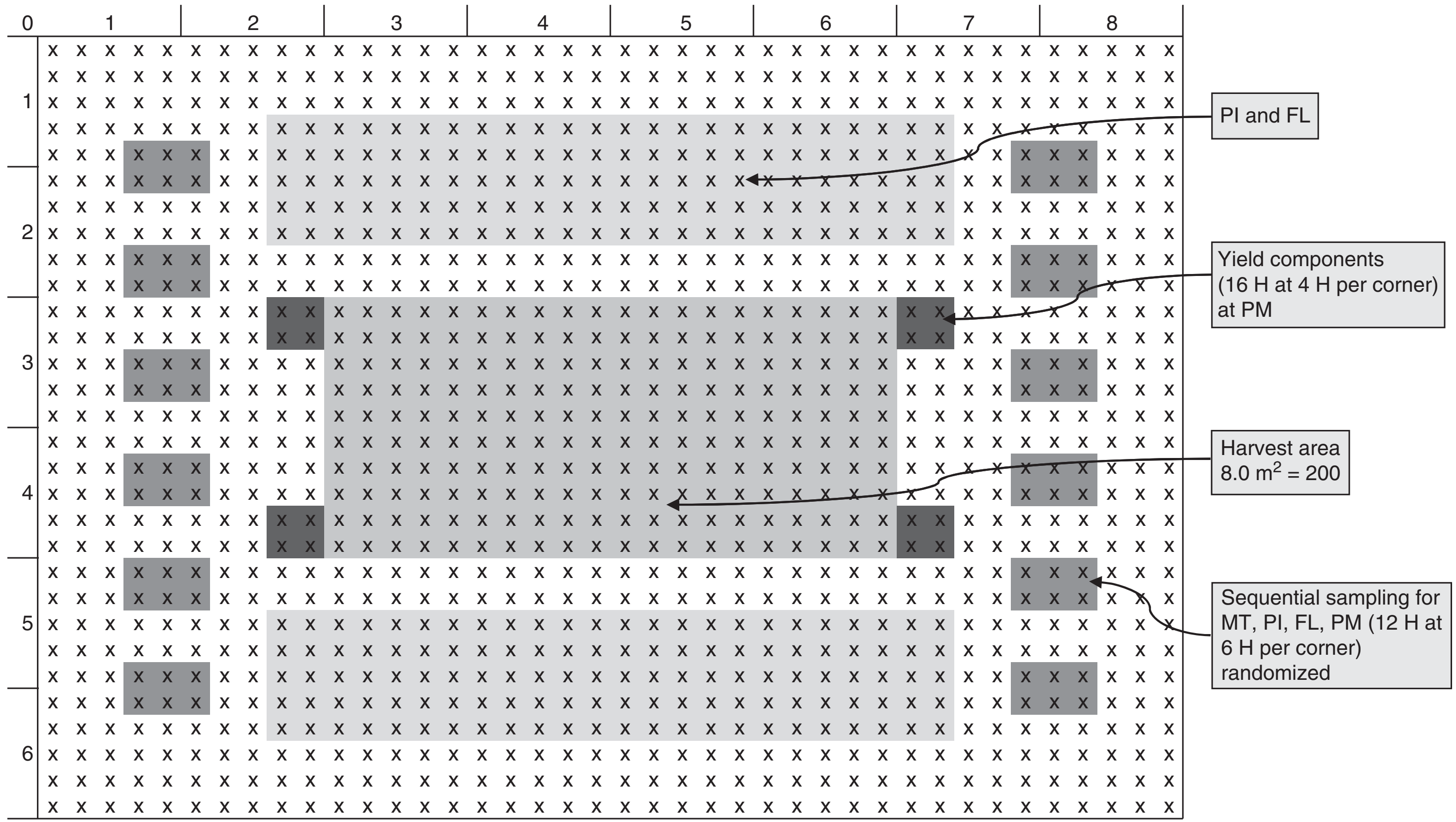

Fig. 20.2. Location of monitoring and destructive sampling sites in each plot (H, hills).

Table 20.1. Phenological period (days after emergence) of rice at Kismat Fultola, Batiaghata, Khulna, Bangladesh, *boro* seasons 2005/6 and 2006/7.

Sowing date	Key phenological characteristics	BRRI dhan28			PVS B8		
		2005/6	2006/7	Mean	2005/6	2006/7	Mean
D_1 = 22	PI	74	77	76	84	79	82
Oct	FL	116	117	117	126	120	123
	PM	155	154	155	154	154	154
D_2 = 01	PI	84	94	89	95	97	96
Nov	FL	112	127	120	123	130	127
	PM	140	154	147	151	154	153
D_3 = 07	PI	93	93	93	102	97	100
Nov	FL	121	125	123	130	127	129
	PM	149	152	151	154	154	154
D_4 = 15	PI	93	90	92	99	91	95
Nov	FL	121	118	120	129	121	125
	PM	147	145	146	147	146	147

PI, panicle initiation; FL, flowering; PM, physiological maturity.

in almost the same period, with PVS B8 being only slightly later. The crop matured earlier in the D_4 (15 November) sowing date compared with the other sowing dates.

Yield and yield component of rice

Tables 20.2 and 20.3 summarize the yield and yield components of the two rice varieties (BRRI dhan28 and PVS B8). Because of heavy stem borer attack, the rice yield was much lower in the *boro* season 2005/6 (Table 20.2), with 20–40% yield loss, than the potential or achievable yield (BRRI, 2003). BRRI dhan28 produced significantly lower yield in the early sowing treatment (D_1).

All the yield-contributing characteristics of BRRI dhan28 were severely affected because of the effect of low temperature at the PI stage (Fig. 20.3), with filled spikelets being affected the most.

In contrast, the highest yield BRRI dhan28 for the 2005/6 season (4614 kg/ha) was obtained in the D_2 treatment, despite its relatively early (1 November) sowing date. The

Table 20.2. Yield and yield components of rice at Kismat Fultola village under Batiaghata Subdistrict in Khulna District, Bangladesh, *boro* season 2005/6.

Seeding date	Productive panicles/m^2 $p < 0.01$	Panicle length (cm) $p < 0.01$	Total spikelet/ panicle $p < 0.05$	Filled spikelet/ panicle $p < 0.01$	Filled spikelet (%) $p < 0.01$	1000 grain wt (g) $p < 0.01$	Grain yield (kg/ha) $p < 0.05$
Variety, V1 = BRRI dhan28							
D_1 = 22 Oct	73.44^{c}	18.29^{e}	–	–	11.67^{e}	18.30^{b}	2708.9^{cd}
D_2 = 01 Nov	359.77^{a}	22.80^{d}	63^{bc}	38^{bcd}	59.71^{ab}	19.07^{ab}	4614.1^{a}
D_3 = 07 Nov	218.36^{b}	24.53^{bc}	64^{bc}	41^{bc}	64.94^{ab}	20.45^{a}	3648.1^{abcd}
D_4 = 15 Nov	241.02^{b}	25.54^{ab}	86^{a}	60^{a}	72.21^{a}	19.11^{ab}	4333.5^{ab}
Variety, V2 = PVS B8							
D_1 = 22 Oct	248.44^{b}	23.35^{cd}	57^{c}	25de	43.60^{cd}	20.61^{a}	4026.7^{ab}
D_2 = 01 Nov	210.55^{b}	25.00^{ab}	58^{c}	22^{e}	38.09^{de}	19.64^{ab}	2531.1^{d}
D_3 = 07 Nov	207.03^{b}	26.14^{a}	66^{bc}	37^{cd}	55.37^{bc}	19.44^{ab}	3824.2^{abc}
D_4 = 15 Nov	214.06^{b}	26.10^{a}	80^{ab}	51^{ab}	64.61^{ab}	20.11^{a}	3322.2^{bcd}

Means followed by similar letter are not significantly different at 1–5% level of significance by HSD.

Table 20.3. Yield and yield components of rice at Kismat Fultola village under Batiaghata Subdistrict in Khulna District, Bangladesh, *boro* season 2006/7.

Seeding date	Productive panicles/m^2 $p < 0.01$	Panicle length (cm) $p < 0.05$	Total spikelet/ panicle $p < 0.05$	Filled spikelet/ panicle $p < 0.01$	Filled spikelet (%) $p < 0.05$	1000 grain wt (g) $p = 0.0319$	Grain yield (kg/ha) $p < 0.01$
Variety, V1 = BRRI dhan28							
D_1 = 22 Oct	17.19^d	18.84^c	57^c	9^d	15.14^c	17.26^d	702.9^c
D_2 = 01 Nov	139.45^c	20.35^{bc}	73^b	36^c	49.39^b	18.34^{cd}	2394.3^b
D_3 = 07 Nov	306.25^a	22.03^{ab}	100^a	82^a	82.37^a	19.33^{bc}	5036.4^a
D_4 = 15 Nov	301.95^{ab}	22.05^{ab}	98^a	76^{ab}	77.29^a	19.38^{bc}	4500.8^a
Variety, V2 = PVS B8							
D_1 = 22 Oct	57.03^d	20.91^{abc}	77^b	10^d	12.76^c	18.75^{cd}	940.2^c
D_2 = 01 Nov	232.81^b	21.65^{ab}	69^{bc}	41^c	59.19^b	21.63^a	2877.8^b
D_3 = 07 Nov	289.06^{ab}	22.47^a	91^a	71^{ab}	78.41^a	21.51^a	5217.9^a
D_4 = 15 Nov	316.80^a	22.76^a	90^a	67^b	74.28^a	20.60^{ab}	5110.7^a

Means followed by similar letter are not significantly different at 1–5% level of significance by HSD.

minimum temperature went above the critical 15°C threshold in the third week of January 2006; this could have averted the low temperature effect on PI of the plants in the D_2 plots, resulting in the high grain yield. Despite the fact that the PI of PVS B8 occurred in the third week of January 2006 when the minimum temperature was close to 15°C (Fig. 20.3), its yield and yield components were not affected as much by low temperatures as BRRI dhan28 in the 2005/6 crop season. This may be because of its slightly longer growth duration than BRRI dhan28 (Table 20.1). In fact, the highest yield of PVS B8 was obtained in the first sowing treatment (D_1) and was not significantly different from yields in the D_3 and D_4

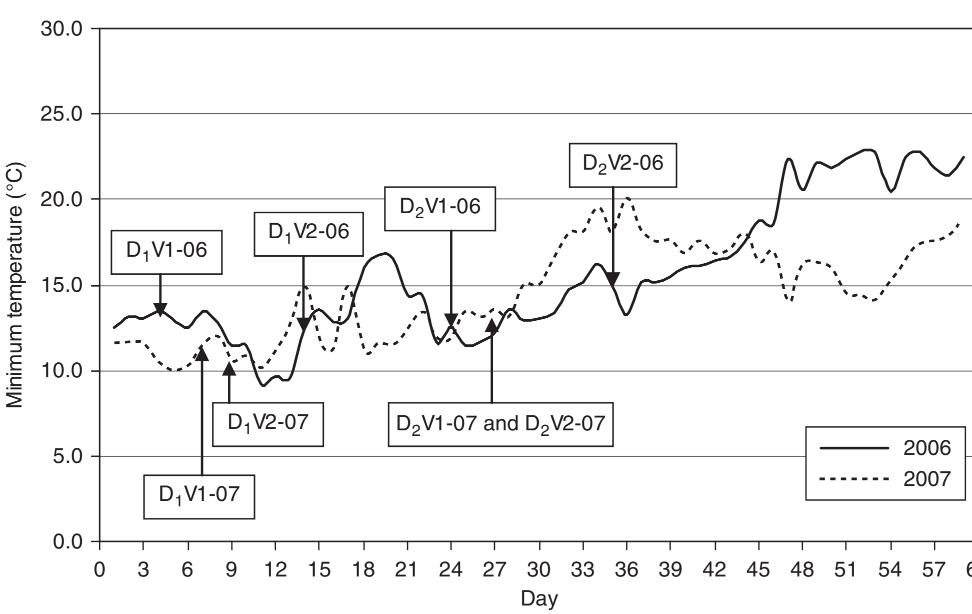

Fig. 20.3. Daily minimum temperature during January and February in Khulna District, Bangladesh in 2006–2007 (PI dates of D_1 and D_2 are shown by arrows).

treatments. The 2005/6 yield of PVS B8 in the D_2 treatment was significantly lower because of stem borer damage and not cold stress.

The D_1 yield of BRRI dhan28 was significantly lower than that of PVS B8, mainly because of stem borer attack aggravated by low temperature at PI. BRRI dhan28 had four times more white-head plants than PVS B8 in the D_1 treatment. In the D_2 treatment, more white-head plants occurred in PVS B8, causing a yield significantly lower than BRRI dhan28. Although stem borer attack was less severe in the D_3 and D_4 treatments, yield loss was also experienced.

Since preventive measures were taken, the crops have not been affected by pest and diseases in the 2006/7 *boro* season. The highest yield of both the rice varieties in D_3 and D_4 plots exceeded 5 t/ha. The effects of sowing dates on yield of both varieties were more marked in the 2006/7 growing season (Table 20.3) than in 2005/6 (Table 20.2), because of the severity of cold stress (Fig. 20.3). The grain yield of both varieties was reduced by 80–85% with D_1 and by about 50% with D_2, whereas yields were similar (4.5–5.2 t/ha) for D_3 and D_4 sowing dates. The reductions in yield were associated with significant reductions in all yield components, with the biggest reductions being in panicle density and floret fertility for D_1.

Grain yields for the D_1 and D_2 treatments were significantly lower in the 2006/7 than the 2005/6 cropping season (Table 20.3 and Table 20.2, respectively) because of low temperatures during the reproductive period of the crop (panicle primordia differentiation and FL). Temperatures below the critical level of 15°C during the reproductive stage greatly reduce yields (De Datta, 1981). Heenan (1984) observed that a low constant temperature of 12°C for 4 days during microspore development decreased fertility by 43% with no application of N and by 65% with 150 kg N/ha. The booting stage (7–14 days before heading) of rice is the stage most sensitive to low temperature, followed by heading or FL. When the low temperature continues for 6–9 days, heading is as sensitive as or even more sensitive than booting (Yoshida, 1981).

Temperatures remained low and below the critical (15°C) level in the January 2007 period (Fig. 20.3), hence affecting PI of both varieties in the D_1 and D_2 plots, resulting in their low yields in the 2006/7 cropping season. The strong correlation between the grain yield and harvest index of both varieties with the minimum temperature at PI (Fig. 20.4) is further proof that low temperature at PI (< 15°C) is responsible for low yield. Long-term temperature records for the coastal region of Bangladesh indicate that minimum temperatures are generally below 15°C, suggesting that early sowing dates (D_1 and D_2 treatments) for *boro* rice could be more prone to low yields because of unfertilized spikelets than late sowing (D_3 and D_4 treatments).

Water requirement for *boro* rice

Land preparation water

The initial soil moisture is an important factor determining the amount of water needed for land preparation. When land preparation activities for the experiments commenced in November, there was standing water in the field because of high rainfall in September and October (Fig. 20.5). Therefore, only a very low amount (31.5 mm) of water was needed for land preparation at the time of the first transplanting (9 November), when all the plots were puddled and a similar water depth maintained (including in the fallow plots, until they were planted for the other treatments). The succeeding irrigation amounts maintained in these plots were considered as the land preparation water.

Field irrigation water

Field irrigation started immediately after transplanting and continued until terminal drainage. Amounts of irrigation water supplied from the river and canal system are shown in Table 20.4. Total irrigation amounts varied from 448 mm (D_4) to 496 mm (D_1) in 2005/6 and from 493 to 494 mm (D_1 and D_4) to 546 mm (D_2) during the 2006/7 cropping season. The highest amount of river water was applied in D_1 (about 350 mm each season) and the lowest in D_4 (about 179–215 mm) sowing plots, respectively. The D_4 treatment used significantly less river water than the other treatments. Conversely, the highest and lowest amounts of canal water were applied to D_4 and D_1 plots, respectively, in both cropping years. The water source was almost split evenly between the river and stored canal water

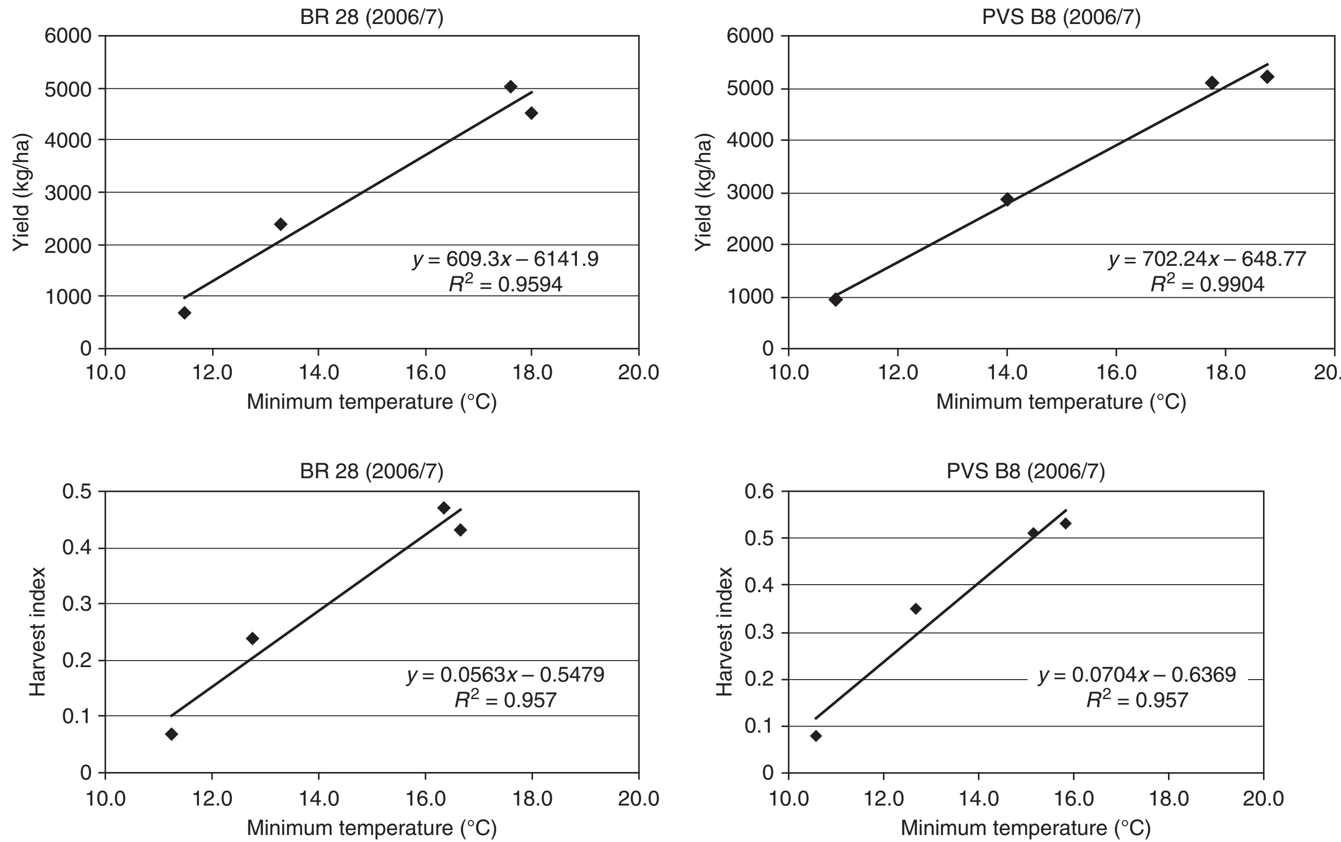

Fig. 20.4. Relationship of yield and harvest index of rice with minimum temperature in the *boro* season 2006/07.

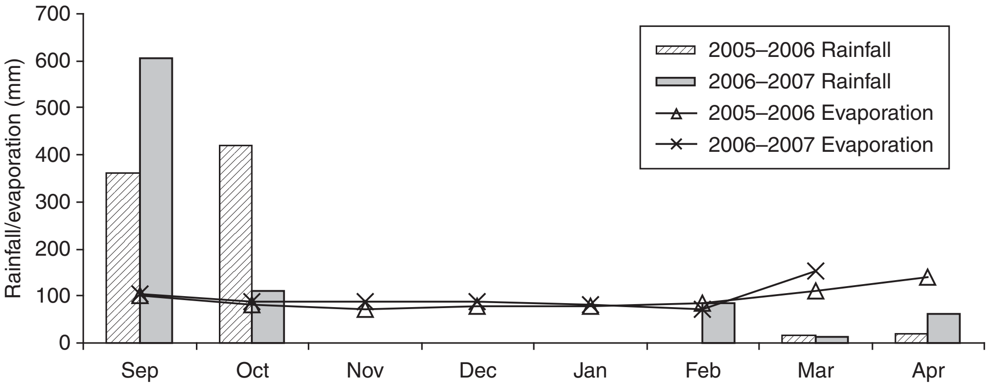

Fig. 20.5. Monthly rainfall and evaporation values at Kismat Fultola, Batiaghata, Khulna, Bangladesh.

Table 20.4. Field irrigation amount (mm) for rice at Kismat Fultola village in Batiaghata Subdistrict, Khulna, Bangladesh, *boro* seasons 2005/6 and 2006/7.

	Irrigation amount (mm)				
Sowing date	River* ($p = < 0.01$)	Canal* ($p = < 0.01$)	Total** ($p = < 0.05$)	Rainfall (mm)	Total water (mm)
2005/6 growing period					
D_1 = 22 Oct	348.61[a]	147.03[c]	495.64[ns]	15.80	542.94
D_2 = 01 Nov	268.78[a]	202.31[b]	471.09[ns]	15.80	567.39
D_3 = 07 Nov	238.21[a]	220.19[b]	458.40[ns]	15.80	603.93
D_4 = 15 Nov	178.86[b]	268.70[a]	448.06[ns]	15.80	636.65
CV	27.24	23.98	4.38	0	7.00
2006/7 growing period					
D_1 = 22 Oct	351.36[a]	142.66[c]	494.02[ns]	95.60	621.12
D_2 = 01 Nov	322.67[a]	223.05[b]	545.72[ns]	95.60	721.82
D_3 = 07 Nov	265.69[bc]	267.85[ab]	533.54[ns]	95.60	758.87
D_4 = 15 Nov	214.63[c]	278.31[a]	492.95[ns]	95.60	761.34
CV	21.07	27.07	5.25	0	9.17

*Mean values followed by common letter are not significantly different at 1% level by HSD; **mean values followed by common letter are not significantly different at 5% level by HSD.

in the D_3 plots in both years. The later the sowing date, relatively more water was derived from the canal to meet irrigation needs in the latter part of the crop season.

Total applied water

On average, the total amount of water applied for *boro* rice cultivation in the 2006/7 crop season was significantly higher than that applied in the 2005/6 crop season (Table 20.4). Correspondingly, the amount of rainfall received in the 2006/7 crop season was 95.60 mm, but only 15.80 mm in 2005/6. Since the river water salinity starts to increase from February, water supply from the canal source is crucial for determining irrigation coverage in the dry/*boro* season. As discussed earlier, the D_3 and D_4 treatments (7 and 15 November sowing) were less likely to face yield reduction because of cold stress. These two sowing dates required an average of 690 mm water for the rice crop (through rain and irrigation), of which about 260 mm (38%) was supplied from the reservoir canal (Fig. 20.6).

Irrigation water requirements would be lower if the D_2 and D_3 treatments were considered (1 and 7 November sowing dates); the D_2 treatment gave moderate yields, despite some crop damage because of cold stress at PI.

Water demand and supply for rice production

The total water requirement and application during the 2005/6 and 2006/7 cropping seasons are shown in Fig. 20.7.

On average, the total water requirement of *boro* rice ranged between 609 and 693 mm over the two cropping seasons, which was comparable with the estimate of 690 mm (mean value of water applied in treatments D_3 and D_4). Total ET and SP requirements increased from 3.49 to 7.00 mm/day from November to March during the 2005/6 season and from 2.78 to 7.54 mm/day over the same period in 2006/7. A slightly deficit irrigation was provided in 2005/6, whereas a slight excess occurred in the 2006/7 season.

Storage capacity of polder 30's hydraulic system

Polder 30 (Fig. 20.8) is typical of the 125 polders constructed by the BWDB in the coastal region of Bangladesh to protect the agricultural lands from salinity intrusion (MoWR, 2005). The land within the polder is protected from tidal inundation by a 40 km embankment. The tidal rivers surrounding the polder – Kazibacha in the east, Sholmari in the north and Bhadra in the west and south – are its natural source of water supply.

The hydraulic system of polder 30 comprises 53 canals totalling 107 km in length; the majority of them are silted up and the banks are either broken or in very poor condition. The canal system of the polder is connected to the perennial rivers through ten drainage sluices (with irrigation inlet and drainage outlet) and 13 flushing sluices/inlets (irrigation inlet only).

The storage capacity of polder 30's hydraulic system was determined on the basis of the canal survey data of BWDB and field survey information collected during the study. Some of

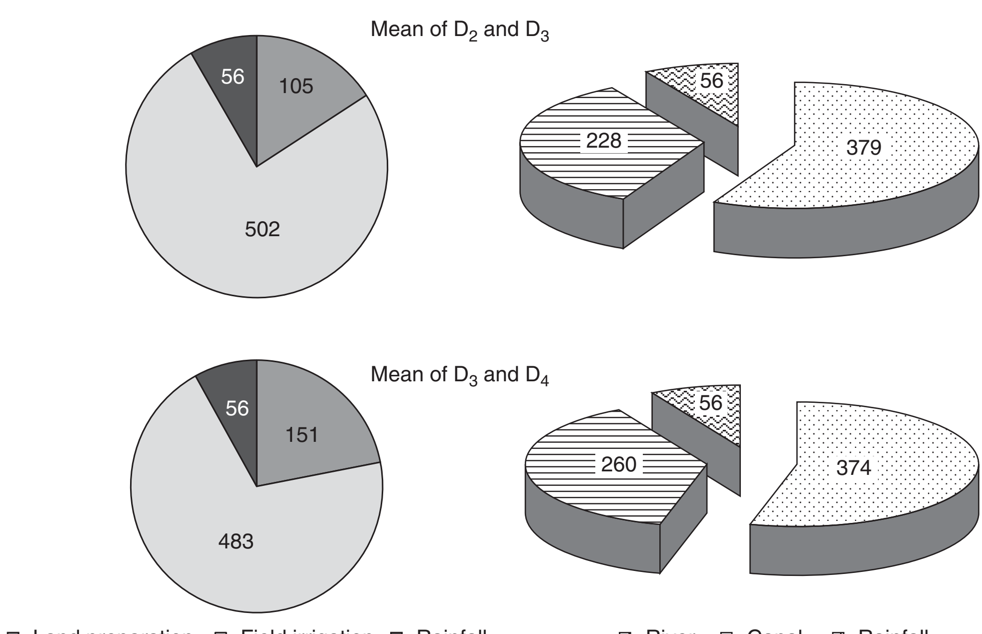

Fig. 20.6. Total applied water (mm) and sources of water supply for *boro* rice cultivation at Kismat Fultola, Batiaghata, Khulna, Bangladesh (top: average of four values of D_2 and D_3 sowing dates; bottom: average of D_3 and D_4 sowing dates).

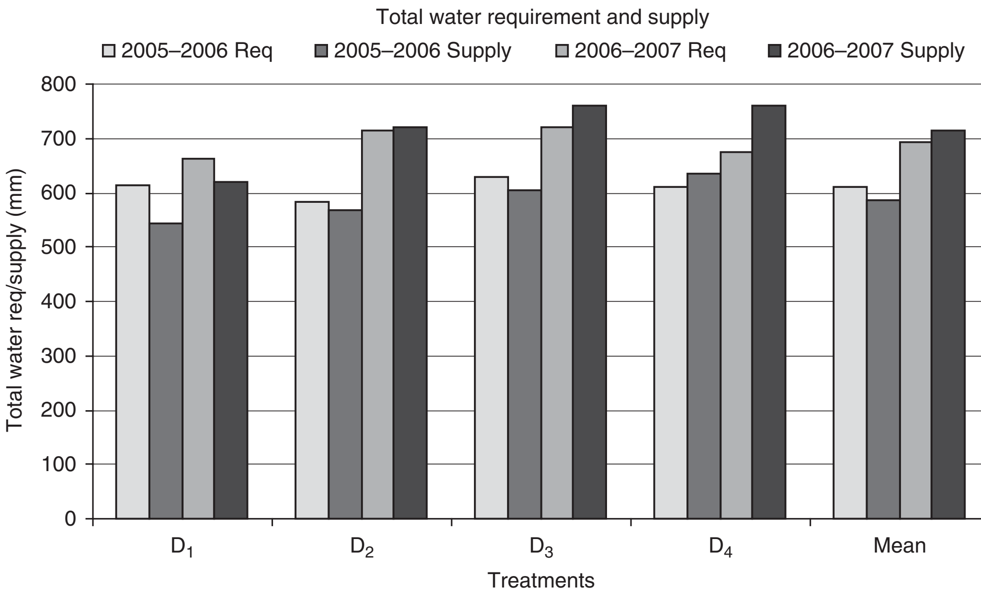

Fig. 20.7. Total water requirement and water supply for rice cultivation at Kismat Fultola, Batiaghata, Khulna, Bangladesh, *boro* seasons 2005/6 and 2006/7.

the canals (20 out of 53 canals) were found to be under fish culture, but drying up of the canals and other natural water bodies in January/February hampered the availability of fish. Maintaining the minimum water level in these canals until the end of March will provide opportunities for seasonal fish culture. Considering fish cultivation and other environmental requirements, 20% of total storage volume is kept in the fish culture canals and 10% in the other canals. The remaining volume is considered as the storage capacity of the hydraulic system for rice irrigation water in the dry season. Storage capacity estimates have been made for two scenarios:

SCENARIO 1. Considering the existing condition and use of the canal system, out of 2.60 million m^3 of total volume of the canal system, about 2.14 million m^3 are available for storing and supplying irrigation water for the *boro* rice crop. The present storage capacity is low because of the very shallow depth of the canals.

SCENARIO 2. The storage volume could be greatly increased with minimal excavation (deepening and widening) of the canals and rehabilitation of the canal embankments at a modest cost. If excavated, the total reservoir volume could be increased to about 6.97 million m^3, with 5.57 million m^3 available for irrigation.

Potential irrigation coverage in the dry season

The potential coverage of *boro* rice in polder 30 depends on water availability throughout the growing season. As the polder is surrounded by three perennial rivers, there is no shortage of water supply during the early part of the *boro* rice-growing season (November–January). Since river water salinity starts to increase in early February, the availability of irrigation water later in the season is most crucial for increasing the irrigated *boro* rice area and its productivity.

The total gross area of polder 30 is 7725 ha, of which 4867 ha is net cultivable. The results of the on-farm study indicate that the total water requirement for *boro* rice cultivation is about 690 mm (considering the D_3 and D_4 sowing dates), of which 260 mm is required from the canal system. Based on the average water requirements from canal storage, and allowing for a 20% system loss, the

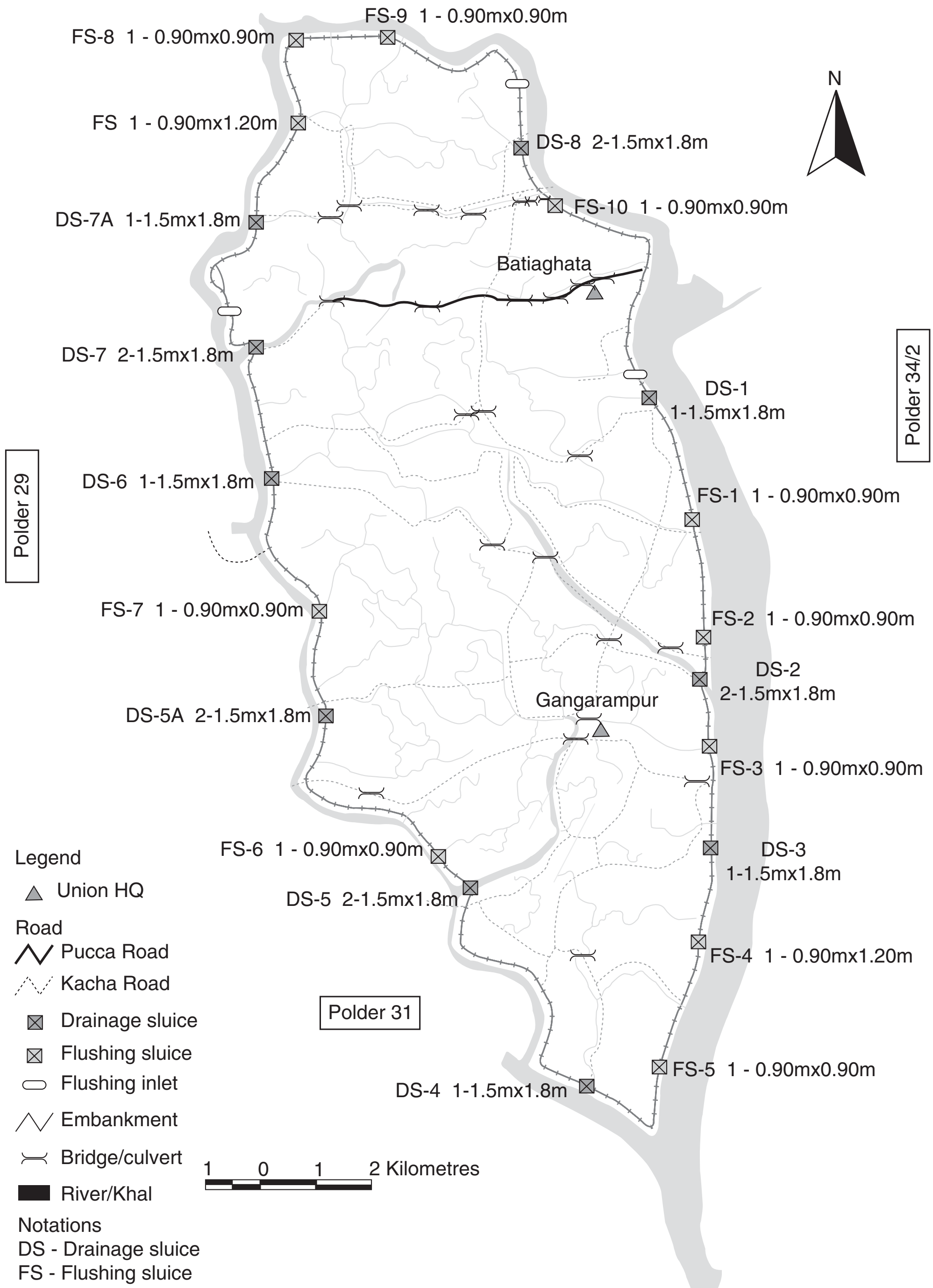

Fig. 20.8. A schematic map of polder 30 located at Batiaghata Subdistrict, Khulna, Bangladesh.

potential irrigation coverage will be 658 ha (13.5% of net cultivable area (NCA)) and 1715 ha (35% of NCA) under scenarios 1 and 2 respectively, with due consideration to water needs for fish culture in the canals.

Conclusions and Recommendations

The on-farm experimental results in the coastal region of Bangladesh indicated that sowing seeds in the second week of November (7–15 November) could produce 4–5 t/ha of *boro* rice using about 690 mm water for the entire growing season. Seeding before 7 November subjected the crop to cold stress at its critical reproductive stage and reduced yield because of unfertilized spikelets. Late sowing (i.e. later than 15 November) would avert cold stress on the crop, but limited availability of fresh water will reduce the irrigated area for *boro* rice cropping.

Water availability for land preparation of the *boro* rice crop is not limiting; most of the rice fields have remaining undrained water from the previous season's crop. Since the river water begins to become more saline in early February, the stored water supply from canal reservoirs is the main determinant of increasing irrigation coverage in the dry season. For *boro* rice cultivation, sowing seeds in the second week of November is recommended for optimum rice yield. Of the total water requirements of the *boro* rice crop, about 260 mm is needed from canal storage (38% of the total water requirement). In polder 30, about 14% of the NCA (4867 ha) could be brought under irrigation with the hydraulic storage system in its current condition. The response from farmers and other stakeholders towards adopting the irrigated *boro* rice technology in the polder area has been very positive. With moderate improvement, i.e. widening and deepening the canals, the dry season irrigation coverage could be increased to 35–40% of the NCA. In response to the recommendations of this project, the BWDB, which is a project partner, is already undertaking excavation of the canals. As and when implemented as planned, the second scenario of expanding the irrigated *boro* rice area in polder 30 is imminently achievable.

Sowing *boro* rice 1 week earlier incurs a moderate risk of yield reduction from low temperature stress, but will increase the irrigation area coverage further. It is also envisioned that the rice area and its productivity could be increased further by introducing cold- and/or saline-tolerant rice varieties in the dry season. Therefore, breeding efforts should be directed to develop cold-tolerant and/or salt-tolerant varieties for increasing the rice productivity of the coastal regions of Bangladesh.

References

BRRI (Bangladesh Rice Research Institute) (2003) *Modern Rice Cultivation* [in Bangla]. BRRI, Gazipur, Bangladesh.

BRRI (Bangladesh Rice Research Institute) (2004) *Annual Internal Review Report of the Plant Breeding Division*. BRRI, Gazipur, Bangladesh.

De Datta, S.K. (1981) *Principles and Practices of Rice Production*. John Wiley and Sons, New York.

Heenan, D.P. (1984) Low temperature induced sterility in the rice cultivars Calrose and Inga as influenced by nitrogen supply. *Australian Journal of Experimental Agricultural Research* 54, 947–956.

ICZMP (Integrated Coastal Zone Management Plan) (2004) *Concept Note on Groundwater Management in Coastal Zone of Bangladesh*. Water Resources Planning Organization, Dhaka.

Mondal, M.K., Tuong, T.P., Ritu, S.P., Choudhury, M.H.K., Chasi, A.M., Majumder, P.K., Islam, M.M. and Adhikary, S.K. (2006) Coastal water resource use for higher productivity: participatory research for increasing cropping intensity in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 72–85.

MoWR (Ministry of Water Resources) (2005) *Coastal Zone Policy*. Ministry of Water Resources, Government of the People's Republic of Bangladesh, Dhaka.

Yoshida, S. (1981) *Fundamentals of Rice Crop Science*. IRRI, Los Baños, Philippines.

21 An Analysis of Environmental Policy Strategies for Coastal Land Conservation in Thailand

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Abstract
Addressing externalities in policy decisions is crucial to ensuring the sustainable use of coastal land. This chapter analyses efficient management options and their trade-offs for coastal land use in Krabi Province, Thailand. Various environmental management schemes, such as zoning, green taxation and effluent standards for managing the externalities from shrimp farming, are explored. Multi-objective programming models are set to maximize both net private benefit and net environmental benefit at the same time, subject to technical constraint sets such as land availability, rice consumption and the carrying capacity of receiving waters for shrimp farm effluent discharges. The analysis shows that a policy strategy based on an effluent standard alone would not guarantee an environmentally friendly outcome. Zoning is a promising instrument to control the local impacts of shrimp farm effluent, whereas zoning plus green taxation would result in a fairer distribution of the benefits and costs to society, thus helping mitigate coastal land use conflicts.

Introduction

In 2007, Thailand earned about 42.9 billion baht or US$1.4 billion from the export of cultured shrimp in the frozen form alone (OAE, 2007). This represents 12% of the world's shrimp market. The economic gains from this trade, however, have had a high environmental cost. Mangrove conservation vis-à-vis shrimp production is a widely recognized coastal land use conflict in tropical countries, including Thailand. The conflict relates to the inherent complexity of the coastal systems, which needs to be well understood and taken into account in decision making. Because of market failures, the negative impacts of coastal land use activities such as shrimp farming on third parties, so-called 'externalities', are not internalized into the private costs of land use.

This chapter highlights Thailand's coastal land use conflicts and the country's policy of conserving the natural environment of the coast. An in-depth analysis was applied to the Provincial Coastal Land Development Zone of Krabi Province (Krabi's CLDZ). A combination of management instruments to promote the environmentally friendly use of coastal lands, specifically to encourage sustainable shrimp farming, is described. The instruments include: (i) zoning – subject to the carrying capacity of receiving waters (i.e. coastal water courses such as public canals and estuaries, excluding seawater) for farm effluent discharges; (ii) an effluent standard – a currently used command and control strategy; and (iii) green taxation (Pigouvian taxes) – an economic incentive-based instrument that corrects for negative externalities (see Baumol and Oates, 1988). The efficient land use options were analysed based on various scenarios of the management schemes using multi-objective programming. The models comprise resource use constraints, environmental constraints (coastal land use-associated negative impacts), as well as private and environmental benefit objectives, all of which are optimized simultaneously. From these models, we can arrive at efficient land use options, which generate the efficiency frontier (Pareto frontier), as well as trade-off rate information among the options. The results provide insights that support decision making on the development of coastal land policies and a master plan.

The next section provides an overview of the CLDZ as the analytical site for this study. The significant environmental impacts and related valuation studies are then presented, followed by a review of environmental policies and regulations in connection with the shrimp sector and mangrove conservation. All of this information contributes to the formulation of the mathematical models. The basics of the modelling method are also provided. Subsequently, the results are presented and the policy implications are discussed.

Thailand's CLDZ

The CLDZ was proposed by Thailand's Land Development Department as a guideline for coastal land management planning at the provincial level.[1] It is classified into 14 zones[2] on the basis of the most appropriate land use type obtained from prioritizing a number of physical suitability maps. The subdistrict (or *tambol* in Thai) boundary is used to demarcate the zone to support the administrative procedure and development at the community level. Consequently, 25 provinces (142 districts; 837 subdistricts) on the Gulf of Thailand and along the Andaman coastline were proclaimed as CLDZs. They cover 21.5 million rai (3.4 million ha) or 6.5% of the kingdom's total land area.

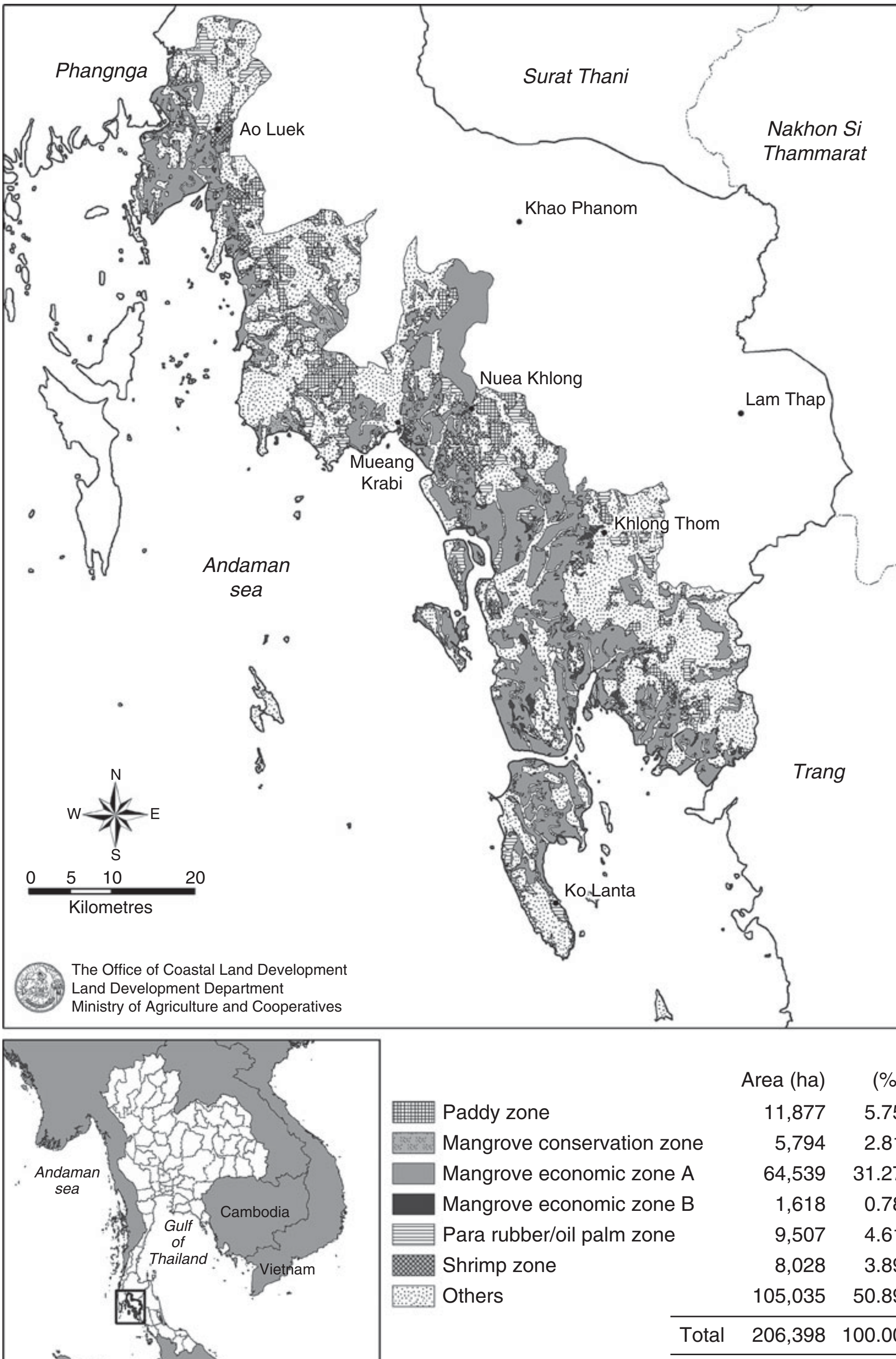
Krabi's CLDZ covers about 1.3 million rai (0.2 million ha) in five districts (28 subdistricts), or 44% of the province's total area. The study areas are the land use conflict zones in Krabi's CLDZ (see Fig. 21.1). These are the aquaculture/shrimp zone, the mangrove economic zone B, the paddy zone and the para rubber/oil palm zone. Various land use activities exist within a particular zone, although a specific land use has been identified as being the most suitable. The aquaculture zone, for instance, is classified as suitable for aquaculture, but it has been found that about 36% (18,140 rai or 2,902 ha) is used for rubber plantation and 13% (6439 rai or 1,030 ha) is mangrove areas. Only 10% (5,080 rai or 813 ha) is used for shrimp farming. On the other hand, in mangrove zone B, about half of the area is left as stand mangrove, whereas the rest is used mostly for rubber plantation and shrimp farms. In both the paddy and rubber/oil palm zones, rubber and oil palm plantations are dominant. However, other uses also exist in these zones.

Conflicts and Externalities

Based on a literature review, the most recognized externalities from shrimp farming in Thailand are: (i) coastal water pollution because of farm effluent discharges; (ii) conversion of agricultural land to farms which, after a certain period of farm operation, are degraded and then abandoned; and (iii) mangrove conversion to farms which results in a significant loss of potential mangrove benefits (see Pongthanapanich, 2006, for details). This leads to overexploitation and misallocation of resources for short-term gains. Addressing potential market failures and economic values of relevant natural resources in policy decisions is crucial to achieving sustainable use of coastal land and reducing conflicts. Summaries of the economic values of mangrove and of the external costs, respectively, are presented in Tables 21.1 and 21.2.

Thailand's Coastal Land Management

The Thai government's efforts at conserving coastal resources and controlling the impacts



	Area (ha)	(%)
Paddy zone	11,877	5.75
Mangrove conservation zone	5,794	2.81
Mangrove economic zone A	64,539	31.27
Mangrove economic zone B	1,618	0.78
Para rubber/oil palm zone	9,507	4.61
Shrimp zone	8,028	3.89
Others	105,035	50.89
Total	206,398	100.00

Fig. 21.1. Krabi's coastal land development zone (CLDZ).

Table 21.1. Economic values of mangrove in southern Thailand.

Items	Values (THB/rai/year)	Note
Direct use value (woods and non-woods)	1,938	Obtained from Sathirathai (1998). The survey was conducted in Tha Po village, Surat Thani Province in 1996. The value is based on the assumption of a mangrove-dependent village
Indirect use value		
– Offshore fishery linkage	272	Obtained from Sathirathai (1998). The study measured the net welfare loss as a result of the decrease in stand mangrove. The Eillis–Fisher–Freeman model is applied. The value is based on the case of an open-access regime. The price elasticity of demand for fishery product equals –2
– Carbon sequestration	341	Obtained from Sathirathai (1998). The total biomass was calculated and converted to derive a carbon equivalent
– Coastal erosion protection	18,310	Modified from Sathirathai and Barbier (2004). The demand for engineering works to stabilize the shoreline is used as a proxy value
Sum of indirect use	18,923	

6.25 rai = 1 ha; 0.16 ha = 1 rai.

Table 21.2. Environmental costs of coastal shrimp farming in southern Thailand.

Impacts	Ex-mangrove (THB/rai/year)	Outside mangrove (THB/rai/year)	Note
Effect of nutrient load to the Andaman Sea	0	0	Pongthanapanich (2006) applied a dynamic-constraint optimization model to measure the effect of green taxes imposed on Thai shrimp farming. The results indicate that the marginal cost of nutrient effect (stock externality) to the Andaman Sea is negligible; but this is not the case for the Gulf of Thailand
Abandoned shrimp farm	6,378[1]	1,385[2]	[1]Based on Sathirathai and Barbier (2004), the reclamation costs of abandoned farms, including mangrove seedling, and maintenance of 52,736 THB/rai for initial cost and 755 THB/rai for annual cost are used as proxy [2]Use remediation cost of pond soil as proxy value. Based on Kantangul (2002), the present value of the cost is 9,296 THB/rai ($t = 10$; $r = 8\%$)
Mangrove foregone benefits	20,861		See Table 21.1
Total	27,239	1,385	

Shrimp farming in ex-mangrove and outside mangrove, respectively, means converting mangrove and converting agricultural land into shrimp farms.

of coastal development activities have centred on the use of mandate control (command and control strategy). Many types of legal instruments were used; for example, environmental acts, royal decrees, cabinet resolutions and notifications. Details of the legislation pertaining to coastal resource management can be found in the Office of Environmental Policy and Planning, or OEPP (1998), the Department of Marine and Coastal Resources, or DMCR (www.dmcr.go.th), and the Pollution Control Department, or PCD (www.pcd.go.th). For reviews of legislation and implementation, see Howarth *et al*. (2001), the Thailand National Committee (2003) and UNEP (2004, 2005). Some regulations that are relevant to the analytical issues are discussed below. It is worth noting that after the government structural reform in 2002, the Ministry of Natural Resources and Environment (MONRE) was established. OEPP, formerly under the Ministry of Science, Technology and Environment, became the Office of Natural Resources and Environmental Policy and Planning, or ONEP (www.onep.go.th), under this new ministry. The same restructuring applied to the PCD, whereas the DMCR is a new agency under the MONRE. These three government agencies play major roles in developing coastal management protocols.

Coastal aquaculture and pollution control

Since 1991, under the Fisheries Act (1947), Article 23 and the proclamation of the Royal Decree empowered by Article 25, shrimp farms and hatcheries have been required to register with the Department of Fisheries (DOF). Under the same proclamation, since 1994, shrimp farms larger than 50 rai (8 ha) have been required to construct an effluent treatment pond that is 10% of the farm's total pond area. Waste discharge into public receiving waters is also prohibited under the Navigation in Thai Waters Act (1913). Meanwhile, coastal water quality standards were classified under the Enhancement and Conservation of National Environmental Quality Act (1992). Directly pursuant to the Act, coastal aquaculture was recently designated as a pollution point source (under the MONRE notification of 14 November 2005), which requires waste treatment to meet aquaculture effluent standards (under the Notification of 19 March 2004). This applies to shrimp farms with a pond area of at least 10 rai (1.6 ha).

Under the Fisheries Act (1947), coastal aquaculture in public waters (such as cockle, oyster and mussel farming) requires permission and payment of a water fee or tax. The fee or tax levels imposed, however, are insignificant and are not related to the quantity harvested or amount of pollution generated. Pond aquaculture (such as shrimp farming) is exempted from the fishery tax under the Act since the cultivation ponds are normally located on private lands. There have been attempts to improve the fisheries law. Recent efforts include the legal advisory mission through the FAO/FISHCODE project, which resulted in drafting of the new Fisheries Act (McDorman, 2000). The Draft Act provides a separate chapter on aquaculture legislation.

Mangrove management

The management regulations related to mangroves are implemented mostly through the proclamation of cabinet resolutions. The relevant examples are as follows:

- Under the cabinet resolution of 15 December 1987, mangroves were classified into two main zones, i.e. a conservation zone and an economic zone. The former covers 20 m of riverside along the estuaries and 75 m of coastline edges. The latter is divided into two subzones. An economic zone A was allowed for wood concession and an economic zone B for other economic uses such as agriculture, aquaculture, mining and housing.
- Despite the above classification, the overall condition of mangroves deteriorated. In the early 1990s, mangrove encroachment along the eastern coast was rampant. This coincided with the boom period of the shrimp industry. In response, the cabinet passed the resolution of 6 February 1990 to resolve the problem by strictly enforcing the cabinet resolution of 15 December 1987. This action was accompanied by suggestions to increase the tax rate for mangrove utilization for shrimp farming and to encourage effective land uses for paddy fields and shrimp farms. However, land users were only charged a small tax or fee, rather than an amount that would compensate for the environmental impacts.
- Additional measures were announced under the cabinet resolution of 4 June 1991. This included the formulation of a mangrove management plan at the provincial level, identifying the boundary of mangrove

zones, mangrove rehabilitation and the prevention of mangrove encroachment.

- Under a cabinet resolution of 23 July 1991, the report titled 'The Current Status of Mangrove and Coral in Thailand' was adopted. As a result of the report, the cabinet passed a resolution that repealed any consideration to granting mangrove use permits.
- Under the cabinet resolutions of 13 August 1996 and 19 November 1996, the renewal of wood concession permits, which began in 1966, ceased.
- Under the cabinet resolution of 22 August 2000, all mangrove zones, including newly generated mangroves, were declared as conservation zones; no use of the mangroves in these zones was permitted. However, those uses (e.g. wood concession, mining) permitted before the cabinet resolution of 23 July 1991 were allowed to continue until their permits expired. Additionally, the idea of a user charge according to the benefits obtained from mangrove use and its environmental costs was brought up. Although none of the market instruments has been implemented, this indicates the policy makers' interest in using this type of measure for coastal management.

The general conclusion was that Thailand had legal instruments applicable to mangroves and land-based pollution, but these were implemented inadequately. Strengthening the political commitment to enforce the laws was suggested (UNEP, 2004).

Other efforts to encourage sustainable coastal resource use included: campaigns to raise public awareness; involving stakeholders in the policy-making process; financial support from the central government to the provinces; the establishment of an environmental fund to support environmental improvement projects; and promoting an environment-friendly certification process which has been implemented in the shrimp aquaculture industry, i.e. code of conduct (CoC). See Pongthanapanich and Roth (2006) for a discussion of this type of voluntary management.

Coastal land use studies were also conducted. The DOF conducted a large-scale study of carrying capacity and zoning of coastal areas for aquaculture, particularly for shrimp farming. The National Research Council, in collaboration with some international agencies, was an important source of funding for mangrove research. The Land Development Department (before the government structural reform in 2002) carried out a study to classify coastal land development zones throughout Thailand in order to inform the preparation of coastal development master plans at the provincial level. This included the development of related environmental action plans by the implementing government agencies. The UNEP/GEF Project 'Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand' has been conducting research on various coastal habitats in Thailand, including mangroves.[3] A book edited by Barbier and Sathirathai (2004) provides 12 chapters of research papers that are very relevant to shrimp farming and mangrove loss issues in Thailand.

In sum, Thailand's coastal land management still relies heavily on a command and control strategy. However, there is a growing interest in the use of economic incentive-based measures for environmental management in Thailand (see Rayanakorn, 2006). Industrial waste and garbage, for example, are already subject to charges. Clean energy use is being subsidized. Environmental fund offices have been established. A recent development is the Thai government's move to establish an environmental court and to establish pollution taxes. So far, none of the economic incentive-based instruments including environmental taxes has been introduced to coastal management. The main purpose of this chapter is thus to pinpoint the potentially efficient outcomes regarding different coastal policy strategies, particularly when a tax regime is being considered, that is when shrimp farm externalities are being accounted for.

Method and Models

This chapter determines the optimal use of coastal land in a multi-criteria framework. Both maximized net private benefit and maximized net environmental benefit objectives are optimized at once. The net private benefit comprises the private gains from land use activities (land use activities are so-called decision variables in the models), whereas the net environmental benefit elicits the implicit economic values of corresponding environmental attributes generated from land use activities. Land availability, rice consumption and carrying capacity of the receiving waters for shrimp farm effluent discharges are set as technical constraints.

The Pareto-efficiency frontier is derived and the trade-offs among optimal coastal land use options along the frontier are then examined. The frontier, as a concept, represents the set of feasible and efficient points (the entire efficient set) that can be approximated from the multi-objective programming method (see Cohon, 1978, and Yu, 1985, for details of concepts and techniques).

The main idea of multi-objective programming is to establish an efficient set of feasible solutions for a multiple criteria (objectives) problem. The efficient set of objective values represents Pareto optimal solutions where improving a solution cannot be made by not worsening other(s). In other words, the solution set is efficient with respect to Pareto preference if, and only if, there is no other feasible solution that is at least as good as the efficient set with respect to all the objectives. The Pareto-efficiency frontier thus contains the feasible and non-dominated/non-inferior solutions.[4] The model of mathematical programming for this study can be formulated as follows:

$$\text{Maximize } Z_1(\underline{x}) = \sum_{j=1}^{n} C_{j1}\, X_j$$

$$\text{Maximize } Z_2(\underline{x}) = \sum_{j=1}^{n} C_{j2}\, X_j$$

$$\text{subject to} \sum_{j=1}^{n} a_{ij}\, X_j \,\{\le, =, \ge\}\, b_i$$

$$i = 1,2,\ldots,m;\ j=1,2,\ldots,n$$

$$\text{and} \quad X_j \ge 0$$

where

$Z_1(\underline{x})$ = the objective function of net private benefit

$Z_2(\underline{x})$ = the objective function of net environmental benefit

X_j = decision variable (land use activity) j

C_{j1} = coefficient of each X_j in objective $Z_1(\underline{x})$ (that is the net private benefit from each activity)

C_{j2} = coefficient of each X_j in objective $Z_2(\underline{x})$ (that is the net environmental benefit from each activity)

a_{ij} = technological coefficient of each X_j in constraint i

b_i = right-hand-side constant of each constraint i

n = number of decision variables

m = number of constraints.

Krabi's CLDZ is the study area. The setting of the decision variables represents all possible land use activities, which are formulated in line with the existing land use, and the CLDZ framework described above. Various scenarios for managing shrimp farming externalities are explored: S1, zoning by considering the carrying capacity of receiving waters for the effluent; S2, enforcing the effluent standard; S3, combined S1 and S2; and S4, S1 combined with the adoption of a proposed green taxation. Table 21.3 shows the model scenarios to observe the consequences of different management strategies proposed to control the impacts of shrimp farming.

Results and Discussion

Figure 21.2 shows the results of efficient sets of coastal land use options in the objectives space $Z_1(\underline{x})$ and $Z_2(\underline{x})$ at P1, P2,…, P6 for each scenario (S1, S2, S3 and S4). P1 and P2 represent the pay-offs when a single objective is optimized, i.e. maximum net private benefit and maximum net environmental benefit, respectively. That is, the total weight is assigned to one objective only. In the multi-criteria framework, the efficient options obtained lie between these two ends, i.e. P3, P4, P5 and P6, regarding different weights of objectives for the options. The frontiers, therefore, show the trade-off rates (i.e. how much would the

Table 21.3. Model scenarios based on various schemes of shrimp farm externality management.

Scenarios	NPB[a] objective	NEB[b] objective	Constraints of land availability	Constraints of effluent discharge from shrimp farms	Constraints of rice consumption
S1: Zoning	Does not account for externalities (no green tax)	Covers mangrove indirect benefits and external costs of shrimp farms[c]	Restricted	Restricted (considers carrying capacity of receiving waters but does not consider effluent standard)	Restricted
S2: Effluent standard	Does not account for externalities (no green tax)	Covers mangrove indirect benefits and external costs of shrimp farms	Restricted	Unrestricted (does not consider carrying capacity of receiving waters but considers effluent standard)	Restricted
S3: Combination of S1 and S2	Does not account for externalities (no green tax)	Covers mangrove indirect benefits and external costs of shrimp farms	Restricted	Restricted (considers both carrying capacity and effluent standard)	Restricted
S4: Combination of S1 and green taxes	Does not account for externalities (imposes a green tax)	Covers mangrove indirect benefits	Restricted	Restricted (similar to S1)	Restricted

[a]NPB and [b]NEB are denoted as net private benefit objective and net environmental benefit objective, respectively; [c]see Tables 21.1 and 21.2 for mangrove benefits and external costs of shrimp farming.

net environmental benefit increase if the net private benefit decreased slightly) among the land use efficient options. The benefits from the existing land use (ELU) for all scenarios are very close to the efficient levels (the frontiers). However, this does not necessarily mean that the lands are allocated efficiently among activities, as is discussed later.

From the trade-off analysis above, the results presented in Table 21.4 suggest the proper efficient solutions (with high trade-off rates) to be considered further. S1 and S4 give the same results in decision space, i.e. numbers of areas by activities. These two scenarios contribute the same amount of total benefit (net private benefit plus net environmental benefit). However, S4 gives a higher net environmental benefit but a lower net private benefit than S1. This is the consequence of internalizing the external costs.

In S1, S3 and S4, the trade-off between P3 and P4 with respect to shrimp farming and mangrove are significant (see Item 1). P3 of all scenarios implies all existing mangroves should be conserved (11,844 rai or 1,895 ha). If the mangroves were converted, it would entail high marginal costs (shadow costs) in the range of 14,550 to 46,590 THB/rai/year – representing an additional cost borne by society for every single rai of mangrove conversion over an optimum level. In contrast, P4 in S1, S3 and S4 shows that all mangroves can be converted to farms. However, keeping the additional mangrove stand would entail a small marginal cost of 2,319 to 2,578 THB/rai/year.

In order to achieve efficiency, the results also suggest the reallocation of land especially for shrimp farming (see Item 2 and 3). In S1, S3 and S4, oil palm plantation can increase 16–17% of the existing area. Specifically, some existing oil palm plantations can be converted to shrimp farms and some in the mangrove zone to mangrove reforestation, whereas a new

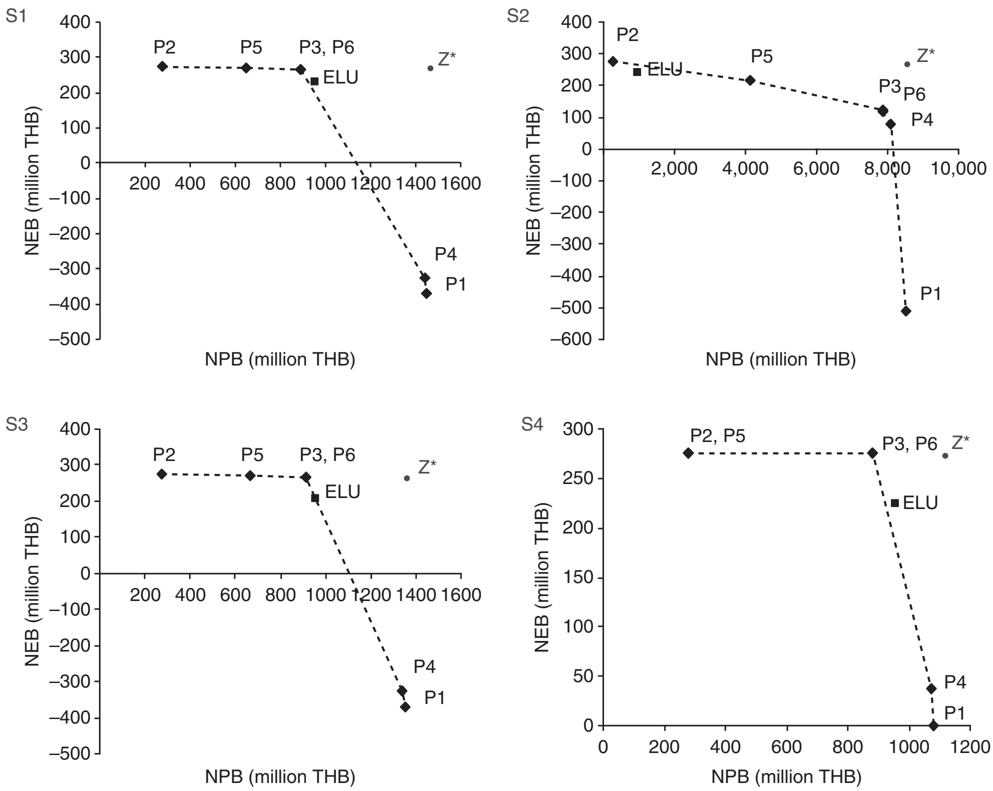


Fig. 21.2. Optimal coastal land use frontiers on objective space according to various scenarios, Krabi Province.
(i) NPB and NEB refer to net private benefit objective and net environmental benefit objective, respectively; (ii) existing land use (ELU) represents the benefits obtained from existing land use; (iii) *Z** is the ideal point of each scenario where both objectives are maximized at the same time.

plantation can be established in the abandoned paddy area. In contrast, S2 suggests the existing oil palm area be reduced by 71%. Given a minimum level of local paddy production, it is suggested that the paddy field be reduced as follows: 25% in S1, S3 and S4 and 47% in S2. Furthermore, there is a slight decrease in rubber plantation, i.e. 3–4% in S1, S3 and S4 but 54% in S2. In short, S2 suggests that vast agricultural lands be converted to shrimp farms. S1, S3 and S4 also show this pattern, but to a lesser extent. Nonetheless, the conversion of paddy production to shrimp farms is not feasible in these three scenarios since there is no access to the receiving waters for effluent discharge because of the surrounding paddy fields.

S2 suggests more than 85% of existing shrimp farms should remain, whereas other scenarios suggest only 15–17% – all farms are located in the aquaculture zone. In addition, S2 shows that the overall number of shrimp farms can increase optimally to much more than the existing number (see Item 4).

The results identify several policy issues. The solution for the dilemma between conserving the remaining mangrove (under the cabinet resolution of 22 August 2000) and developing the mangrove into shrimp farms (which is allowed under the resolution of 15 December 1987) relies critically on the decision maker's preference. Promoting the development coincides with option P4 in S1, S3 and S4, all of which lean towards private benefit, whereas P3 would encourage conservation. However, based on the information on shadow costs and with the uncertainty of land use impacts on coastal systems, P3 is deemed to be a promising proactive option.

Table 21.4. Optimal coastal land use options with high trade-offs in various scenarios, Krabi Province.

Items	Activities	Existing land use 1999 data[a]	S1P3 and S4P3	S1P4 and S4P4	S2P3	S2P4	S2P6	S3P3	S3P4
1. Optimal coastal land use (OCLU)[c] (rai)	Reforest	0	3,644	3,644	3,168	0	2,868	3,644	3,644
	Mangrove	11,844	11,844	0	11,844	11,844	11,844	11,844	0
	Palm	28,164	33,051	33,051	8,064	8,064	8,064	32,606	32,606
	Para rubber	109,105	105,424	105,424	50,420	50,420	50,420	105,121	105,121
	Shrimp	7,184	5,556	17,400	93,040	96,208	93,340	6,482	18,326
	Paddy	11,950	9,006	9,006	6,315	6,315	6,315	9,006	9,006
	Sum	172,851[b]	168,525	168,525	172,851	172,851	172,851	168,703	168,703
2. Changes: OCLU minus ELU (rai)	Reforest		3,644	3,644	3,168	0	2,868	3,644	3,644
	Mangrove		0	−11,844	0	0	0	0	−11,844
	Palm		4,887	4,887	−20,100	−20,100	−20,100	4,442	4,442
	Para rubber		−3,681	−3,681	−58,685	−58,685	−58,685	−3,985	−3,985
	Shrimp		−1,628	10,216	85,856	89,024	86,156	−702	11,142
	Paddy		−2,944	−2,944	−5,635	−5,635	−5,635	−2,944	−2,944
3. Percentage change (%)	Reforest					0%			
	Mangrove		0%	−100%	0%	0%	0%	0%	−100%
	Palm		17%	17%	−71%	−71%	−71%	16%	16%
	Para rubber		−3%	−3%	−54%	−54%	−54%	−4%	−4%
	Shrimp		−23%	142%	1,195%	1,239%	1,199%	−10%	155%
	Paddy		−25%	−25%	−47%	−47%	−47%	−25%	−25%

4. Optimum shrimp farms: conversion of other land uses to farms (rai)	Shrimp	Abandoned paddy field	33	33	4,336	4,604	4,604	39	39
	Shrimp	Mangrove	0	11,844	0	0	0	0	11,844
	Shrimp	Palm	2,634	2,634	20,100	20,100	20,100	3,073	3,073
	Shrimp	Para rubber	1,821	1,821	56,825	58,685	56,825	2,124	2,124
		Shrimp farm 7,184 rai	1,068	1,068	6,176	7,184	6,176	1,246	1,246
	Shrimp	Paddy	0	0	5,603	5,635	5,635	0	0
		Sum	5,556	17,400	93,040	96,208	93,340	6,482	18,326
5. Net benefits (million Baht/year)			S1P3 and S4P3	S1P4 and S4P4	S2P3	S2P4	S2P6	S3P3	S3P4
	NPB	934	890 and 881	1,438 and 1,075	7,860	8,099	7,886	912	1,342
	NEB	222	26 and 276	–326 and 37	122	80	118	265	–328
	NPB+NEB[d]	1,156	1,157	1,112	7,982	8,178	8,004	1,178	1,014

[a]ELU is existing land use – 1999 data, the Office of Coastal Land Development, Land Development Department; [b]including abandoned paddy fields totalling 4,604 rai; [c]compared to the classification of Krabi's CLDZ: aquaculture zone 44,261 rai, mangrove economic zone B 8,322 rai, paddy 66,985 rai and para rubber/palm 53,283 rai; [d]NPB and NEB are denoted as net private benefit objective and net environmental benefit objective, respectively.

The management design based on the aquaculture effluent standard alone, S2 (which is the current instrument being implemented), does not guarantee an environmentally friendly outcome. Although this scheme would encourage mangrove conservation, the results show that the shrimp farm area needs to expand from 7,184 rai (1,149 ha) to more than 93,000 rai (14,880 ha) to reach efficiency. This level of expansion would be beyond the carrying capacity of the receiving waters and overcapacity would not be signalled until a disease outbreak has occurred. This implies that an effluent standard should not be a stand-alone policy.

The combination of zoning with an effluent standard, S3, offers higher optimal shrimp farms than the zoning scheme alone, S1. This results from compliance with an effluent standard, from which a lower discharge of load concentration can be expected. However, the benefits obtained are not significantly different. Using policy S3 would cause unnecessary economic hardship as compared to S1. This implies that S1 is a more promising scheme than S3. However, a better reallocation of the benefits of S1 occurs when a green tax is imposed, i.e. S4. Although the optimum land use patterns do not differ between S1 and S4, S4 leads to a non-negative net environmental benefit since the externalities are internalized.

Lastly, some limitations of the method applied should be noted. The model specified is an abstraction of the real world situation. Only significant variables and constraints were observed in this study. Additionally, the model's formulation is constrained by the availability of data – especially data on the carrying capacity of the receiving waters. Nevertheless, the values of the parameters were estimated conservatively. To relax the assumption and the uncertainty, sensitivity analysis was conducted. The consequences of change in the allowable load for shrimp farming can then be investigated. It shows that when the allowable load of ammonia from shrimp farm discharge is changed, the results also change. That is, increasing the allowable load would increase the optimum shrimp farm area from the base case, some of which results from retaining the existing farms in the aquaculture zone and some from converting the oil palm and rubber plantations. Conversely, the lower the allowable load, the lower the optimum number of shrimp farms.

Conclusions and Recommendations

This chapter presents an analysis of and comments on the environmental policy strategies for coastal land conservation. Management involves deciding the best allocation of land among several competing uses. The optimum options for coastal land use in Krabi Province and their trade-offs were explored. The scenario analysis based on a multi-criteria framework allows the investigation of the efficient outcomes of policy choices on shrimp farm externality management. The results reveal that, in the long run, the effluent standard alone (as being implemented) would not be able to encourage conservation of the natural environment of the coast. Instead, efficient management based on a zoning scheme is found to be a proper instrument to control pollution from farm effluent, but the distribution of benefits and costs to society is not improved without the use of a green tax. This implies that, technically, a zoning scheme should be enough, but socially it is not.

A more stringent policy such as imposing a green tax is recommended as a combined measure with zoning, particularly when decision making tends to lean towards development rather than conservation. The tax would serve as an incentive for polluters to take more responsibility for the damage or potential damage they cause. This would help to induce among the land users more environmentally friendly behaviour. In contrast, it would be difficult for a non-economic incentive-based strategy to do so. It should be noted that the damages caused by cumulative nutrient build-up in the seawaters, mangrove conversion and abandoned farms were considered in the analysis of the tax rates (see Pongthanapanich, 2006). The previous study found that the tax rate on the nutrient effects to the Andaman sea was null, but the taxes should be imposed for the other two items, i.e. mangrove conversion and abandoned farms (see Appendix 21.1 for the different tax rates). Nevertheless, zoning should still be implemented to control nutrient pollution in public water bodies such as canals and estuaries.

Appendix 21.1

Table A. Suggested tax rates and socially optimal production level for Thai shrimp farming.

Items	The Gulf of Thailand (ex-mangrove)	The Gulf of Thailand (outside mangrove)	Andaman (ex-mangrove)	Andaman (outside mangrove)	Total
1. Mangrove tax (THB/rai/year)	14,316	0	17,412	0	
2. Abandoned farm tax (THB/rai/year)	4,377	1,232	5,323	1,371	
3. Discharge tax (THB/t)	16,543	16,543	0	0	
Shrimp production (t)	127,545	9,496	20,682	10,055	167,778

Shrimp farming in ex-mangrove and outside mangrove means shrimp farming in converted mangrove and converted agricultural land, respectively.
Modified from Pongthanapanich (2006).

Notes

[1] The coastal zone is defined as that area bounded by the edge of the watershed and the continental shelf. By this definition, the coastal zone consists of two parts, i.e. land and sea. The coastal land is divided into two areas: (i) the Inner Influenced Zone (IIZ) that is strongly influenced by the sea; and (ii) the outer influenced zone that covers the outer area of the IIZ up to the watershed, which is influenced by fresh water. The CLDZ, according to the definition of the Land Development Department, covers every single subdistrict that falls within the IIZ.
[2] These comprise agriculture (paddy, orchard, para rubber, oil palm, coconut, horticulture, pasture, aquaculture), forest, urban area, military area, conservation area, swamp, beaches, mud flat, islands, mountains, abandoned mining area, salt pan, peat and water body.
[3] The project was funded by the Global Environment Facility (GEF) and implemented by the United Nations Environment Programme (UNEP) in partnership with seven riparian states bordering the South China Sea (Cambodia, China, Indonesia, Malaysia, Philippines, Thailand and Vietnam). The project became fully operational in February 2002. The overall goals were to create an environment at the regional level that fostered and encouraged collaboration and partnership in addressing the environmental problems of the South China Sea, between all stakeholders and at all levels, and to enhance the capacity of the participating governments to integrate environmental considerations in national development planning.
[4] The terms 'efficient solution', 'Pareto optimum', 'non-dominated' or 'non-inferior' solution are used interchangeably in the relevant literature.

References

Barbier, E.B. and Sathirathai, S. (eds) (2004) *Shrimp Farming and Mangrove Loss in Thailand*. Edward Elgar, Cheltenham, UK.

Baumol, W.J. and Oates, W.E. (1988) *The Theory of Environmental Policy*. Cambridge University Press, New York.

Cohon, J.L. (1978) *Multi-objective Programming and Planning*. Academic Press, New York.

Howarth, W., Hernandez, R.E. and Houtte, A.V. (2001) *Legislation Governing Shrimp Aquaculture: Legal Issues, National Experiences and Options*. FAO Legal Paper Online No 18, FAO, Rome (www.fao.org/legal/Prs-OL/lpo18.pdf, accessed 4 June 2009).

Kantangkul, P. (2002) Impact of shrimp farming on arable land and rehabilitation of resultant salt-affected soils: socio-economics and agricultural economics aspects. Final report, FAO Project TCP/THA/8922, Rome.

McDorman, T.L. (2000) Final report on legal advice to Thailand. FAO/FISHCODE Project. GCP/INT/648/NOR: Field Report C-4. FAO, Rome.

OAE (Office of Agricultural Economics) (2007) *Basic Information: Agricultural Economics, Year 2550*. Agricultural Statistics Document No 413. Ministry of Agriculture and Cooperatives, Bangkok [in Thai].

OEPP (Office of Environmental Policy and Planning) (1998) *Cabinet Resolutions and Laws in Relation to Coastal Resource Management*. Ministry of Science, Technology and Environment, Bangkok [in Thai].

Pongthanapanich, T. (2006) If Thai shrimp were taxed, how much should it be? *Aquaculture Economics and Management* 10(2), 147–162.

Pongthanapanich, T. and Roth, E. (2006) Voluntary management in Thai shrimp farming. *Aquaculture Economics and Management* 10(3), 265–287.

Rayanakorn, K. (2006) *The Legislation of Economic Instruments for Environmental Management in Thailand*. National Health Foundation Bangkok [in Thai].

Sathirathai, S. (1998) Economic valuation of mangroves and the roles of local communities in the conservation of natural resources: case study of Surat Thani, South of Thailand. Research report submitted to Economy and Environment Program for South-east Asia (EEPSEA), Singapore.

Sathirathai, S. and Barbier, E.B. (2004) Comparative returns of mangroves for shrimp farming and local direct and indirect uses in Surat Thani Province. In: Barbier, E.B. and Sathirathai, S. (eds) *Shrimp Farming and Mangrove Loss in Thailand*. Edward Elgar, Cheltenham, UK, pp. 210–230.

Thailand National Committee (2003) *Legal Aspects and Institutional Framework Regarding Coastal Wetlands in Thailand* UNEP/GEF/SCS/RTF-L.1/11.

UNEP (The United Nations Environment Programme) (2004) Reversing environmental degradation trends in the South China Sea and Gulf of Thailand. Report of the Second Meeting of the Regional Task Force on Legal Matters. UNEP/GEF/SCS/RTF-L.2/3.

UNEP (The United Nations Environment Programme) (2005) Reversing environmental degradation trends in the South China Sea and Gulf of Thailand. Report of the Third Meeting of the Regional Task Force on Legal Matters. UNEP/GEF/SCS/RTF-L.3/3.

Yu, P.-L. (1985) *Multiple-Criteria Decision Making: Concepts, Techniques, and Extensions*. Plenum Press, New York.

22 Conflicts and Governance: Perspectives on an Eastern and Western Coastal Wetland in India

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Abstract
Governance in the current context demands a plurality of actors in decision making drawn from the spheres of state, civil society and business. There is an inherent assumption of harmony among these spheres leading to complementary outcomes in 'good governance'. In the real world, however, conflict is the norm rather than the exception. Hence, this study takes natural resource conflicts as an entry point to understand the larger theoretical and empirical aspects of challenges to governance. It compares the process of environmental degradation, conflicts because of competing land uses and challenges for governance in two of the largest wetland lagoons on the eastern and the western coasts of India. It will map the actors, their interests and stakes in the conflicts and examine ways and means of resolving them. This is expected to throw light on the central theme of the problem of governance in natural resources management, particularly the role of the state in a situation where multiple stakeholders and competing interests are involved.

Introduction

Potential and dormant conflicts are always inherent features of natural resource management. When competing interests claim control of particular resources, conflicts are manifested and these can then assume a myriad of forms. Sometimes, conflicts lead to immobility that in turn generates more intense conflicts later. This calls for developing a more comprehensive understanding of conflicts in terms of the structural conditions of their genesis, evolution, the actors involved and their changing stakes as a prerequisite to reflecting on issues related to the governance of natural resources. The governance challenge regarding natural resource use is to balance the need for economic growth with the demands and aspirations of different social groups, future generations and the environment.

This chapter discusses and compares the process of environmental degradation, conflicts because of competing land uses and challenges for governance in two of the largest wetland lagoons on the eastern (Chilika lake) and the western (Vembanad lake) coasts of India (see Narayanan, 2009a). These lakes form the outfall in the delta that is the confluence of four rivers in Kerala and three rivers in Orissa. The major aims of the chapter are to illustrate: (i) the twin process of environmental degradation of the biophysical system and social marginalization of sections of people directly dependent on the lakes resulting from a process of capitalization of resources; (ii) the evolution of conflicts by mapping the actors involved; (iii) the fragmented nature of (state) governance structures, which are unable to grapple successfully with the conflicts; and

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(iv) identification of the levels, nature and role of appropriate governance structures for the integrated management of the lakes.

The methodology is qualitative, involving in-depth field data collection after a review of the relevant literature. The fieldwork for the Vembanad study was undertaken in 2003 and the Chilika study was undertaken in 2007. The Vembanad study was more comprehensive and involved multiple visits, and was a follow-up and part of a larger study (Narayanan, 2003). The conclusions from this study pointed to the need for intermediate level (between state level and local level) governance structures for the management of natural resources – in the Vembanad case, this should be at the lake level. A review of the literature for Chilika reveals that the biophysical system, multiple uses and nature of conflicts are similar (although the multiplicity of uses, interests and interplays make Vembanad much more complex). The major difference is the presence of a governance structure, namely the Chilika Development Authority (hereafter CDA), as conceived in the recommendations of the earlier study on Vembanad. Therefore, the course of action suggested for Vembanad was already available in Chilika. Hence, the fieldwork on Chilika focused on two major issues – conflicts and the effectiveness of the CDA as an intermediate level governance structure.

The chapter is organized as follows. The next section highlights the commonalities between Vembanad and Chilika, followed by a discussion of the nature, history and interests involved in the conflicts in the two lakes. The subsequent section reflects on the implications for governance, by first identifying the major issues from Vembanad and then comparing them with Chilika, especially the effectiveness of the CDA.

Chilika and Vembanad: Overview of Commonalities

Wetlands are very productive ecosystems and perform various ecological functions such as maintaining underground freshwater levels and aquatic gene pools, and regulating water temperature and nutrient levels for aquatic fauna. They hold rainwater and minimize the impacts of floods and drought, prevent salinity intrusion in coastal areas and check coastal erosion. Wetlands have multiple uses and thus support millions of livelihoods, especially those of 'ecosystem people' (see Gadgil and Guha, 1995) like fishers, entirely dependent on the productivity of such systems. Wetlands are recognized internationally as areas rich in biodiversity, but are shrinking rapidly and significantly because of conversion to various other land uses. Considering the importance of wetlands as vital habitats, the Ramsar Convention has recognized nine Ramsar Sites in India, which also face grave environmental degradation that has consequences for the livelihoods of those who depend on them.

Chilika and Vembanad lakes both fall inside river deltas. Freshwater runoff from the rivers that drain into the lakes gives them an estuarine character, whereas the connections with the sea make them lagoons (hereafter, however, we simply refer to them as lakes) with saltwater inflows. Because of their being part fresh water and part saltwater, a wide range of fresh, brackish and saltwater environments exists within the lagoons. This results in very high productivity and the presence of a variety of habitats that allow the proliferation of a large number of species, including a host of migrating birds in search of wintering sites. Both lakes harbour an assemblage of marine, brackishwater and freshwater biota, a number of which are now listed as endangered, threatened or vulnerable by the IUCN. On account of this rich biodiversity and increasing threats to the environment, Chilika was designated as a Ramsar Site in 1981 and Vembanad in 2002. The marshy tracts of Nalabana Island in Chilika Lake and Pathiramanal Island in Vembanad Lake are notified bird sanctuaries, with the entire wetlands identified as priority sites for conservation and management by the Ministry of Environment and Forests, Government of India. Because of their scenic beauty, both lakes support flourishing tourism industries that in turn generate a heavy load of waste, which pollutes the lakes. The hundreds of boats and speedboats that crisscross the lakes take a heavy environmental toll on the ecosystems. The most important socio-economic feature is that both lakes support fisheries that are a lifeline to tens of thousands of fisherfolk and which contribute significantly to India's international trade.

Vembanad Lake, a part of the Vembanad–Kol coastal wetlands in the south central part of Kerala state, is a low-lying area with backwaters, canals and stream networks. The Achencoil, Pamba, Manimala and Meenachil rivers, originating from the eastern hills, discharge their water and sediment into Vembanad Lake, the largest brackishwater body in southern India. The backwaters are connected to the Arabian Sea, which brings tidal influence and seasonal salinity into the system, a sizeable area of which lies below sea level. A highly fertile tract of land replenished by silt brought by the river systems, the area has been well suited to rice cultivation since earlier times. Reclamation of land for cultivation and flood control used to be undertaken by private farmers, with assistance from the state (Pillai and Panicker, 1965).

Chilika Lake is the largest lagoon in Asia, spread over the three coastal districts of Puri, Khurda and Ganjam. Hydrologically, three major rivers influence Chilika – Mahanadi, Rushikulya and Bhargavi. Apart from the biodiversity and ecological peculiarities illustrated in Table 22.1, Chilika Lake sustains the livelihoods of more than 200,000 people living in the 141 villages around it. Capture fisheries, the traditional livelihoods of traditional fishers, is organized through 92 primary fishery cooperatives. Six types of traditional fishing methods are practised (see Ghosh and Pattnaik, 2006, p. 118 for details).

Both lakes face similar processes of environmental degradation. Their area and depth are being reduced as a result of siltation from inflow. Salinity-related problems (such as decline in the stock of fish and prawn) is also serious in both lakes. Clogging of the mouth and salinity-related problems are compounded in Chilika with the variations in freshwater inflow through rivers because of the development of dams upstream. In Vembanad, the construction of a salinity barrier, which is being operated ineffectively, has affected the system. Because of the dwindling

Table 22.1. Some relevant features of Chilika and Vembanad Lakes.

	Vembanad–Kol wetland	Chilika Lake
Area (km^2)	1591	906–1165
Location	Kerala State in South India	Orissa State in East India
Coverage: spread over three districts	Alleppey, Pathanamthitta, Kottayam	Puri, Khurda, Ganjam
Declared as Ramsar Site	2002	1981
Ecosystem	Lakes connecting rivers (estuarine) and sea (lagoons) rich with an array of freshwater and marine flora and fauna including migratory birds and mangroves	
Biodiversity of estuarine lagoons	The estuarine zone and organically rich sedimentary substratum of the inshore region makes it a highly preferred habitat for shrimps, finfish, shellfish, a nursery of several species of aquatic life and a transitional ecotone between sea and land. Spotbilled pelican is the third largest population of more than 20,000 waterfowl with 91 species of resident/local migratory birds	As an estuarine lagoon, it supports several endangered, rare, threatened and vulnerable species such as the Irrawady dolphin, dugong, green sea turtle and spoonbill A survey revealed an overall 706 species of flowering plants belonging to 488 genera and 119 families. The Zoological Survey of India reported over 800 species with 217 fish species and 37 species of reptiles and amphibians
Environmental degradation	Decreased depth and freshwater flows, decline in biodiversity, increased pollution levels (agriculture, industrial, domestic sources)	
Livelihood crisis	Fish catches have declined	

Compiled from World Wildlife Fund India (2006) and Ghosh and Pattnaik (2006).

of salinity, the area covered by invasive weed species has increased. The weeds restrict the movement of juvenile prawns from the sea to the lagoon and reduce the area available for breeding and spawning of some important fish varieties. Hence, biodiversity has decreased and fish catches have also declined. Traditional fishers are the people most affected by these ecosystem changes. Agricultural pollution, an externality of high-input cultivation coming from upstream in Chilika, and polder cultivation of rice in the periphery of Vembanad have affected the ecosystems of both lakes seriously. The early 1990s saw the mobilization of fisherfolk against the seasonal closing of the salinity barrier in Vembanad and enclosures for prawn culture in Chilika. The protests led to law and order problems that have been recurring periodically.

Conflicts

The conflicts in both the Vembanad and Chilika lakes result from the twin processes of the environmental degradation of the biophysical system and the social marginalization of sections of people who are directly dependent on the lakes for their livelihoods. The major trigger of conflicts is the capitalization of resources by powerful social groups. This section illustrates the evolution of conflicts with a mapping of the actors and interests involved.

Conflicts in Chilika Lake as a result of the enclosure of the commons

A change in government policy regarding the leasing of fishing rights that served to hamper the access of traditional fishers to fishing grounds and which also gave rise to shrimp culture that enclosed portions of the lake was the major trigger of the conflicts. Because of the rich fisheries resources, a large number of people have been dependent on capture fisheries in Chilika, and these are the traditional fishers (TF). From 1959, the rights for fishing were traditionally communal and the Central Fishermen Cooperative Marketing Society (CFCMS), a federation of primary societies of fishers, was given the lease rights for fishing. The CFMCS subleased these rights to primary cooperative societies of traditional fishers. This ensured that the fishing right remained within the community of TF. In the 1980s, the demand for prawn in the export market attracted people to engage in culture fisheries, basically shrimp culture in Chilika. The most daring example of such capitalization was a proposal by the TATA group to start prawn culture in a large area in Chilika in 1985. A major campaign against this proposal was launched by the trade union of traditional fishers – Chilika Matsyajeebi Mahasangh (CMM) – which received wide support from other sections of society, especially the student movement under the leadership of Bhaktaveer Das. The TATA group had to withdraw the proposal because of popular resistance. This prompted the movement to push the campaign further to include the removal of all culture fisheries from Chilika.

Until 1990, very few leases were given to non-fishers. Those that were granted were for domestic consumption. In 1990, the state government decided to start aquaculture in Chilika Lake and formulated a new leasing policy. Chilika was to be divided into zones for capture fisheries (for TF) and culture fisheries (for non-fishers). TF societies approached the High Court of Orissa to protest this zoning scheme. The High Court verdict was that even if the TF had sole customary rights, non-fishers were engaged in fishing in the lake and hence came out with a ruling that 'balanced' the claims of the competing parties. Of the 47,000 acres, 27,000 acres were to be assigned for capture fisheries. Of this amount, 14,000 acres were to be given to non-fishers for capture fisheries. This in a way legitimized the illegal capture fisheries practised by non-fishers and triggered a series of protests by the TF. The pertinent question posed by the legal adviser of CMM was that since fishing in Chilika Lake was a hereditary right on common property, how could the state subdivide this right to an outsider? The state, it was claimed, was intervening in the customary rights of poor fishers when the opportunity for lucrative culture fisheries was opening up. The major problem with culture fisheries is the construction of enclosures that reduce the area available for capture fisheries and privatize and capitalize the lake, leading to environmental degradation and a livelihoods crisis. Over a period of time, large areas of capture fisheries were encroached illegally and turned into culture fisheries by powerful people who were mostly based in the state capital, and who invested through local people. It is essentially a victory of the greed of the influential elites over the livelihoods of the marginalized.

In 1993, Khalamuha Fishermen's Cooperative Society approached the High Court of Orissa to protest against the illegal prawn culture in Chilika Lake. A fact-finding mission was appointed under the chairmanship of Dr Ghanashyam Das. He reported that those who were involved in this were powerful, possessed weapons and that it was the duty of the state to end this practice since it was growing into a societal menace. The government did not take any action. The TF continued agitation under the auspices of the CMM and demanded that the government place a total ban on all unauthorized shrimp culture in the lagoon. In spite of the Supreme Court Order in 1996 to ban shrimp culture within 1000 m of the high water line of Chilika (related to the Coastal Regulation Zone Act of the Government of India), the state government did not do anything to stop this practice. Its inaction was partly because of the composition of the people engaged in shrimp culture: they were usually powerful sections of society and had strong links to the state. The Orissa Vidhan Sabha (state legislative assembly) appointed a committee in 1997 with Mr Debendra Singh as Chair to investigate the matter. It was concluded that all culture fisheries should be stopped and the rights of traditional fishers in Chilika Lake be re-established. There was no follow-up action from the government. Hence, even with all the legal weapons in the hands of the state, the government did not act to curb the illegal culture fisheries in the lake.

The breaking point happened when the state leased the lake area near Kalijayi (named after a legendary goddess of the fishers) to a high-ranking ex-bureaucrat. The CMM decided to 'recapture' Kalijayi. The TF went in 200 boats and symbolically recaptured the site and put the following demands to the state: (i) ban prawn culture; (ii) form a trust comprising of TF to manage Kalijayi; and (iii) release all traditional capture fishery areas from illegal culture fisheries. Seeing the opportunity in such a mobilization to address also the issue of prawn culture, the CMM gave an ultimatum to the government in 1999 to remove all illegal prawn culture *gherries* in 15 days, after which time they would start clearing the *gherries* themselves. On 29 May 1999 after one such operation, the CMM activists conducted a press conference to clarify their position and protested to the general public. That same night, without provocation, the police fired on the activists who were staying in Soran village. Four people died on the spot and one died later, and several were injured. The government appointed a commission of enquiry to examine this incident with Justice P.K. Tripathi as Chair. Armed with the information that a bill legitimizing culture fisheries in the lake – the Chilika Regulation Bill 2002 – might be tabled, the CMM submitted a memorandum to the Chief Minister demanding a complete ban on prawn culture and the entry of non-traditional fishers to the lake. The Bill was first proposed in 2001 and cleared by the State Cabinet. However, it was held back because of fierce opposition. Introduced again on 26 March 2002, it was referred to a Select Committee of the House on 3 April 2002, with instructions to submit a report by the end of the eighth session of the 12th State Assembly in 2003. The Committee considered the Bill's general features, then went over it clause by clause and finally submitted a report which was approved on 9 December 2003. However, the strength of the people's movement prompted the state government to defer passing the Bill once again (Pattanaik, 2005). These events clearly show the state's eagerness to legitimize culture fisheries, but also the strength of the people's movement to prevent this happening.

Conflicts in Vembanad Lake because of rice-centric development

Lake Vembanad serves as an extensive nursery ground for marine prawns and sustains a lucrative fishery. For centuries, fishing has been an important occupation for the local population.

There are both subsistence and commercial fisheries in the backwaters. However, almost all the (state) development interventions in Kuttanad were oriented towards making it into a rice-centric economy. In order to promote double cropping in the region, two engineering structures were suggested: a spillway to drain off the flood waters and a barrier to check the intrusion of saltwater. The salinity barrier was meant to limit the damage caused by the high spring tides in November and saltwater intrusion in February–March. It was thought that the growing season could be extended and cropping intensity increased. Rice cultivation, traditionally systematized in tune with nature's rhythms (of monsoon floods and summer salinity), however, was disrupted by the engineering interventions. Staggering of the crop season and the resultant lack of discipline in rice cultivation after the construction of the salinity barrier has affected the natural balance of the system (KWBS, 1989).

The periodic tidal flow, which used to flush the water body, has been prevented completely. Consequently, the water drained off from the rice fields, containing large amounts of pesticide and fertilizer residues, remains stagnant. Widespread fish mortality was reported in Kuttanad in 1990 and studies suggested that deterioration of the environmental quality of the system was the prime reason (Nair and Pillai, 1993). The progressive reduction of salinity and degradation of the system has led to the decline or disappearance of several fish species. Increasingly, the fisheries resource depletion has threatened the livelihoods of fisherfolk in the region. Thus, the activities carried out by fishers and farmers are in conflict, as seen particularly in the controversy regarding the operation of the salinity barrier.

The western side of Vembanad Lake is dominated by fishers. In earlier times, they were mobilized politically on class/occupational lines by the communist parties. However, their number and their financial, political and social power remain inferior to the vocal group of farmers and agricultural labourers. Rice cultivators dominate the eastern part of Vembanad Lake. The farmers and agricultural labourers are organized interest groups which are numerically, financially and socially more powerful than the fishers. The fishers would like the barrier to be fully open by November–December, since the tidal flow into the lake is intense and carries fingerlings into the lake. When the barrier is closed, this tidal action is lost and many important types of fishing gear, which take advantage of the tidal flow of water, cannot be used. The progressive reduction in catch over time has alerted the fishers to the negative impacts of the barrier.

The farmers argue for closing the barrier prior to the high tidal flow so that their embankments are protected. Their crops are staggered, mainly because of the delay in the harvest of the rice they have cultivated, and that in turn delays the opening and closing of the barrier, which affects the fisherfolk. The interests of the two sections are thus in conflict. The steady fall in the catch and the increase in price have led the fishers into direct conflict with the rice farmers. The salinity barrier is generally closed in November–December to facilitate early sowing of the rice crop. The conflict has come to revolve around the closing of the barrier after the monsoon in November–December. Table 22.2 summarizes the actors and strategies in the conflict.

The usual procedure for closing the barrier starts with the issuance of a notification by the Public Works Department (PWD) of the

Table 22.2. Points of rupture in the conflict.

Fishers	Farmers
Demand early opening to use tidal flow (otherwise cannot operate many fishing gears) and for salinity in the system	Demand late opening and closing because tides affect embankments. Harvest is delayed because of non-availability of labour and salinity poses risk of crop loss
Do not allow closure: (i) protest; (ii) bribes; (iii) obstruction	Lobbying politicians
Supported mainly by Dheevara Sabha	Support of all major political parties

Kerala government. However, fishers frequently make representations to stop the barrier from being closed or often physically prevent Irrigation Department personnel from closing the shutters of the barrier; it is only after the intervention of the civil administration and the police that the shutters can be closed. In most years when their representations have not have the necessary effect, physical obstruction has been resorted to, with the fishers diving down to the bottom of the lake to lay stones to prevent the barrier closing fully. A law and order problem has thus been created, the resolution of which often becomes the responsibility of the District Collectors of Alleppey and Kottayam districts falling on either sides of the Vembanad Lake. Although the opening of the barrier is fixed for 15 March, because of the standing crops in some area, it is often delayed until May. This affects the livelihoods of the fisherfolk adversely. However, the societal power relations ensure that the rice farmers' concerns get preferential treatment compared to the fisherfolk, already disadvantaged by their caste, class and political position in the social structure. The last days of 2001 and the beginning of 2002 witnessed an uprising by the fisherfolk in Kuttanad demanding the permanent opening of the salinity barrier.

The Hindu fishers belonging to the backward Dheevara caste are inland fishers who traditionally fish in the Vembanad Lake. Dheevara Sabha's activism against the salinity barrier began to intensify in the late 1990s. From 1975 to 1992, the salinity barrier was never opened before May (although it is supposed to be opened by the end of March). This was because the farmers delayed the rice harvest and because of the political clout of farmer organizations, which were able to influence the government. During this time, there was a steady decline in the fish catch. In 1991, because of widespread fish disease and the environmental degradation of the lake caused by the salinity barrier being closed, it was opened by April. The early opening showed a perceptible change in fish availability, which prompted the fishermen's associations to press for an annual early opening of the barrier. But, from 1996, it was again delayed. The mobilization and protests of the Dheevara fishers intensified.

There were visible and covert forms of conflict. Whereas the fishers tried to obstruct the closing of the barrier by putting large stones under it, the farmers demonstrated on land, usually by disrupting road traffic. Strategies also differed between the groups. The farmers, with their political clout, tried to lobby the politicians so as to influence the operation of the barrier and sometimes took their agitation to the street. They used sound media management tactics, with regular reports and features referring to an 'agricultural collapse' in the region. The fishers' strategies were more visible, with street and boat demonstrations. They also had covert strategies, such as obstructing the closure of the barrier by putting stones below the shutter and bribing lower level staff in charge of the barrier operations. One fisherman was killed when he was trapped while placing a stone under a closing shutter. Regular police patrols on land and by boat were introduced after this incident to make sure that the shutters were not tampered with.

The last days of 2001 and the beginning of 2002 witnessed a massive uprising by the fisherfolk against the salinity barrier. The government appointed a committee with members who were District Collectors, Members of the Legislative Assembly (MLAs), Members of Parliament (MPs), district officers of government departments and representatives of fishers and farmers belonging to various political parties. A democratic forum was thus created for negotiation. In spite of the negotiating forum, the political imbalance mentioned earlier made sure that the operation of the barrier was not timely, and thus weighed heavily against the interests of the fishers. The backdoor lobbying of farmers within the political realm was much more effective than the visible agitation strategies adopted by the weaker group of fishers.

The fishers, though a marginalized group, were powerfully mobilized, with their culture playing a major part ('Hindu fishermen who have a traditional right over fishing in Vembaband Lake'). The small size of the group and the homogeneity of its membership were strengths supporting their effective mobilization. Constant pressure tactics (including opportunistic politics) to achieve their ends also helped them further their struggle. The committee for 'optimum' solutions was the first step in negotiations. Consistent data generation and technical knowledge of the depleting fish stocks by scientists and environmentalists gave legitimacy to their cause. With this, the pressure tactics mounted, especially with the disruption of closure in 2001, and the permanent opening of the barrier was demanded.

The government then appointed a commission of enquiry with a scientist as Chair. Meanwhile, there were a host of studies conducted by scientific institutions that highlighted the depletion of the fisheries stock and the pollution of Vembanad Lake. Many studies pointed to the negative effects of prolonged closure of the salinity barrier. The commission, after examining these data and conducting wide consultations, arrived at the conclusion that timely operations with a 3-month closure period (as originally conceived by the project) would be the optimum solution in order to balance all the competing claims. For the past 4 years, salinity barrier operations have been optimized, bringing into fruition the protests and mobilization of the fishers.

Implications for Governance

The governance of natural resources is problematic because of often-conflicting economic, sociocultural and environmental values, and because of the political influence of the various interest groups involved. Any natural resource use which emphasizes one value at the expense of another may invite resistance, and thus conflict. Natural resources do not conform to political boundaries and this may lead to spatial discrepancies and conflict. The nature of the resources and demography demand that the level of administrative jurisdiction for each governance structure has to be clarified. This discussion of governance is limited to case studies, which may provide some pointers on the larger issue of the governance of natural resources. As mentioned earlier, the conclusion of a study undertaken earlier in Vembanad (Narayanan, 2009b) clarified the need for a coordinating body at the lake level. The presence of the Chilika Development Authority (CDA) prompted this study of the effectiveness of such a coordinating institution for governance. The strong biophysical parallels and the nature of conflicts also offered scope for comparison. Hence, the arguments in this section are presented in sequence – the problems shown by Vemabanad followed responses in Chilika because the presence of a coordinating institution like the CDA is the focus. Governance issues are discussed from the perspectives of administrative/techno-managerial efficiency and social justice, which provide competing prescriptions.

Governance – administrative and techno-managerial

Coordination of sectoral agencies

It is clear that there is fragmentation of governance structures in both lakes. Sectoral interests dominate the priorities of 'line' departments (at state level) such as departments of agriculture, fisheries, tourism and forest and environment. Both the Chilika and Vembanad lakes partly fall in three districts. In the Vembanad case, there is an interesting conflict of interests between the revenue administrations on the two sides of the lake, and also between the departments of agriculture and fisheries centred on the operations of the salinity barrier. The respective District Collectors, MLAs and MPs on different sides of the lake try to represent and pursue the interests of their dominant constituencies. The Department of Agriculture highlights the interests of farmers, the Department of Fisheries the interests of fishers (including the environmental externalities). The Department of Irrigation is caught in the crossfire between the interests of the farmers and the fishers. It is always caught on the horns of a dilemma as it operates the opening and closure of the salinity barrier. The Kerala Water Authority (KWA) requires the salinity barrier to be closed for freshwater availability. The Regional Agricultural Research Station (RARS) is responsible for monitoring salinity intrusion into the lake. The closing date of the salinity barrier is supposed to be fixed, based on objective scientific data. However, in practice, the political process described earlier guides the barrier's operation. Thus, horizontal sectoral divisions with the 'line' department approach of the government system with different ministers (at federal level) heading their empires are a major problem. The departments function within narrow defined technical programmes, which may be counterproductive to the larger natural resource system. This horizontal differentiation within the state apparatus gets a spatial dimension when District Collectors and local government institutions from different sides of the region take opposing stances in the conflict. In Vembanad, there is a complete failure of coordination.

In Chilika, the Government of Orissa created the Chilika Development Authority in 1992 as a coordinating institution to balance the various claims of people dependent on the resource and facilitate effective liaison with the government and other agencies involved in the management of Chilika. The management of Chilika was through the revenue, fisheries, tourism and forest departments involved in respective sectoral activities. The CDA was created primarily to protect the unique lagoon ecosystem and to coordinate multiple institutions for coordinated resource management. This was a response to the inclusion of Chilika in Ramasar's Montreux record of degraded wetlands. Since its genesis was related primarily to the environmental degradation faced by the lake, the Forest and Environment Department was given administrative jurisdiction of the CDA with a governing body composed mainly of bureaucrats and people's representatives (see Box 22.1 for details). The CDA is supposed to work with flexible procedures, unlike a government department, to restore the ecosystem with the backing of academic studies and biophysical interventions, coordinating the work of departments and, most importantly, taking on board the aspirations of the local people by working through NGOs and CBOs. According to Ghosh and Pattanaik (2006), the institutional framework of Chilika is based on a principle of multisectoral collaboration, with the CDA playing the role of central coordinating agency. They feel that much more statutory powers are needed for it to rise to the level of an agency that can diffuse conflicts arising from the overlapping authority of agencies. However, what they do not seem to realize is the lack of any mechanism for local people's voices to be represented

Box 22.1. Governing body of the Chilika Lake.

Governing Body Members of the Chilika Development Authority

Chairman

1. Chief Minister, Orissa

Members

2. Member of Parliament, Puri
3. Member, Orissa Legislative Assembly, Brahmagiri
4. Member, Orissa Legislative Assembly, Chilika
5. Chief Secretary to Government, Orissa
6. Agriculture Production Commissioner, Orissa
7. Secretary to Government, F & E Department
8. Secretary to Government, Home Department
9. Secretary to Government, F & ARD Department
10. Secretary to Government, Tourism Department
11. Secretary to Government, Revenue Department
12. Secretary to Government, Finance Department
13. Chief Wildlife Warden, Orissa
14. Director, Environment and Special Secretary, F & E Department
15. Collector, Puri
16. Collector, Khurda
17. Collector, Ganjam
18. Dr (Mrs) Priyambada Mohanty Hejmadi
19. Dr C.L. Trisal, Director, WISA
20. Nominee of Ministry of Environments & Forests, Government of India

Member-Convener

21. Chief Executive, Chilika Development Authority

in the CDA. This is evident from the structure of the governing body, with representation mostly by officials (17) and influential politicians (4).

Political economy of policy formulation and implementation failure

Apart from issues such as administrative coordination, the larger structure under which policies evolve and programmes are implemented is also important. Scott (1998) criticizes the overt preoccupation with efficiency as revenue maximization and the related problems of social marginalization. Governance, in conventional thinking, focuses on efficiency-oriented programmes such as boosting rice production for larger social needs to ensure food security, which the state has to ensure. Rice-centric planning by the state in the Vembanad case led to a large-scale transformation of nature. The large engineering interventions necessitated central planning and coordination of institutions and disciplined action by farmers (like systematizing cultivation to facilitate the recommended timely operations of the salinity barrier).

The lack of capacity of the administrative machinery to plan and implement the centralized design is evident. Hence, there was systematic dilution in the technical plan to rationalize operations of the salinity barrier by restricting closure to the peak season of the crop calendar. Such exact technical blueprints may fail to be implemented in a social structure where the dominant groups such as farmers may not conform to the regulatory framework of the state. Farmers' political clout and their non-conformance with the crop calendar, especially timely harvesting, led to the early closing and late opening of the barrier, affecting the lake's ecology adversely and the marginal occupations dependent on it. The rent-seeking tendencies of officials and political interference with their working are additional stumbling blocks. Here, we note the discrepancy between technical blueprints for governance and the societal power relations that thwart their realization. Uncertainty regarding nature's processes is another constraint. The unintended consequences of the construction of the salinity barrier in Vembanad only surfaced after a decade.

The opening of a new lagoon mouth was the CDA's most important physical intervention, with technical studies and recommendations by the National Institute of Oceanography and the Central Water and Power Research Station (CWPRS). According to the CDA, this has improved the hydrology, decreased invasive freshwater weeds, improved biodiversity, reduced silt loading from catchments and increased fish catches, and thus the incomes of fishers. However, there are warnings from biological scientists and environmentalists on some unintended consequences of the technical intervention of opening the new mouth in Chilika. Biologists are wary of making the ecosystem completely marine by allowing the free flow of tides into the lagoon. This could affect the freshwater biota in the system and change the character of the ecosystem. There are also concerns about the danger of flooding low-lying villages in the event of high waves such as a tsunami because of the open mouth of the lagoon (Dr G.K. Rao, Institute of Education, Bhubeneswar, 2007, personal communication). Environmentalists have already pointed to the destruction of many grass species that cannot tolerate such high levels of salinity. Such species are important for the numerous migrating birds that feed on them. The change in flora resulting from the change in salinity has affected the distribution of birds seriously. They also highlight the livelihood crisis of fishers in the nearby villages where the new mouth was opened. These fishers cannot engage in fishing because of the enhanced tidal effects (Mr Biswajeet Mohanty, Secretary, Wildlife Society of Orrisa in Cuttack, 2007, personal communication). They point to the unscientific nature of the CDA intervention, which was not preceded by proper modelling studies, with evidence of new deposition of sediments in the middle of the new lagoon mouth.

In the Chilika case, there was a clear policy bias from 1991 onwards to legitimize culture fisheries by the state. Such bias is continuing with the new industrial policy (see Das and Narayanan, 2009) and the latest bill drafted in 2002 (the Chilika Regulation Bill), designed to legitimize culture fisheries, that the government tried repeatedly to table in the state legislature. The class composition of people engaged in culture fisheries and the close links to state machinery are evident. This explains the repeated failure to implement the recommendations of a commission of enquiry by the Orissa High Court, Legislative Committee and a Supreme Court Order to ban culture fisheries. It also highlights the ineffectiveness of the 'ceremonial' removal of *gherries* by the Revenue Department: these return within days of removal. In the Government of Orissa's newly proposed bill, the Orissa Fishing in Chilika (Regulation) Bill, the District Collector can grant leases to the Orissa State Fishermen Cooperative Federation Ltd. It is also mandatory to communicate the details of such leases or subleases to the CDA. Thus, the bill has identified the CDA as the central authority empowering it to make regular inspections, demolish illegal structures, search and seize any article of objection and seek the help of police wherever needed (Ghosh and Pattnaik, 2006). With hindsight, it is clear that it is not the absence of policies or rules but the structure of governance that ensures implementation failure. The CDA as a governance structure is striving to gain control over governance, with the demand of bringing the line department officials in the jurisdiction of the lake under the CEO's administrative control. However, for such techno-managerial plans to be effective, accountability of government institutions has to be ensured. Only then will democratic governance flourish and equity issues be addressed seriously.

Governance: with social justice

Although governance with a distinct focus on efficiency can bring numerous benefits, a criticism is that the dominant groups' interests tend to be privileged. In the case of Vembanad Lake, in spite of a technical blueprint and widespread consensus about the need for rational operation of the barrier, lobbying by powerful farmers cleared the way for their interests to be privileged in decision making. The case of continuation and enhancement of culture fisheries in Chilika Lake is similar. However, equity concerns become important in governance from the perspective of democratic citizenship (Chandoke, 2003). In the spectrum of actors including the state, civil society and the market, the democratic citizen can expect justice most aptly from the state, and hence the need to define the role and scope of the state in governance. For the state to be made more responsive to citizens' demands, empowerment through mobilization is crucial. Such empowered voices can facilitate effectively democratic governance that ensures equity-centred development approaches.

A concept of governance grounded in the notion of democratic citizenship needs the inclusion of all voices – even those of the most marginalized. Mobilizing, empowering and bringing these voices to the negotiating table are important. Concerning the form of conflict, farmers in Vembanad use 'backdoor manoeuvring' in the political realm to achieve their aims. The culture fisheries lobby in Chilika makes the state machinery immobile, so they can continue their practice. The marginalized traditional fishermen use agitation as a tactic of protest, as well as covert tactics such as placing a physical object to obstruct the closing of the salinity barrier in Vembanad. Such claim making is the first stage. In Vembanad, the constant pressure building by fishers empowered through mobilization resulted in the formation of a committee led by the District Collector, with representation from competing sections of society. This was followed by a series of negotiations, whereby the fishers' representatives used the research results from various academic institutions that pointed to environmental degradation and the need for rationalization of the operating of the salinity barrier. They could also mobilize the opinions of environmentalists to further their cause in the negotiation forums. Fishers accelerated their protests and pressed for the permanent opening of the barrier. This led to the appointment of a commission of enquiry under a reputed scientist that suggested timely operations of the barrier, as suggested originally in the design (with the closure of the barrier restricted to 3 months). The government accepted this report and timely operations of the barrier have been carried out during the past 2 years. However, sustainability of this resolution of the conflict depends on the continuity and institutionalization of the process, including continued effective involvement by the state machinery.

There is less optimism about the Chilika Lake case, although the government could not, until now, legitimize the illegal culture fisheries because of the mobilization of the traditional fishers. The CDA tried stakeholder participation and communication through a network of NGOs and CBOs to implement an outreach programme of awareness related to Chilika's environment. According to the former CEO of the CDA, they learned from the conflict in 1999 that unilateral decisions could intensify conflicts. This was the key reason for the changed policy of participation. He also claimed that many activities, especially the new mouth restoration, were carried out through a consultative process with the community, and this enhanced the confidence of the local population.

There are two problems with such a participatory strategy. First, the NGOs are funded by the CDA. They are used merely for environmental education activities (which might have a larger relevance), thereby sidelining the real livelihood issues and politics of marginalization described earlier. Second is the 'benevolence' involved. One of the active NGO leaders complained about the policy shift of undermining NGO involvement by the new CEO who took charge in June 2006. During my interview, he was not apologetic about this shift, since he found that the Forest Department had the capability to undertake the activities of the NGOs. As for representation of the civil society in the governance structure of the CDA, he was adamant that people were represented through their agents like MLAs and MPs, and that there was no need for any more NGO involvement. However, he argued vehemently for the administrative control of officers in other government agencies in the jurisdiction of Chilika to be brought under the CDA for effective coordination with adequate control. This raises questions about any possibility of a shift to more democratic governance and clarifies the important role of the actor, along with the structure needed for such a shift. Therefore, along with structural changes, sensitive and committed individuals are also needed for a shift in governance practices, which will then translate current benevolent notions of 'participation' to real practices of democratic governance.

Conclusions: Framework for Democratic Governance

The level of governance is important for the state to be effective and depends on the nature of the natural resources at stake and the socio-political context. In this case, the state government is too far away spatially to conceive of the specific issues at the regional level. The district administration and *panchayat raj* (local self-governing) institutions cannot take care of these, since they involve multiple districts and *panchayats*. The *panchayat raj* bodies especially may deepen the conflicts because of their local focus and partisan attitude to local resource use concerns, with the risk of being influenced by local elites. Even with the current CDA working limitations, such an intermediate governance structure is needed to coordinate the following:

1. Policy formulation that has explicit equity concerns and sensitivity to local needs. Technical studies, and hence transparent knowledge generation about the natural resource system and land use dynamics, must be combined with local knowledge and solutions that incorporate the perceptions of all stakeholders – the study results and information about any planned interventions have to be shared with the communities.
2. Horizontal coordination of sectoral concerns of the line departments such as agriculture, fisheries, irrigation, etc., and vertical coordination of the state, district, block and *panchayat* levels of government.
3. Building a platform for negotiation of citizen group interests (inclusive of the mobilized and empowered) and helping to evolve negotiated solutions.
4. Regulating and implementing policies evolved through the above-mentioned process with effective and transparent monitoring mechanisms – in conflict situations, the engagement of a legitimate intermediary (power is not the criteria for legitimacy) within a legal framework (Fig. 22.1) that ensures procedural equity.

The main danger in the above proposal is the tendency for bureaucratization of 'authorities', such as those already in place, e.g. the CDA. This is where the governance structure of this

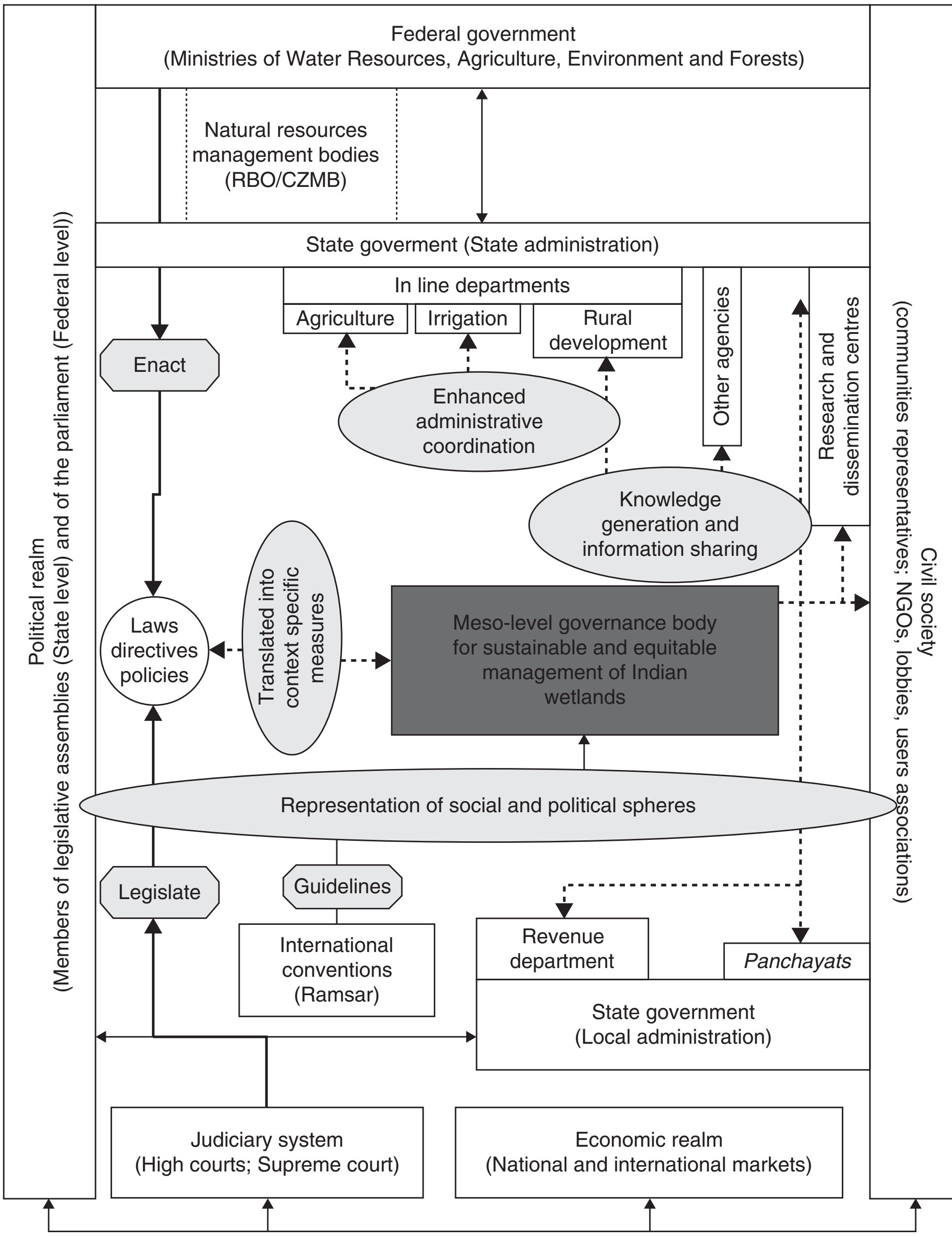

Fig. 22.1. Suggested framework for formulation and implementation of a democratic governance mechanism through intermediate-level governance structures.

authority consciously has to bring in civil society participation – especially at the regional level. The state, civil society and business have to realize they have complementary roles and comparative advantages in their complementary spheres of development and should be able to function with mutual accommodation. The state predominantly has the resources, structures and the conventional authority for governance. Business can create new wealth and employment. These two spheres combined could help further governance from the point of view of efficiency. Civil society can play the watchdog role to ensure that social justice is not lost sight of. Here, mobilization and empowerment of the marginalized sections and bringing their voices to the negotiating table is important, especially in situations of conflict. With constant vigilance between the three societal spheres, the state could act as a neutral arbitrator.

Governance of natural resources thus needs spatial delineation of boundaries (depending on the resource availability pattern, e.g. watershed, river basin, lake, etc.), institutional structures with defined levels and scope of jurisdiction (with upward and downward linkages with other structures of governance) and the complementary functioning of the three societal spheres of state, civil society and business. However, such coordination will not be just techno-managerial but also political, and hence the need for a democratic space to exercise citizen's rights. This is also because the actors in the various spheres wield unequal powers, and hence the need for mobilization of the marginalized sections who might be at the receiving end of 'development'. Here, conflicts become signs of a healthy polity where there is latitude to mobilize and empower those who lose out. Thus, democratic governance of natural resources also demands a conceptual understanding inclusive of mobilization.

Acknowledgements

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References

Chandoke, N. (2003) A critique of the notion of civil society as the 'Third Sphere'. In: Rajesh, T. and Mohanty, R. (eds) *Does Civil Society Matter? Governance in Contemporary India*. Sage, New Delhi, pp. 27–58.

Das, S. and Narayanan, N.C. (2009) Alloyed projects, metalled resistance: a case of bauxite mining in Orissa. In: Narayanan, N.K. (ed.) *Where Do We Go from Here? State, Natural Resource Conflicts and Challenges to Governance*. Academic Foundation, New Delhi, pp. 221–246.

Gadgil, M. and Guha, R. (1995) *Ecology and Equity: The Use and Abuse of Nature in Contemporary India*. Penguin Books, New Delhi.

Ghosh, K.A. and Pattnaik, K.A. (2006) Chilika lagoon: experience and lessons learned brief (www.iwlearn.net/publications/ll/chilikalagoon_2005.pdf/view, accessed 5 August 2009).

KWBS (Kuttanad Water Balance Studies) (1989) Kuttanad water balance study – draft final report. BKH Consulting Engineers, Thiruvanathapuram, India.

Nair, P.V.R. and Pillai, V.K. (1993) Changing ecology of the Vembanad Lake. In: Nair, R.R., Nair, K.P.V. and Joseph, C.A. (eds) *Rice in Wet Land Ecosystem*. KAU, Trichur-10, India, pp. 280–285.

Narayanan, N.C. (2003) *Against the Grain: The Political Ecology of Land Use in a Kerala Region, India*. Shaker Publishers, Maastricht, Germany.

Narayanan, N.C. (2009a) State, governance and natural resource conflicts: background paper. In: Narayanan, N.C. (ed.) *Where Do We Go From Here? State, Natural Resource Conflicts and Challenges to Governance*. Academic Foundation, New Delhi, pp. 15–38.

Narayanan, N.C. (2009b) Water control structures and conflicts in Lake Vembanad: governance as mobilisation. In: Narayanan, N.C. (ed.) *Where Do We Go from Here? State, Natural Resource Conflicts and Challenges to Governance*. Academic Foundation, New Delhi, pp. 91–116.

Pattanaik, S. (2005) Chilika: a contested space (http:// www. Infochangeindia.org/features377.jsp, accessed 5 August 2009).

Pillai, V.R. and Panicker, P.G.K. (1965) *Land Reclamation in Kerala*. Asia Publishing House, Bombay, India.

Scott, J.C. (1998) *Seeing Like a State: how certain schemes to improve the human condition have failed*. Yale University Press, New Haven, Connecticut.

World Wildlife Fund India (2006) Vembanad–Kol Wetland (http://www.wwfindia.org/about_wwf/what_we_do/freshwater_wetlands/our_work/ramsar_sites/vembanad___kol_wetland_.cfm, accessed 5 August 2009).

23 Farmers' Assessment of Resource Management and Farm-level Technological Interventions in the Mekong Delta, Vietnam

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Abstract
Bac Lieu, a coastal province in the Mekong Delta of Vietnam, faced rapid changes in environmental and socio-economic conditions in the early 1990s when the government started investing in the construction of a series of coastal embankments and sluices along the coast. The purpose of these interventions was to prevent saltwater from entering freshwater rice perimeters and to increase rice production in the area. This chapter synthesizes the data from participatory rural appraisals (PRAs) designed to understand the major factors behind changes in socio-economic conditions in the province, as perceived by farmers. The PRAs were conducted in 2000 and 2007 and were aimed at recording farmers' assessments of resource management and farm-level technological interventions in three different zones that had been impacted by water management and salinity control interventions for a long, an intermediate or a short time: the early intervention zone (EIZ), the recent intervention zone (RIZ) and the marginal intervention zone (MIZ), respectively. Community-identified significant change (CISC), a tool to capture learning on significant community changes, was used to understand the impacts of the government's interventions in these three zones. CISC gave important insights into the changes in community life in the three areas and the main factors leading to these changes according to the farmers' perceptions. These factors were changes in the government water management strategy and new technological interventions at farm level. The introduction of fresh water has supported the diversification of farming systems in the EIZ. The use of brackishwater for shrimp farming in the RIZ and MIZ has increased household income but is risky and poses environmental hazards in the RIZ. New technologies for both rice and fish production have improved household conditions and increased incomes.

Introduction

Coastal zones are home to the poorest of the poor, support much of the world's food production, transportation and recreation needs, while also delivering important ecosystem services. The coastal environment is under pressure and has undergone rapid changes in recent times. A case in point is Bac Lieu Province, which lies in the coastal southern part of the Mekong Delta of Vietnam. Driven by economic, institutional and demographic forces, the province has undergone rapid changes in land use, natural resources – especially water – management, technologies and land use policies. These changes were brought

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about by many actors and have impacted strongly on the environment and farmers' livelihoods (Hoanh *et al.*, 2003; Tuong *et al.*, 2003; Gowing *et al.*, 2006; Hossain *et al.*, 2006). The changes and their impacts are multifaceted and can be analysed from many perspectives. It is important to understand the assessment of the people living in the area, as they feel the full force of the consequences of any interventions. This chapter examines farmers' evaluations of the land use policies, resource management and farm-level technological interventions carried out in Bac Lieu Province for the past decade and the impacts they have had on farmers' livelihoods, especially those of the poor, in different zones of the province.

Methodology

Study site and selection of sample villages

The study focused on Bac Lieu Province, which covers an area of 252,000 ha, of which about 208,000 ha are cultivated (GSO, 2004). The province is subject to the effects of saline intrusion, which previously entered up to 50 km inland during the dry season, thus limiting rice production to only one wet-season crop of traditional rice (Gowing *et al.*, 2006). Forced by the need for food security in the early 1990s, the government sought to promote rice production in this area by reducing the salinity problem through the construction of a series of sluice gates and embankments along the coast of the province to prevent saltwater from entering the Quan Lo Phung Hiep freshwater canal (a main canal connected to the Mekong River) and to increase irrigation capacity. The first sluice was built and became operational in 1994; then the zone protected from saltwater intrusion gradually expanded westward as successive sluices were completed (Fig. 23.1). This water management programme allowed salinity-protected rice farmers in the eastern part of the province to intensify their rice production, with double or triple cropping of rice. As the freshwater zone gradually spread westward, the local economy was undergoing rapid change. The demand for rice production was declining because of the low profitability of the rice crop and, at the same time, shrimp culture was booming as a result of high local and export prices (Gowing *et al.*, 2006). Traditional extensive shrimp farming systems based on the natural recruitment of larvae were quickly replaced by semi-intensive monoculture production systems (Hoanh *et al.*, 2003). From 1998, shrimp farming was widespread in the western part of the project area. However, there was a contradiction between shrimp farming and the land use policy of rice intensification in this saline-protected area. The government continued to build sluices and the freshwater zone continued to expand westward up until 2000. This caused a decline in saltwater, which adversely affected the production of shrimp and the fish catch within the area, thereby potentially reducing household incomes through the loss of shrimp and fish revenue (Hossain *et al.*, 2006). The conflict reached a peak in 2001 when shrimp farmers destroyed a major dam to allow saltwater to flow into the saline-protected area for shrimp farming (Tuong *et al.*, 2003). The situation prompted the government to re-examine the policy of emphasizing rice production and to explore alternative land uses in the protected area, which could accommodate both intensive rice cultivation in the eastern part and shrimp-based farming in the western part of the province (Hoanh *et al.*, 2003). Because of the phased construction of the sluices, canal water became fresh in different zones of the province at different times. Hossain *et al.* (2006), on the basis of soil types and when the canal water had become fresh, classified the study area into three zones:

- Zone 1 – early intervention zone (EIZ), situated in the east of the project site (east of the 1998-isohaline). It is characterized by alluvial soil types. The water and environment changed from a brackishwater ecology to a freshwater ecology before 1998. The EIZ represents areas where conditions have been impacted by water management and salinity control intervention for a long time.
- Zone 2 – recent intervention zone (RIZ), located in the middle section of the study

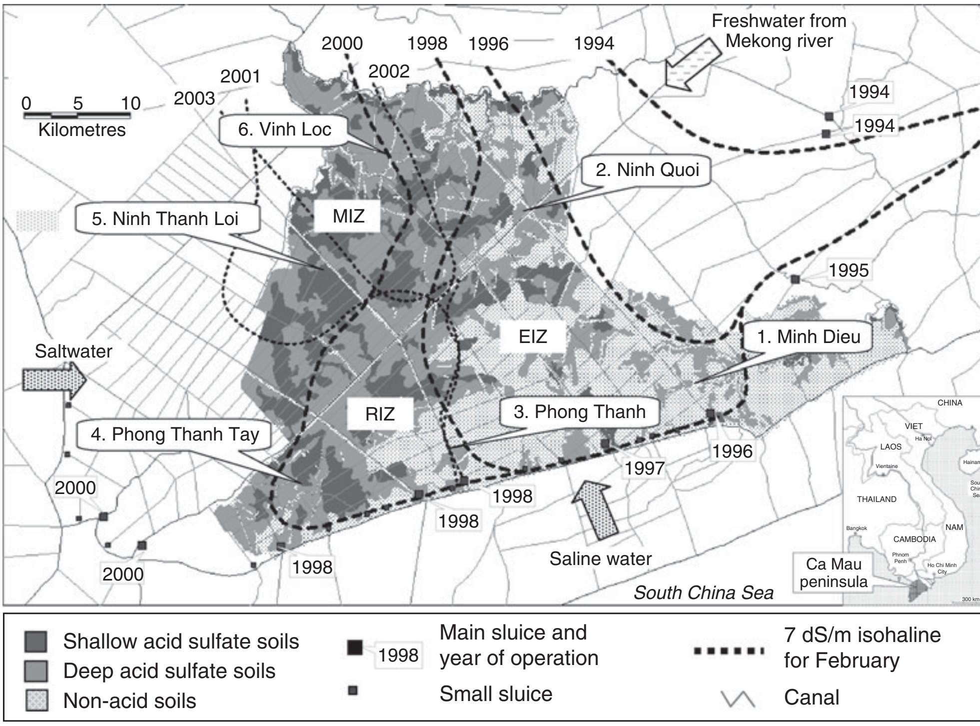

Fig. 23.1. Map of the project area with location of villages under investigation and the three zones: EIZ, early intervention zone; RIZ, recent intervention zone; MIZ, marginal intervention zone (source map from Gowing *et al.*, 2006).

area, in between the 1998 and 2000-isohaline. Large areas of this zone have acid sulfate soils. Water and the environment changed to a freshwater ecology after 1998 and before 2000. The RIZ represents areas where conditions have been impacted by water management and salinity control intervention for a medium length of time.

- Zone 3 – marginal intervention zone (MIZ), lies in the west and north of the 2000-isohaline. The zone was not affected significantly by the closure of sluices because saltwater could flow throughout the area from the West Sea when the sluice system was closed. The MIZ represents the situation in the coastal area in the absence of water management and salinity control intervention.

We selected six villages, two from each zone, to collect data on the farmers' assessments of the changes in the livelihoods of the community over time induced by salinity control and farm-level technological interventions. The name of the villages and a summary of the characteristics covered by the PRAs are presented in Table 23.1.

Collection of farmers' assessments

This study employed the participatory rural appraisal (PRA) method and the community-identified significant change (CISC) method (see Shayamal and Orly, 2006) to collect farmers' perceptions and assessments of the changes induced by salinity control and farm-level technological interventions. The CISC method engages community members in identifying and analysing significant changes in their lives and how these changes are linked to development interventions from within or outside their community. CISC comprises of seven steps. In brief, these seven steps involve:

Table 23.1. Characteristics of villages selected for PRA assessment.

Name of village	Zone	Type of village	Salinity controlled since	Soil characteristics	Number of hamlets in which a PRA was conducted
Minh Dieu	EIZ	Early intervention	Before 1998	Alluvial soil types	2
Ninh Quoi	EIZ	Early intervention	Before 1998	Deep acid sulfate soils	2
Phong Thanh	RIZ	Recent intervention	Between 1998 and 2000	Deep acid sulfate soils	2
Phong Thanh Tay	RIZ	Recent intervention	Between 1998 and 2000	Shallow acid sulfate soils	2
Ninh Thanh Loi	MIZ	Marginal intervention	After 2000	Shallow acid sulfate soils	2
Vinh Loc	MIZ	Marginal intervention	After 2000	Shallow acid sulfate soils	2

(i) reflectively telling the story of community involvement in a specific development initiative – use of timeline; (ii) analytically identifying the domain of significant changes in community life – use of change flow chart; (iii) meaningfully describing specific significant changes under the identified priority domain – use of comparative visualization for a set of indicators identified by them; (iv) creatively examining the factors contributing to the most significant change identified under the priority domain – use of multifactor actors' diagrams; (v) writing stories; (vi) sharing the stories; and (vii) sharing lessons learned. In this study, only the four main steps (i–iv) were employed.

Three PRA exercises were conducted to gather data to flesh out the four steps mentioned above. The first PRA was carried out in 2000 and the second PRA was in 2003 and covered all six selected villages. The 2000 PRA was considered to be an original baseline study to draw a general picture of the project area. In order to provide an impact-focused assessment of the influence of government interventions, a follow-up qualitative PRA assessment and CISC were conducted in February 2007 in the same six villages.

A PRA assessment or focus group discussion (FGD) was conducted at village and hamlet level. For this purpose, two hamlets were selected from each village (Table 23.1). At the village level, the PRA involved 5–7 stakeholders: a representative of the people's committee, the agricultural officer of the village, the land management officer of the village, the statistical officer of the village, a representative of the farmers' association and a representative of the women's union. For the PRA at hamlet level, the research team worked with a key informant panel (KIP) consisting of 10–15 stakeholders: hamlet leader, farmers, shrimp seed (juvenile) producer, etc. Voices from the field were recorded through the PRA sequence to know the impact of government water management interventions.

To capture all events that may have resulted in changes in the farmers' livelihoods, a timeline analysis was employed. Large sheets of paper were used to document major events or changes before the construction of the sluice gate, during the freshwater period and the return of the brackishwater period (where it happened). Through these time periods, 1996–2000, 2000–2003 and 2003–2006, participants were asked to give details about their livelihoods, rice and shrimp cultivation situations and the problems they encountered. In particular, participants were asked to recall policy and technology interventions that influenced them in each of the years referred to above.

To assess the impact of policy and the technological interventions on farmers' livelihoods within the different zones, a comparative visualization (before and after) for a set of indicators (housing state, household income, source of income, life conditions, etc.) identified by the stakeholders was used.

Through a diagrammatic presentation, the participants were asked to identify and analyse the factors that contributed to the most significant changes. The actors were also identified corresponding to their contributions.

We also conducted household surveys (reported by Khiem and Hossain, Chapter 32, this volume) to gather data on household economic gain to understand, in a meaningful way, specific significant changes with regards to household income. Households were stratified into three different groups (poor, medium and better-off), based on the results of a classification made by key informants and hamlet leaders. Data pertaining to household income gathered from 2000, 2003 and 2007 surveys were combined in the analysis. This led to a quantification of relative household income by estimating economic gain for every 2 years from 1996 to 2006.

Results

Policies and technology interventions at farm household level

The historical timeline of major events based on the community's experiences in the EIZ can be seen in Table 23.2. In the EIZ, according to the key informants, as the first sluice became operational in 1994, the salinity in this area started to decrease and in 1997, the area became almost free from salinity intrusion. Within the protected area, the duration of freshwater conditions expanded in line with the policy to promote the diversification of land use systems. For instance, the government provided several kinds of low interest loans to farmers in order to promote agricultural production, particularly to improve fruit tree gardens and to promote the intensification of rice, with double or triple cropping of rice.

In 1997, farmers started to invest in orchards, with mango being the major fruit tree in the area. Since 1996, most swampland has been converted to rice and farmers have tried further intensification by growing two or three rice crops. In addition, in 1997 farmers started to grow upland crops on paddy fields or on relatively high land.

In line with policy guidelines, farmers also reported that they had received technical support, which they had applied in their fields.

- In 2001, farmers assessed integrated pest management (IPM) technology.
- In 2002, they applied row seeding and used a 're-transplanting tool'. The 're-transplanting tool' is a farmers' innovation that is employed to reduce labour costs in re-transplanting rice and makes the rice plant recover fast after re-transplanting.

Table 23.2. Historical timeline, early intervention zone, 2007 PRA.

PRA – At the EIZ		
Time	Important events	Remarks
1994	Built a sluice to prevent salinity	
1996	Water in canal became fresh	
1997	Started to grow double rice	Previously grew only one rice crop
1997	Reclaimed garden: grew mango Grew upland crop: maize, cucumber, watermelon	Farmers increased income by growing upland crop
1999	Started to grow triple rice	20% of farmers applied
2001	Applied IPM on rice	
2002–2003	Applied row seeding Applied '3 reductions, 3 gains' technique	Farmers were successful in applying this technology
2004	Practised rice–fish system	The system introduced by Can Tho University (by project)
2006	Some damages by brown plant hopper (BPH) and diseases on rice	50% of the village fields damaged by BPH
2006–2007	Good harvest of rice	

- In 2003, farmers applied 'three reductions, three gains' technology. This is a new technology package in rice production disseminated by government extension services. The technique recommends the reduction of seeds, fertilizers and pesticides, in order to gain high yield, high quality and high income.
- In 2004, they applied the integrated rice–fish system.
- In 2006, farmers used high-quality seeds and self-produced high-quality seeds.

In RIZ, a historical timeline of major events is presented in Table 23.3. According to the participants, before 1996 farmers used to grow one local saline-tolerant rice crop in the rainy season and shrimp in the dry season. From 1998, as the salinity control sluices became operational and canal water in this area gradually became fresh, some areas under shrimp were converted to grow modern rice varieties, in line with the government's policy of rice intensification. However, rice yields in this area were very low because of the presence of acid sulfate soils. By 2001, shrimp farmers destroyed a major dam to get saltwater flowing for shrimp farming. This situation prompted the local government to revise its land use policy of emphasizing rice production to accommodate shrimp cultivation in this zone, while maintaining areas of intensification of rice in the EIZ. This was achieved by opening the salinity control sluices at the boundary of this zone to allow saltwater to enter the zone during the dry season. Details of the change in sluice operation are described in Hoanh *et al.* (2003). Since then, the major production systems have been shrimp-based and, with the help of government extension services, farmers have started to diversify their shrimp farming practices.

- In 2002, farmers reduced stocking density and improved pond management for tiger shrimp cultivation.
- In 2004, farmers applied an integrated shrimp–rice system plus fish farming.
- In 2004, farmers applied an integrated shrimp plus crab and fish system.
- In 2004, they applied shrimp–*hen bien* (*Scirpus littoralis* Schrab.) systems. In this system, farmers grew *hen bien*, a type of salt-tolerant sedge, in the shrimp pond. Farmers reported that *hen bien* supplied shade for shrimp and had the ability to 'clean the field' by absorbing excessive nutrient and other pollutants.

Table 23.3. Historical timeline, recent intervention zone, 2007 PRA.

Time	Important events
Before 1996	Before the construction of the sluice gate: Brackishwater (Jan–Jun) and freshwater (Jul–Dec) Natural/wild crabs, shrimp and fish 1 rice crop – average yield of 3.1 t/ha (with IR42) Natural shrimp/fish whole year (from Jan–Jul) Additional income from pig husbandry and nipa leaves
1996–1997	Constructed sluice gates and surrounding dykes to prevent saltwater
1997 onwards	Freshwater period: Practised 1–2 rice crop/year: 1st crop Jun–Sept (avg yield: 2.3 t/ha) 2nd crop Oct–Jan (avg yield: 2.1 t/ha) Find off-farm jobs outside village (HL- 20,000 VND/day) Low income but sustainable
2001	New water management system let the brackishwater in Brackishwater whole year (freshwater around Oct) Cultured shrimp/fish/crabs No rice production
2001–2003	Successful shrimp/fish culturing High income from shrimp (avg: 23 million VND/ha)
2004–2005	Mostly unsuccessful shrimp farming No livestock raising

Hen bien thus improved shrimp yield and at the same time could be used for producing handicrafts.

The historical timeline showed that farmers had made considerable efforts to adopt polyculture shrimp farming systems by combining crab and fish in shrimp ponds. This was done because monoculture shrimp farming was more risky than polyculture farming. If the shrimp died, farmers could still harvest crab and fish. Farmers also paid much more attention to reducing pollution caused by shrimp farming by, for example, growing *hen bien* in the shrimp pond.

In the MIZ, farmers reported that this zone was not affected much by the sluice systems built at the east side of the study area as saltwater could flow into the area from the West Sea. Therefore, from 1997 farmers started to rear shrimp. As in the EIZ and the RIZ within the protected area, farmers in this zone received policy and technological support from the local government.

Impact of resource management and farm-level technological interventions on farmers' incomes

Early intervention zone

Domains of significant changes in community life in the EIZ are shown in Fig. 23.2 and Table 23.4. Farmers in the EIZ argued that their life conditions became more stable with increases in income from the diversification of agricultural production activities. Many farmers started to build new houses as income increased and they observed such changes starting to unfold. These significant changes show contrasting images of what or how farmers were before with their life at present. Through focus group discussion, farmers recalled that during 1999 farmers tried further intensification by cultivating three rice crops, but the yield was low and they reverted to double cropping of rice. On the relatively high land, they started growing vegetables, maize and fruit trees as the area became

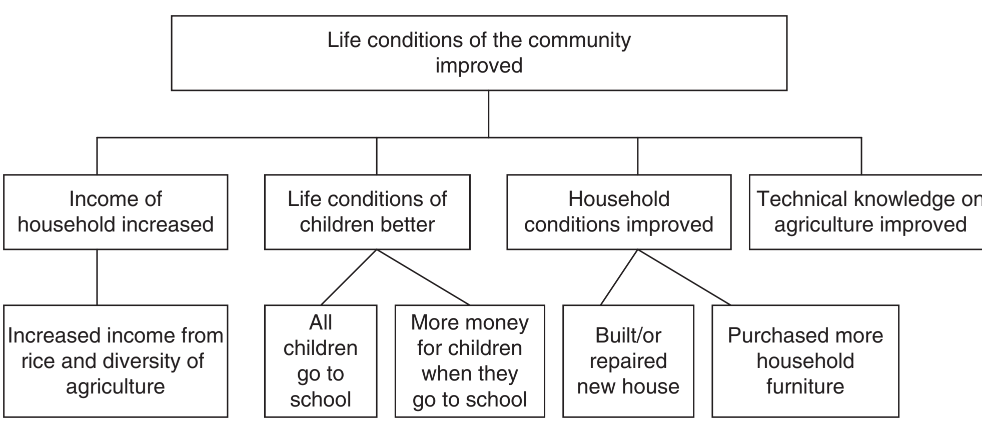

Fig. 23.2. Flow chart of significant changes in community life in early intervention zone, as perceived by medium and better-off groups of farmers, 2007 PRA.

Table 23.4. Illustration of comparative visualization (before and now) of significant changes in community life in early intervention zone, 2007 PRA.

Situation before		Situation at present
• Simple house	➡	• Concrete house
• Low income		• High income
• Fewer sources of income		• More sources of income
• Poor life conditions		• Better life conditions
• Environment not polluted		• Environment polluted

flood-free and had year-round provision of fresh water. The intensification of rice farming and diversification in agriculture generated household income for all members. Later, with the support of the government extension services and scientists from Can Tho University, intensification with three rice crops was successful. They started to apply row seeding and the 'three reductions, three gains' technology, and these offered enhanced income generation. Farmers also acknowledged that intensification of rice farming generated employment for family and hired work for the landless and other local resident farmers. In 2004, some farmers in the zone started to practice rice–(freshwater) fish systems. According to these farmers, raising fish in rice fields generates income that is much higher than the income obtained from mono rice systems. Moreover, rice–fish systems are better for the environment because farmers adopting them refrain from using pesticides.

Figure 23.3 illustrates the household income evolution and structure of income sources by stakeholder groups. The salinity control intervention positively affected the livelihoods of all categories of households in this zone. The better-off and medium farmers benefited the most through improved agricultural production systems, especially rice. The poor group, which relied more on fish capture and wage labour (e.g. harvesting rice, shrimp-pond making) as important sources of income, did not improve much prior to 2003. From 2003 onwards, as major canal systems became fresh, farmers concentrated on rice production in their fields and relied less on the hiring out of their labour to other farms.

Recent intervention zone

Figure 23.4 presents the evolution of household income over the study period. For the better-off and medium groups, replacement of shrimp by rice cultivation as canal water gradually became fresh did not result in economic improvement from 1996 to 1998. Rice yields in this area were very low because of the presence of acid sulfate soils. Farmers received fewer profits from rice, with some farmers losing money. This had an impact on the livelihoods of all farmers in the area. Many farmers accumulated significant debt. Some improvement in rice yield occurred during 1998–2000, but this was not substantial. The poor group suffered most during this water freshening priod. They often lacked access to land and their livelihoods were heavily dependent on wage labour (working for shrimp farms)

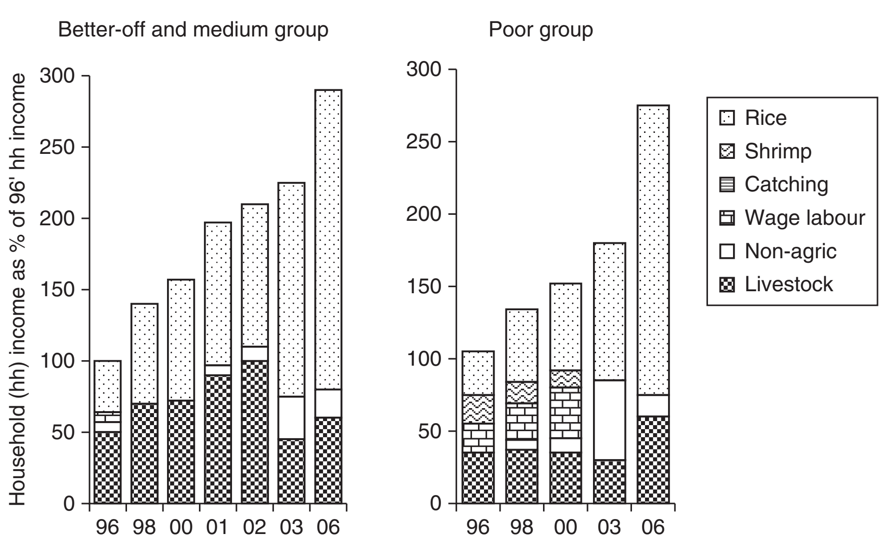

Fig. 23.3. Evolution of household income and income sources over time, as perceived by farmers in the early intervention zone. The 1996 household income was used as the baseline (100%).

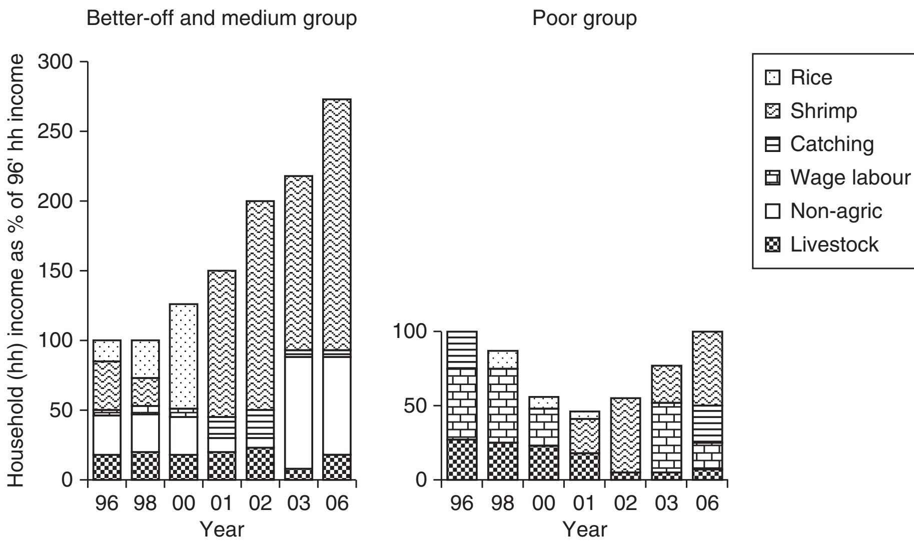

Fig. 23.4. Evolution of household income and income sources as perceived by farmers in the recent intervention zone (the 1996 household income was used as the baseline (100%)).

and catching natural fish and shrimp in the saline canal water. All these sources of income declined as the canal water became less saline. The farm income structure changed again in 2001, when the government allowed the intake of saltwater: income from shrimp raising became increasingly important in all groups of farmers. Later, with the help of government extension services, farmers started to diversify and adopted multi-culture shrimp-based farming (with crab, fish and sometimes *hen bien*). This resulted in increasing household income for farmers, especially for the better-off group. They reported improvements in their life conditions, in particular many farmers invested in new motorbikes and motorboats, and some built new houses as their incomes increased (Fig. 23.5).

The poorer group did not benefit much from the new technologies. They reported that they lacked the knowledge to keep up with new technologies and that they lacked the money to invest in them. They had to supplement their incomes with working for others and catching wild fish.

All the farmers acknowledged that rearing shrimp in this area was a high-risk business because of mass mortality as a result of disease, and there were also environmental consequences.

Marginal intervention zone

Before 1997, farmers in this area could grow one crop of salinity-tolerant traditional rice in the rainy season, followed by shrimp in the dry season. After 2000, the local government adjusted the land use and provided loans for shrimp production, which encouraged the expansion of shrimp farming in the area. Farmers reported that in 2001, 100% of the area was under shrimp. Many farmers rotated dry-season shrimp with one traditional rice crop in the rainy season, and this shrimp–rice system proved to be sustainable. Farmers here also practised integrated shrimp production with crab and fish. This system also proved to be successful in the area.

Figure 23.6 presents the results of farmers' assessments of changes in the economic conditions from 1996 to 2006. Farmers argued that even though the area was not affected significantly by the salinity control intervention, there was, however, an impact on their livelihoods. Household incomes increased in both the medium and poor groups between 1996 and 2006. Shrimp rearing became the most important source of household income, particularly for the medium group (Fig. 23.6). Farmers also acknowledged that brackishwater

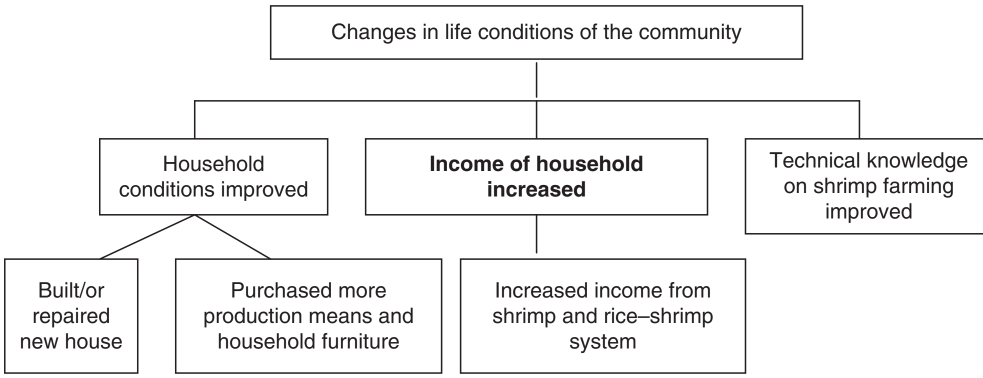

Fig. 23.5. Flow chart of significant changes in community life in recent intervention zone, as perceived by the better-off group of farmers, 2007 PRA.

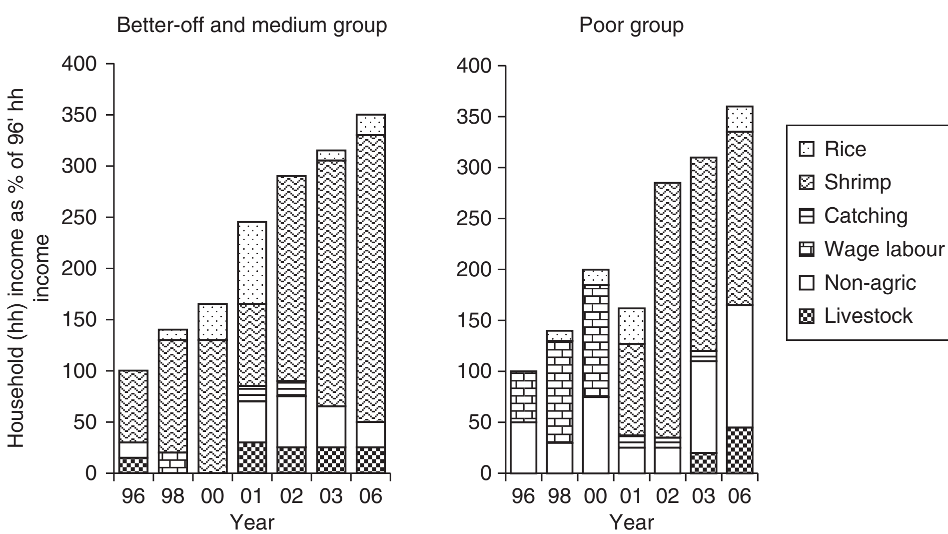

Fig. 23.6. Evolution of household income and income sources as perceived by farmers in marginal intervention zone (the 1996 household income was used as the baseline (100%)).

aquaculture generated an opportunity for farmers to diversify their incomes with lower levels of investment.

Factors and actors that influenced the community's significant changes

Farmers in the EIZ identified three main factors that contributed to the improvement of households' life conditions and the incomes that they were currently enjoying (Fig. 23.7).

These factors were: increased irrigation capacity, the application of suitable technology and support of public services and loans. Of these factors, the prevailing increase in irrigation capacity was seen as most important. They cited the government water management policy, which allowed the intensification of rice farming by growing two or three rice crops or by diversifying with vegetables, maize and fruit trees.

In line with the policy to promote double or triple cropping of rice, some new technologies were introduced to farmers (for

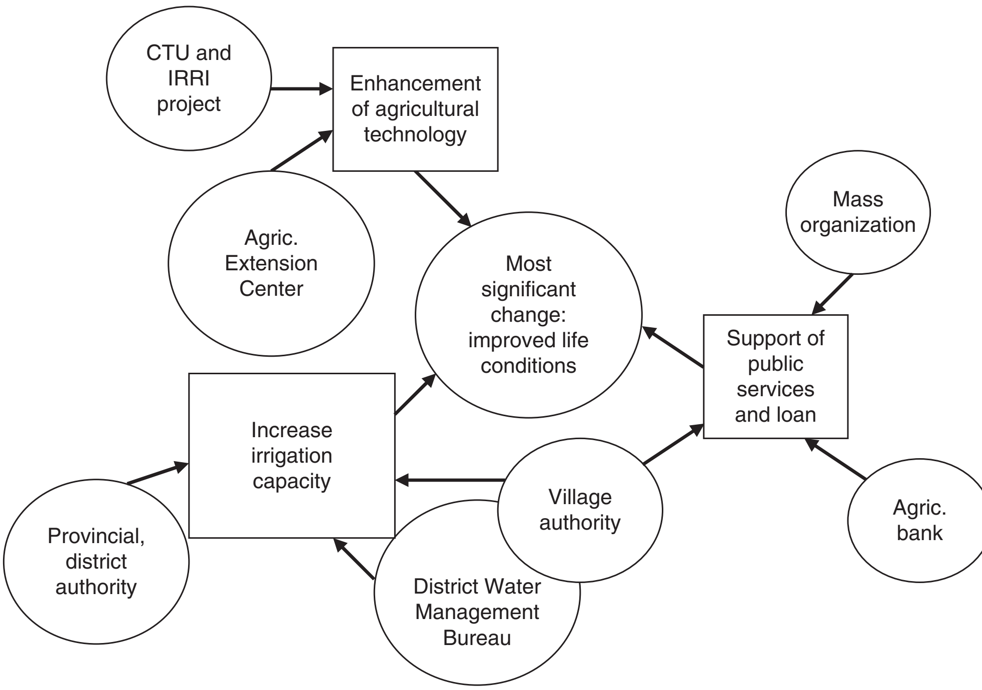

Fig. 23.7. Factors and actors that brought about the desired change or outcome, as perceived by farmers in the early intervention zone.

example, new short-duration rice varieties, 'three reductions, three gains' technologies, etc.). These new technologies are still of interest to farmers, as the techniques are suited to the area and are profitable. Public services and loans provided to farmers have been shown to be important because these continue to address households' needs. As such, farmers are able to access these loans from government banks and they also receive some credits from mass organizations for agricultural production activities. The Agricultural Extension Center (AEC), a government organization under the Department of Agricultural and Rural Development (DARD) of Bac Lieu Province, has had the biggest influence in promoting agricultural production in the area, according to members. It has provided them with training on agricultural techniques, demonstration plots and new rice varieties. Together with the AEC, the Can Tho University and 'IRRI project' have also provided training, on-farm trials, etc. These training courses, on-farm trials and field-day sessions have enhanced agricultural technology for farmers and allowed them to manage and use their resources effectively. The District Water Management Bureau has played an important role in the agricultural production of the villagers, as it has managed and supplied the freshwater in the zone.

Farmers in the RIZ and the MIZ identified their increased income as the most significant change they have observed (Fig. 23.8), allowing them to purchase more production facilities, and build new houses. They also identified three factors that had contributed to the increase in household incomes, namely responsive land use policy, adoption of suitable aquaculture technology and the support of public services and loans. Figure 23.8 also shows that farmers perceived that the AEC and Water Management Bureau were most influential and played the most important roles in bringing about the desired change.

Despite the positive impacts, farmers said that the water management scheme in the area still upheld a top-down approach. Sometimes, the scheme for water management (operated by the Water Management Bureau) did not fit with farmers' requirements. Farmers suggested

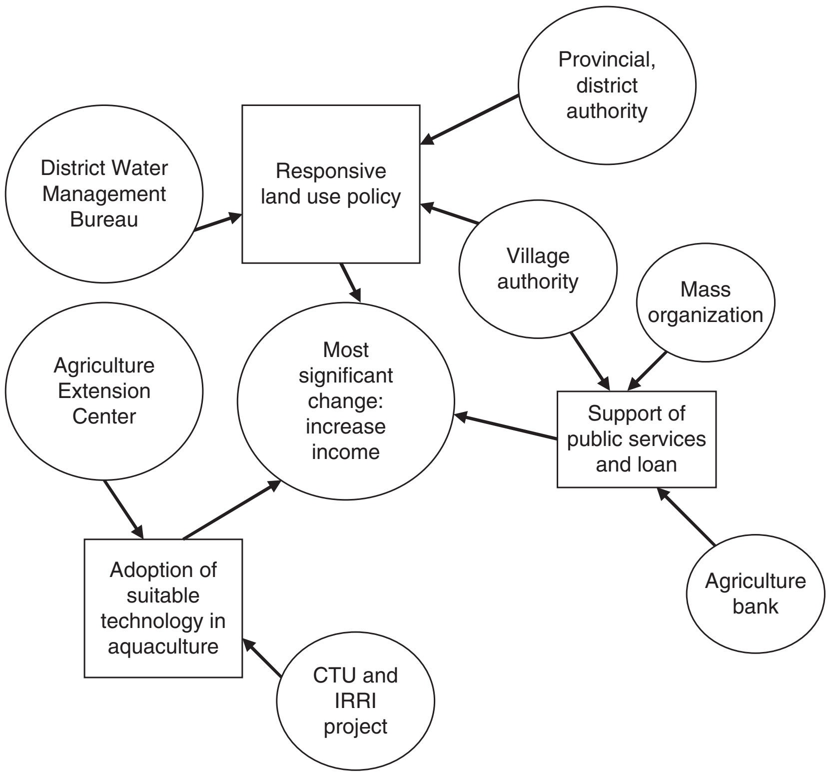

Fig. 23.8. Factors and actors that brought about the desired change or outcome, as perceived by farmers in recent and marginal intervention zones.

the formation of a collective or community-based water management system that might help them manage their resources better.

Conclusions

The PRA and CISC framework offered insights into the changes in community life within different zones subjected to different timing and degrees of salinity control interventions, in a coastal area of Vietnam. Salinity control interventions solely for rice intensification had both positive and negative effects on the livelihoods of farmers. The revised water management/salinity interventions and responsive land use policy that accommodated agricultural and aquacultural diversification, together with improved production technologies, improved the livelihoods of the majority of people. This would suggest that the regional management of resources is not a trivial matter with respect to optimal resource use that promotes increased household incomes. The low and unstable yield of shrimp and the environmental hazards brought about by shrimp farming in both recent and marginal intervention zones suggests that the sustainability and productivity of saltwater resources could be further improved by transferring suitable technologies and farming practices. According to farmers, most of the secondary canals need to be dredged and the management of water resources should be based on community participation.

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References

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 48–60.

GSO (General Statistics Office) (2004) *Statistical Yearbook 2004*. Statistical Publishing House, Hanoi.

Hoanh, C.T., Tuong, T.P., Gallop, K.M., Gowing, J.W., Kam, S.P., Khiem, N.T. and Phong, N.D. (2003) Livelihood impacts of water policy changes: evidence from a coastal area of the Mekong river delta. *Water Policy: Official Journal of the World Water Council* 5(5/6), 475–488.

Hossain, M., Ut, T.T. and Bose, M.L. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 30–47.

Shayamal, S. and Orly, B. (2006) *Community-Identified Significant Change. A Facilitator's Guide*. Revised version 2006. International Institute of Rural Reconstruction (IIRR), Silang, Cavite, Philippines.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Bar, J.J.F. and Ben, D.C. (2003) Impact of seawater intrusion control on environment, land use strategies and household incomes in a coastal area. *Paddy and Water Management* 1, 65–73.

24 Assessing Needs, Constraints and Livelihood Opportunities in Coastal Saline Environments: a Case in Orissa, India

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Abstract

The coastal saline ecosystem in Orissa State, eastern India extends from the shore of the Bay of Bengal to about 15 km inland. Salinity occurs because of the intrusion of seawater during high tides through surface channels, creeks and rivers, particularly during the dry season, but decreases with freshwater flushing in the wet season. Salinity reaches its highest during April–May due to the increase in temperature from February onward, with a consequent increase in evapotranspiration and salt accumulation on surface soils. Because of poor pre-monsoon showers during April–May in some years, soil salinity still persists and can affect crop establishment seriously in early June. Moreover, a shortage of irrigation water limits the cultivation of dry-season rice and other non-rice crops. This study develops a systematic understanding of target environments and the livelihoods of the people in these areas as a basis for exploring opportunities to improve land and water productivity, as well as farmers' livelihoods through varietal improvement and proper crop management practices. Baseline social (including gender analysis) and economic surveys using a pre-tested structured questionnaire of 50 households were conducted in six villages in Jagatsinghpur District to assess the socio-economic characteristics of the farming households, indigenous knowledge and farming practices, gender roles, use of rice varieties on different land types, share of rice and other sources of income in livelihood systems and the profitability of current rice cultivation practices and inputs. Through focus group discussions, farmers identified their problems, prioritized their needs and matched them with opportunities to improve their livelihood. Farmers gave positive feedback on participatory experiments involving salt-tolerant rice varieties and associated crop and water management technologies conducted in their fields, for both wet and dry seasons. Improved varieties had at least twice the yields of traditional varieties that yielded less than 1.5 t/ha. Sunflower is well accepted as a rotation crop after rice. With the new varieties, farmers felt more secure that they would have a continuous supply of rice for a year instead of 4–9 months, as was the case before the project began. Several lessons were learned from this research: (i) the need for a strong interaction between biological and social scientists in problem-oriented research; (ii) the use of community participatory approaches in the design, validation and dissemination of technologies; (iii) the need to enhance the capacities of both men and women farmers in rice production technologies and improved seed management; (iv) the need to anticipate and address constraints to the widespread adoption of rice and rice-based technologies; (v) inclusion of both men and women farmers in evaluating new salt-tolerant varieties; (vi) expansion of sunflower production as a suitable crop for saline areas, after rice; and (vii) the need to evaluate additional crops adapted to these saline areas and which have a high market value.

Introduction

Salinity is a major obstacle to increasing production in rice-growing areas worldwide (Scardaci *et al*., 1996). In India, high salt content in the soil is a continuing problem, resulting in low crop productivity and land degradation. Around 8.5 million ha of the total cultivated land in this country are affected by high salt accumulation. The effects of salinity on agriculture can be dramatic. As salt builds up, it affects both wet- and dry-season crops. Ultimately, farmers have to abandon part of their area, leaving landscapes that show a patchwork of productive irrigated fields and abandoned saline land (Thiruchelvam and Pathmarajah, 1999). In coastal Orissa, this problem is severe because of seawater intrusion and the rise of shallow saline groundwater, especially during the dry season; but this condition decreases with freshwater flushing in the wet season, limiting cropping mainly to rice production. Rice productivity, none the less, is very low in this region (1.0–1.5 t/ha) due to the lack of suitable varieties, unavailability of good-quality irrigation water and poor management. Other abiotic stresses such as drought, flash floods and cyclonic disturbances during October–November also contribute to low productivity. Despite these obstacles, farmers continue to grow rice, as it remains the only option.

Direct interventions to improve water and soil quality in salt-affected areas are costly and require major infrastructure development. The financial returns for such investments are low. For most rural poor in these areas, the only hope is to make the best of their poor-quality water and land to meet their food needs. There is a need to develop appropriate and sustainable production systems that deal with the problems of food security and livelihood improvement of the resource-poor farmers. Improving rice productivity in coastal Orissa would improve the household food supplies of subsistence farmers. The ability to achieve higher productivity in less time and by using untapped land and water resources would also release pressure on crop production in other more favourable areas. This would allow farmers to engage in other off-farm activities that could generate more income.

Efforts to develop and deploy salt-tolerant varieties must be accompanied by improved crop management that enhances the survival and robustness of the crop to withstand stress and stabilize yields. Water management, together with soil reclamation and crop management, are key to enhancing crop survival and productivity, as well as improving soil quality in these areas. It is possible to extend the window of freshwater availability for raising non-rice crops along with dry-season rice through water-harvesting techniques. Our hypothesis is that improving and stabilizing the productivity of salt-affected areas would enhance water productivity substantially. A multidisciplinary approach is needed that integrates improved germplasm with management interventions at the crop, field and farm levels. The first step undertaken in this research was to assess needs and constraints and to identify livelihood opportunities for rice farmers by enhancing crop management. This in turn would lead to stabilizing land and water productivity. Work was done to evaluate rice varieties/germplasm and introduce some management options for rice cultivation during wet- and dry-season cropping. Several non-rice crops have been evaluated over the past 3–4 years under rice-based crop production systems.

Objectives

This project was undertaken to develop a systematic understanding of the livelihood of resource-poor farmers in the coastal saline areas of Orissa as a basis for improving the land and water productivity of rice-based crop production systems through environmentally sustainable and socially acceptable genetic improvement and management strategies. Specific objectives were to:

1. Characterize farmers' livelihoods (including gender roles), cropping systems and crop production management and farming practices in selected salt-affected rice-farming villages.
2. Identify farmers' constraints in crop production under saline conditions and present possible opportunities to improve farmers' livelihoods.

3. Obtain farmers' feedback on introduced recommended technologies in the coastal saline rice areas of Orissa.

Methodology

The International Rice Research Institute (IRRI) in collaboration with the Indian Council of Agricultural Research (ICAR) and the Central Rice Research Institute (CRRI) in Cuttack, Orissa, India, started benchmark surveys on salt-affected areas in coastal Orissa in 2004. This project is under the initiatives of the Global Challenge Program on Water and Food (CPWF) Project No 7. Principal investigators–collaborators facilitated the work, especially in selecting the project sites, sample respondents and subsequent management of the household surveys and data collection.

Site selection

Research sites were selected carefully based on the geographical extent of the area affected by coastal salinity, the physiographical conditions and the importance of rice as the major crop grown in the area. The selected villages for this project are situated in Ersama Block of Jagatsinghpur District of Orissa. These villages (Chaulia, Kankan, Gangadevi, Patna, Ambiki and Kimilo) are about 80–95 km away from the CRRI and 4–10 km away from the Bay of Bengal near Paradeep port. Among these villages, Chaulia and Kankan suffer from severe salinity problems and other abiotic stresses. Jagatsinghpur falls under the south and south-eastern coastal plain agroclimatic zone of Orissa. Soils are mostly saline and acidic to neutral in reaction. Climate is mostly subtropical, hot and humid. The important rivers, Hansua and Sankha, are linked directly to the sea. The average annual rainfall is around 1560 mm, but the entire block is prone to both drought and floods because of variability in monsoon rain during the cropping season. Besides salt stress, problems of initial or terminal drought, submergence or waterlogging, flash flood and cyclonic disturbances are frequent.

This region is mostly monocropped with rainfed rice grown on 17,859 ha out of the 19,365 ha total cultivated area. Farmers are very poor, having small landholdings. Farming is the main source of livelihood, although some people are also engaged in fishing. Most farmers cultivate their own land, whereas some are engaged in sharecropping. The average household size is six individuals. Patna and Ambiki showed the largest family size (eight) and Chaulia had fewer (five) family members (Table 24.1). The land and water productivity of these areas can be improved substantially through the introduction of salt-tolerant germplasm and suitable management options in a rice-based crop production system.

Data collection

Participatory rural appraisal (PRA) tools such as focus group discussions (FGDs) on key topics, a cropping calendar and pie diagrams were used to collect village-level information. Fifty household respondents representing different

Table 24.1. Number of households and total and average household size by village in Ersama Block of Jagatsinghpur District of Orissa, India.

		Household size	
Village	Number of households	Total	Average
Chaulia	19	89	5
Kankan	12	76	6
Gangadevi	9	55	6
Patna	3	24	8
Ambiki	5	39	8
Kimilo	2	13	7
Total	50	296	6

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

socio-economic groups based on their landholdings were selected and interviewed using a structured pre-tested questionnaire. The information collected was primarily biophysical characteristics such as land, land use, varietal use and yields, and socio-economic aspects such as labour use by source and gender in each crop operation, cost of inputs and returns from rice cultivation, income sources and amount, environmental protection practices and perceptions of their economic situation. PRA tools were used in identifying farmers' needs and opportunities to improve the livelihood of their households (Saha *et al.*, 2006). Qualitative information was gathered through FGDs to understand farmers' attitudes toward new technologies (Zolvinski, 2008). In selecting the respondents, special attention was paid to ensuring women from different social groups were included. Secondary data related to biophysical characterization, institutional and infrastructural settings and the presence of NGOs were also collected from the Block Development Office and the State Agricultural Department.

Results

Characteristics of farm households

The average age of male farmers is 44 years. This implies that farmers are in their active age to engage in labour-intensive farming activities. They have the potential to try new varieties and improved crop management practices. Literacy rates are high, at 80%, with an average of 6 years in school. The adult male population, however, has a higher literacy rate of 87% than its female counterpart (73%). Among the young population (5–15 years old), the literacy rate is 99%, indicating that farmers, irrespective of their socio-economic status, are now more aware of the advantages of sending their children to school. The younger populations from the lowest social class are motivated to pursue a university education due to the government's policy of reserving seats for them. It is interesting to note that all girls go to school, whereas 2% of boys are illiterate. This indicates the greater awareness of parents to educate their daughters, which is a positive development in terms of reducing the disparity in access to education between boys and girls.

Table 24.2. Household characteristics in Ersama Block of Jagatsinghpur District of Orissa, India.

Characteristic	Value
Average age (male operator)	44
Average age (wife)	39
Average years in school (male operator)	6
Average years in school (wife)	4
Literacy rate (in %)	80
Adult population (16 years old and above)	
Male	87
Female	73
Young population (5–15 years old)	
Male	98
Female	100

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

Members of farming families are engaged mainly in agriculture. Results revealed that 81% of male adults were engaged directly in farming. Other adult males were engaged in business, private jobs and services, while 52% of the population was non-working, consisting of students and jobless family members (Table 24.2).

Socio-economic groups by farm size

As shown in Fig. 24.1, almost half (48%) of the farm families are very poor, with less than 1 ha of landholding (marginal category), whereas 40% of them have 1–2 ha of cultivated land (small category). Only 12% of the total farm families have more than 2 ha of landholding (medium and large category). These findings indicate that it is difficult for farming households to ensure rice security from their own production only. Rice is grown during the wet season only and on limited lands. Thus, marginal and small farmers have to diversify their sources of income. However, according to Ramasamy and Selvaraj (2006), even though technologies are available to restore the productivity of degraded lands, their adoption by farmers is poor. Hence, this project identified the constraints to adopting of

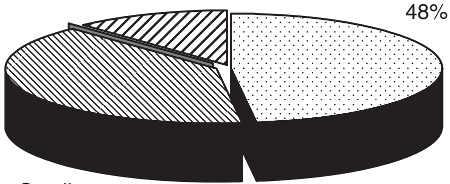

Fig. 24.1. Socio-economic groups by farm size in Jagatsinghpur District in coastal Orissa, India.

technologies and recommended strategies/technologies to overcome these limitations to increasing rice productivity.

Physical characteristics of the cultivated lands

The biophysical characteristics of the research sites are shown in Table 24.3.

Land type

More than half (54%) of the total cultivated area under rice is intermediate lowland and is prone to flooding. Less than half (45%) of the area for rice cultivation is medium land, which is rainfed shallow lowland and prone to drought and submergence. A negligible proportion (1%) of the total rice-growing belt is upland, wherein rice varieties with shorter maturity (90–100 days) are generally grown during the wet season.

Soil type

The soil in the major rice-growing area is sandy loam (59%) and is found mainly in shallow lowland. About 39% of the total rice-growing belt has clay loam soils. This area is mostly intermediate lowland. Only 2% of the total rice area is loamy sand and this can be found in the uplands, where short-duration rice varieties are grown during the wet season. In general, soil salinity is low during the wet season but increases during the dry season, reaching 6–11 dS/m or more. The pH of the soil varies from 5.0 to 7.0.

Sources of irrigation

Some 88% of the total cultivated rice land is not irrigated, specifically in the wet season. However, a low proportion (10%) of farmers use local irrigation systems through harvested rainwater, some of which is stored in small ponds and ditches and some in low-elevation lands. Other farmers irrigate their land using high- and low-lift pumps to lift water from ponds.

Land use

Land use by season

Rice is the main crop grown during the wet season, covering 87% of the total cultivated land. In highland and homestead uplands, farmers grow vegetables on 10% of the total cultivated land during the wet season. About 3% of the cultivated land is left fallow at lower elevations because farmers do not have suitable varieties or management options for these lands.

In the dry season, rice is grown on 5% of the total cultivated land with partial irrigation facilities from harvested rainwater. Some 87% is left fallow because of high soil salinity, poor quality, scarcity of irrigation water, and lack of knowledge on suitable crops that can be grown under such situations. Data show that, starting in February, the electrical conductivity (EC) of

Table 24.3. Physical characteristics of the target villages.

Characteristic	Description
Land type	Lowland (54%), medium land (45%)
Soil type	Sandy loam (59%), clay loam (39%), loamy sand (2%)
Type or severity of salt-affected areas	Coastal salinity (moderate to high)
Type of irrigation	No irrigation (88%)

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

water stored in small ditches and ponds starts to increase, making them unsuitable for irrigation. A higher proportion (8%) of land is planted with vegetables. For both seasons, farmers grow perennial crops such as betel vine, cashew nut, coconut, fruit crops and other horticultural crops on about 48% of the total land area. Fish are raised in ponds and small ditches on about half of these lands as an alternative income source. The rest (4%) is planted to other crops (Table 24.4).

Farming practices in rice cultivation

Improved varieties and associated crop production management practices suitable for saline rice areas are needed to improve the livelihoods of poor farming families. However, before technologies are introduced, scientists need to understand farmers' practices and indigenous knowledge. This section presents farmers' practices in rice cultivation in normal and saline soils and the technologies needed to improve them (Table 24.5).

Rice varieties used

Farmers basically use one or two local varieties from the following: Bhaluki, Bhundi, Lunabokra and Rahspunjar. According to the farmers, the local landraces have certain advantages over the existing improved varieties; that is, early maturity, better ability to withstand salinity stress at early growth stages, higher tolerance of diseases such as false smut and less grain discoloration; they are easy to thresh; and they have less deterioration in seed quality. However, yields are low at about 1.5 t/ha.

Land preparation and crop establishment

Farmers generally start seedbed preparation during the wet season only after the first monsoon rain. They plough and puddle the field with a country plough and then drain out the standing water after 2–3 days to wash out the salts. In the dry season, the seedbed is normally prepared during late December to early January by puddling the field twice. The pre-germinated seeds are sown in wet beds. Seedlings, aged 25–30 days, are transplanted randomly in normal soils, whereas, in saline soils, farmers use 50- to 60-day-old seedlings. Primary tillage of the land is done during the wet season only after the pre-monsoon rain in June, followed by final land preparation after enough rainwater has accumulated in the field during late July to early August. In the dry season, this is done in mid-January. Farmers with marginal to small landholdings usually use a country plough, whereas those with large landholdings use their own or hired tractor/power tiller for land preparation. Wet-season rice is transplanted during late July

Table 24.4. Land use in different seasons in the target villages.

	Wet season		Dry season		Both seasons	
Agriculture	Total area (ha)	%	Total area (ha)	%	Total area (ha)	%
Rice	42.73	87.04	2.55	4.53		
Vegetables	5.07	10.32	4.40	7.82		
Potato			0.04	0.07		
Mixed rabi crops			0.61	1.08		
Betel vine					0.46	3.22
Cashew					3.84	27.07
Coconut					1.54	10.83
Fruits					0.57	3.99
Horticulture					0.40	2.85
Others					0.61	4.27
Fish					6.79	47.78
Fallow	1.29	2.64	48.74	86.51		
Total	49.09	100.00	56.34	100.00	14.20	100.00

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

Table 24.5. Current farming practices adopted by farmers in rice cultivation during the wet season and new technologies being introduced.

Field operation	Normal soil	Saline soil	Technology being introduced
Land preparation	Cultivation after first monsoon showers, followed by puddling before transplanting	Cultivation after first monsoon showers, followed by puddling before transplanting	Summer ploughing during February–March, followed by shallow tillage during May prior to monsoon. Puddling twice at 7- to 10-day intervals and proper levelling
Selection of variety	Long-duration photosensitive HYVs (high-yielding varieties) of rice such as Gayatri, Savitri, etc.	Local landraces (long duration) such as Rashpunjar, Bhaluki, Bhundi, etc.	Salt-tolerant HYVs of rice such as Lunishree, SR26B in intermediate lowland, SR26B and Pankaj in shallow lowland
Time of sowing in nursery	After receipt of first monsoon rain, that is, second fortnight of June	After first monsoon rain, that is, second fortnight of June	No new technology introduced since sowing time is dependent on rain
Nursery management	No fertilizer or chemicals	No fertilizer or chemicals	Spraying of pretilachlor at 0.8 kg/ha to reduce weed infestation; application of well-decomposed FYM at 5 t/ha during land preparation and fertilizers at 10 kg/ha NPK for robust and tall seedlings
Seedling age and spacing	25- to 30-day-old seedlings; random transplanting	50- to 60-day-old tall seedlings; random transplanting	30- to 40-day-old seedlings and planting at 15 × 15 cm spacing for shallow lowland; 50-day-old seedlings and planting at 15 × 10 cm spacing for intermediate lowlands
Planting time	Late July or early August	Middle of August	Late July to early August
Nutrient management	N at 25–30 kg/ha as basal only or no fertilizer	No fertilizer	Application of well-decomposed FYM at 5 t/ha + prilled urea at 20 kg N/ha or green manuring with *Sesbania* with 15 kg seed/ha or urea super granules at 45 kg N/ha in intermediate lowland Green manuring with *Sesbania* + *Azolla* or green manuring with *Sesbania* + urea (20 kg N/ha) in shallow lowland rice fields
Weed management	Hand weeding at 40–50 days after planting or no weeding	No weeding	Mechanical weeding by cono-weeder at 25–30 days after planting
Plant protection	No plant protection	No plant protection	Seedling root dipping in chloropyriphos solution to protect against stem borer
Harvest and postharvest operations	Late harvesting due to labour scarcity and standing water, threshing by bullock or manually and storage	Late harvesting due to labour scarcity and standing water, threshing by bullock or manually and storage	Harvesting at proper time (75% maturity) to avoid shattering loss, threshing by paddle thresher available on hired basis, proper cleaning and drying before storage
Cropping system	Rice–fallow or rice–blackgram/greengram	Rice–fallow	Rice–rice or rice–sunflower/*Basella*/watermelon/okra/chilli/pumpkin/groundnut depending on salinity and land situation and by partial irrigation with harvested rainwater

to mid-August after sufficient washing and dilution of salts by rainwater. This facilitates a reduction in soil salinity to ensure better crop establishment and minimal crop damage at early growth stages. Wider plant spacing is used because farmers believe that it reduces the risk of crop lodging at the late vegetative and flowering stages, especially when cyclonic disturbances with high wind velocity and heavy rainfall occur. Growing dry-season rice, although not a common practice in this area, started as a contingency measure in 2000 after the complete loss of the wet-season crop due to the Super Cyclone in 1999. The crop often suffers significant yield losses due to water scarcity during the flowering and ripening stages, and higher soil salinity is usually encountered because of increasing temperatures from March onward. Irrigation is generally given for 3–5 days after the standing water disappears. The crop is harvested manually using a sickle and threshing is also done manually by beating small paddy bundles against a bamboo frame/wooden platform or by trampling using bullocks (Saha *et al*., 2006).

Fertilizer application and plant protection

Farmers in coastal Orissa generally do not apply chemical fertilizers. Only a few of them apply N fertilizer after seedling establishment. No control measures are taken against insect pests and diseases during the wet season. Manual weeding is done once or twice during crop growth, although some farmers do not use any weed control measures.

Cropping pattern

The rice–fallow cropping sequence is predominant in the shallow lowland in all the villages. However, rice–rice, rice–sunflower and rice–vegetable cropping sequences were adopted in limited areas under partial irrigation, particularly in the shallow lowlands in villages such as Chaulia, Gangadevi and Kimilo. In Kankan village, farmers raise vegetables (including potato, chilli and *Basella*), watermelon and cowpea during the dry season on homestead highlands and medium lands with partial irrigation. Thus, more farmers establish small ponds to harvest rainwater and grow other crops for domestic consumption and sales.

Gender division of labour in rice production

Labour is an important resource in rice production. Small and marginal rice-farming households rely heavily on the availability and quality of family labour. To complete rice operations during peak seasons, members exchange their labour or hire additional labourers. Within a farm household, the wife and husband have assigned tasks depending on their degree of specialization and culturally dictated tasks. These tasks may be done separately or jointly by men and women. Men are responsible mainly for preparing the land and establishing nurseries, whereas the women do the transplanting, weeding and application of farmyard manure (FYM) on the soil. Both men and women participate in the rice harvest. Postharvest activities such as manual threshing and winnowing are done mainly by the women. During the wet season, men and women contribute 66 and 23%, respectively, of the total labour inputs (71 days/ha) in rice production. The rest (11%) is done jointly by both men and women (Table 24.6).

Labour inputs of female family members were higher among the marginal farming households than on small and medium/large farms. These results indicate that female family labour participation increases with poverty. In general, marginal farm households depend on female members to fulfil the labour requirements in rice production. With the participation of female family members, farming households save on expenditures on pulling seedlings from nurseries, transplanting, weeding, harvesting and threshing. Women are also mainly responsible for selecting seeds for the next season and storing them. Aside from crop production activities, women are engaged in dairy management, particularly collecting fodder and feeding the livestock. However, despite their contributions to rice production and postharvest, women lack access to the seeds of improved varieties and lack information on how to maintain seed quality and on crop management technologies. Among nuclear households, wives are compelled to make ‘on-the-spot’ decisions when their husbands migrate to urban and other rural areas for non-farm employment. Thus, they need to be trained, not only in

Table 24.6. Labour input (person-day/ha) by size of landholding according to gender division of labour.

	Marginal		Small		Medium and large		Total	
Sources of labour	Days	%	Days	%	Days	%	Days	%
Family labour								
Male	46	64	43	61	27	41	43	61
Female	18	25	14	21	10	15	16	22
Total	64	89	58	82	37	56	58	83
Hired labour								
Male	–	–	4	6	18	28	4	5
Female	–	–	1	1	4	7	1	1
Total hired labour days	–	–	5	7	22	35	5	7
Other crop operations shared by male and female	8	11	7	11	6	9	7	11
Total labour								
Male	46	64	47	67	45	69	47	66
Female	18	25	16	22	14	22	17	23
Both male and female	8	11	7	11	6	9	7	11
Total labour days	72	100	70	100	65	100	71	100

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

improved seed health practices but also in all aspects of rice production.

Costs and returns of rice cultivation

Rice production in these areas is quite risky. Every year, farmers gamble their limited cash, time and energy to produce their staple food. They have a limited marketable surplus to sell to the market and have to diversify their sources of income and livelihood. Farmers face increasing costs of inputs such as fuel and chemical fertilizer and wages for hired labourers, thus reducing their net returns. Technologies are needed to increase productivity and profitability in rice production. Table 24.7 shows the net returns on rice production based on the salt-affected parcels of sample farmers interviewed.

On average, farmers spent Indian rupees (INR) 6500/ha on rice production. Among the requirements for rice cultivation, the highest proportion of the expenditures was on hiring labourers (78%). A low proportion was spent on seed and seedling establishment (10%), fertilizer (5%) and land preparation (5%). The total cost of inputs during the wet season was higher for marginal farmers (INR6745/ha) than for small (INR6359/ha) and medium to large farmers (INR5727/ha). The higher cost of cultivation for marginal farmers can be attributed to the rental of tractors for land preparation and the purchase of seed and more labour for different agricultural operations, particularly among farming households whose principal male farmers have migrated.

Total gross returns were INR8320/ha, of which 91% was obtained mainly by imputing the value of the grain and straw (9%). Total gross returns were higher for marginal farmers (INR8889/ha) than for small (INR7906/ha) and medium to large farmers (INR7419/ha). The average net returns obtained by farmers from rice cultivation without considering the size of their landholding were INR1852/ha. Among the different landholding categories, marginal farm families earned the highest returns (INR2146/ha) compared with small (INR1547/ha) and medium to large farmers (INR1692/ha). This is probably because farm labourers of households with marginal landholdings consist mostly of family members; thus, they are very much concerned with their production as this is their main source of income and food. This is shown by the high yield (1.96 t/ha) obtained by marginal farmers.

Sources of livelihood

Poor farming families resort to different sources of livelihood to spread their risks. Among the

Table 24.7. Costs and returns of rice production (INR/ha) by size of landholding.

Item	Marginal	Small	Medium and large	Average
Parcel area (ha)	0.55	0.87	2.06	0.86
Yield (in t/ha)	1.96	1.78	1.63	1.89
Returns (INR)				
Value of production	8061	7238	6836	7585
Value of by-products	828	669	583	735
Total returns	8889	7906	7419	8320
Costs (INR)				
Plough	399	179	165	283
Mechanical plough	88			42
Seed cost	676	656	463	642
Fertilizer cost	313	317	236	305
Animal manure	19	40	128	40
Pesticide cost	64	56	62	60
Labour cost	5152	5028	4592	5035
Other expenditure	33	84	82	59
Total costs	6743	6359	5727	6468
Net returns	2146	1547	1692	1852

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

sources of income, animal rearing and fish cultivation or fishing contributed 42% of the total income, the highest income-earning activity, closely followed by the cultivation of agricultural and vegetable crops (35%), wherein 13% came from rice and 22% from other crops (i.e. vegetables, betel vine, cowpea, cashew nuts, chilli and other mixed rabi crops). Other means of income were agriculture related (15%), such as working as agricultural labourers for other farms and rental fees for agricultural inputs such as power tillers, tractors and threshers by medium and large farmers. About 8% of the total income was generated from other non-farm sources such as business and services in different sectors (Fig. 24.2).

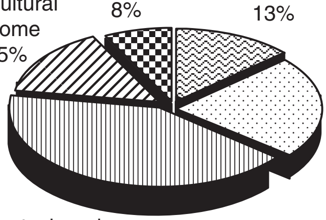

Fig. 24.2. Proportion of income obtained from different sources.

Both men and women from marginal households generally earn the highest proportion of their income (34%) by working as agricultural labourers, followed by cultivating rice (23%) and rearing livestock and fish (21%). A significant amount (11%) was also obtained from other non-farm activities such as running small shops and pulling a rickshaw (Fig. 24.3a). For small farming families, livestock, fish rearing and catching fish (51%) were the highest income earners, followed by the cultivation of perennial crops such as betel vine, coconut and cashew nut (15%), closely followed by rice cultivation (12%; Fig. 24.3b). The same trend was observed for medium and large farmers. Half of their total family income generally came from livestock rearing and fish cultivation. About 36% of their total income was generated from the cultivation of other crops such as betel vine, coconut, cashew nut, banana and papaya. Only 4% of their total income came from rice cultivation, which indicated that, when household size increased, dependence on rice cultivation decreased (Fig. 24.3c).

Constraints to improving crop productivity and livelihood

Some 92% of the respondents identified a lack of awareness of suitable technologies and

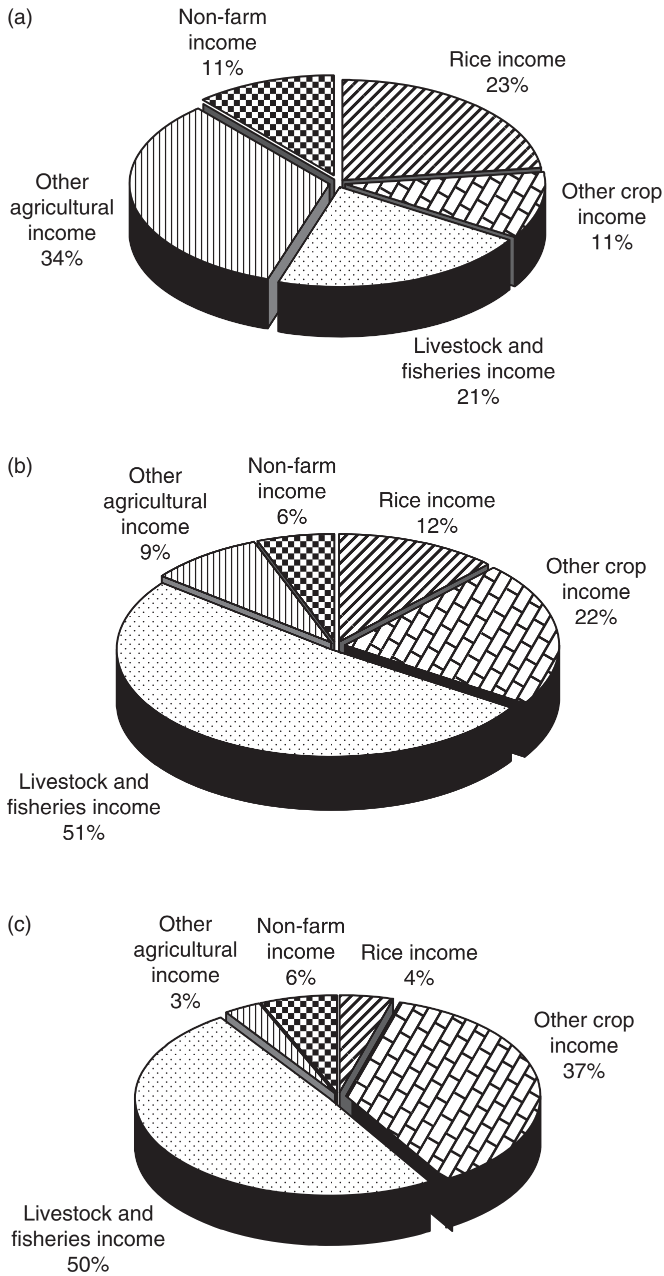

Fig. 24.3. Proportion of income sources to total household income of (a) marginal farming households, (b) small farming households and (c) large farming households.

technical knowledge as the main constraints to improving crop productivity. Since this region is generally affected by natural calamities such as flood, drought and cyclones almost every year, about 70% of the respondents felt that the problem of natural calamities was the second most important constraint to improving their livelihood. The unavailability of salt- and submergence-tolerant rice varieties (38%) ranked third, whereas the lack of capital for

Table 24.8. Constraints identified by farmers as obstacles to improving their livelihood.

Problem	Number	%
Lack of technology and technical knowledge	34	92
Calamities	26	70
Lack of salt- and submergence-tolerant varieties	14	38
Lack of capital	11	30
Lack of employment opportunities	5	14
Monocropping	5	14
Small landholding	5	14
Poor infrastructure	3	8
Poor economic conditions	2	5
Low price of outputs	2	5
Total	107	

Baseline Survey on Rural Households, IRRI–ICAR–CRRI CPWF Project, 2004.

field operations ranked fourth. Other important problems mentioned by the respondents were a lack of employment opportunities in the villages, monocropping of rice, small landholdings, poor infrastructure, poor economic conditions and the low price of outputs in the village market (Table 24.8).

Opportunities for improving farmers' livelihood

Opportunities to solve these problems were discussed by concerned scientists, farmers and field functionaries of the State Agricultural Department working at the village level. To improve land and water productivity, several technologies were validated and farmers evaluated these technologies in their own fields with the guidance of the research team of the CRRI in participatory experiments. These technologies included the use of salt-tolerant rice varieties for the wet and dry seasons, new techniques for land preparation, early transplanting of dry-season rice, the use of fertilizers and green manures, alternative sources of good-quality water for irrigation and expanding the area grown under sunflower as a dry-season crop after wet-season rice (Singh *et al.*, Chapter 19, this volume). It is seemingly now too early to make quantitative assessments of the adoption of the technologies introduced by the project at target sites. Thus, qualitative assessments were conducted to capture the most significant changes that have occurred due to the project and also to elicit farmers' experiences in validating the technologies (Zolvinski, 2008). Farmers' feedback on the introduced technologies is discussed below.

Improved rice varieties

Farmers grew salt-tolerant improved varieties such as SR26B, Pankaj, Gayatri and Ramchandi during the wet season and CSR-4, Canning, Annapurna and Naveen during the dry season. Lunishree and SR26B in intermediate lowlands, SR26B and Pankaj in shallow lowlands under saline conditions and Gayatri in non-saline conditions performed well during the wet season. By using improved varieties, the additional cost (INR400/ha) is only the difference in seed price. With the price of local seeds at INR5/kg and improved seeds at INR13/kg, farmers are getting additional net returns of INR7400/ha. Net returns from local varieties are INR5600/ha, with INR13,000/ha from improved varieties.

CSR4 and Annapurna did well during the dry season. The increased yield from the improved varieties grown in the wet season, plus an additional/expanded dry-season rice crop, allowed farm households to grow enough rice for the whole year. 'We no longer think about whether we will have enough to eat the next year', say the farmers. Farmers reported that improved varieties yielded 2.5–4 t/ha compared with traditional varieties that had a maximum yield of 1.5 t/ha. For grain quality, the farmers liked the improved varieties with medium-slender grain because their price was INR800 (US$19.18) per quintal compared with medium-bold grains at INR600 (US$13.63) per quintal. Farmers indicated more satisfaction after eating bolder grains than after eating finer grains because the former digested easily when eaten. Farmers preferred varieties that 'lasted longer in the stomach' as their work required more energy. However, farmers complained that the improved varieties were more susceptible to stem borer infestation, which damaged 10–20% of the crop. In contrast, traditional varieties had good pest tolerance. The women also mentioned that the improved varieties were not suitable for making fermented breakfast (*pokhal*), which traditionally was prepared by the households in these villages. Farmers also preferred salt- and submergence-tolerant varieties that were resistant to lodging and had medium-slender grains that commanded a higher price in the market (Zolvinski, 2008). More salt-tolerant lines are being tested and evaluated through participatory varietal selection.

New techniques for land preparation

Farmers started using new techniques for land preparation, such as ploughing during the summer months (February–March) and using hired tractors and power tillers for puddling. Summer ploughing was done once or twice to reduce salt accumulation on the surface, followed by shallow tillage during May prior to the monsoon.

Early transplanting for dry-season rice

Farmers noticed an improvement in crop conditions when transplanting in mid-January, when salinity was lower. The usual practice was to transplant about 1 month later. Farmers now prepare their nurseries in December, in time for early transplanting. Earlier transplanting does not interfere with field operations for the rainy-season crop. Farmers say that timely nursery establishment is important for the dry season and they are willing to wait to harvest the rainy-season crop as it will not incur a yield penalty.

Use of chemical fertilizers

Before the project, farmers did not use any organic or chemical fertilizers during the wet season. With the information provided through CRRI scientists, they learned the contribution to productivity of using FYM and chemical fertilizers. They used diammonium phosphate, GroMor, urea and potash in limited amounts through soil incorporation by ploughing at the time of final land preparation, particularly under shallow lowland conditions. More fertilizers, particularly N (about 80 kg/ha), were being used for dry-season rice, whereas some farmers topdressed N and K. Even during nursery seedbed preparation, farmers started to apply fertilizers through soil incorporation and topdressing (N for wet-season rice), if it was necessary. These new practices helped to increase the growth and vigour of seedlings and to improve the establishment of transplanted rice under stress conditions (drought, salinity and submergence). However, a few farmers still do not use any fertilizer because of a shortage of capital.

Use of green manures

Farmers said that they had seen the difference in crop performance when they used the *Sesbania* green-manuring system and *Azolla* (an aquatic fern) as biofertilizers, particularly during the dry season. However, *Sesbania* does better in clay soils, which have better moisture-holding capacity, than in sandy soils. Farmers tend to highlight the weed control properties of *Azolla* more than its soil nutrient benefits. In their words, *Azolla* 'keeps the water cooler', which they believe inhibits weed growth. Scientists admit that *Azolla* can control weeds, but they dispute the farmers' explanation of the process. *Azolla* inoculum, according to the farmers, can be multiplied easily in small ponds. Some farmers use green manures with *Sesbania* combined with *Azolla* as a dual culture. In some cases, green manure is combined with urea, as in shallow lowland rice fields, to produce a reasonably good yield. In intermediate lowland areas, farmers apply well-decomposed FYM plus prilled urea or green manures using *Sesbania*. These nutrient management practices speed the growth of rice seedlings, which then increases their tolerance of salinity and submergence stresses.

Using older seedlings and closer seedling spacing

Farmers are convinced that the new practice of transplanting 50- to 60-day-old seedlings at 15-cm intervals can improve crop performance. They observed that rice had better tillering ability and better panicles with these practices. This is comparable with the usual practice of transplanting 30- to 40-day-old seedlings randomly at about twice the length of the new spacing. Sometimes, they have to use seedlings older than 50 days when rainfall delays transplanting.

Alternative sources of high-quality water for irrigation

Most farmers use harvested rainwater stored in small ponds or some ditches for irrigating their nursery and transplanted crops, particularly during the dry season. However, the quality of irrigation water is very poor because of the high salinity in the area. With the construction of sluice gates across the Hansua River, farmers in Kimilo village revealed that the availability of fresh water for irrigation had increased. Nevertheless, in Ambiki village, which still has no sluice gate, saltwater intrudes directly into agricultural fields.

Expanding the area grown under sunflower as a dry-season crop after rice

The sunflower crop is well accepted by the farming community at the target site during the dry season because of its wide adaptability in saline soil, lower water requirement than summer rice and supply of edible oil for home consumption. The average cultivation cost of a sunflower crop is INR11,000/ha and the net returns are INR16,300/ha. This new crop grown after rice is well accepted by farmers. Although rice is a staple food crop, cooking oil is an important household commodity. Farmers, especially the women, would like to double the area planted to sunflower. They like the fact that sunflower can be pressed for cooking oil, which saves them money usually spent on purchasing this essential household commodity. The residue or 'cake' from the pressing process can be used for livestock/fish feed and as fuel for cooking.

Farmers' training on rice seed health management and seed multiplication

The production of healthy seed and its proper storage are very important in coastal environments because of the prevalence of high temperature and humidity. Thus, there is a need to enhance farmers' awareness of seed health management for improving crop yield. Keeping this in mind, farmers' training on 'Rice Seed Health Management' was organized in 2005. Twenty-five men and women farmers from different adopted villages participated. Hands-on training was carried out on the selection of healthy seeds from rice fields, the cleaning and grading of harvested seeds and seed processing and safe storage. Trained farmers are now producing seeds from the improved rice varieties in large quantities under the supervision of CRRI scientists. The seeds they produce are returned for distribution among other farmers. This has helped greatly in disseminating improved varieties.

Conclusions

Farmers gave positive feedback on participatory experiments on salt-tolerant rice varieties and associated crop and water management technologies conducted in their fields for both the wet and dry season. Improved varieties showed at least double the yield of traditional varieties, with a yield potential of 1.5 t/ha. Sunflower grown after rice is well accepted during the dry season. With the new varieties, farmers feel more secure that they will have a continuous supply of rice for the whole year, instead of for only 4–9 months, as occurred before the project began. Moreover, scientists in the past seldom consulted women farmers on varietal use and crop management practices. For the first time, women were involved in training on seed health practices and also in project activities such as field days, meetings, etc. As a result, women are now more confident and outspoken in giving their views, which are important in facilitating the uptake of technologies. Through farmer participatory approaches, validation of acceptable technologies increases their chances for adoption. Aside from improving the livelihood of the people in these coastal saline environments, this project has led to paradigm shifts among biophysical scientists in working with farmers and communities.

Several lessons were learned from this research: (i) the need for strong interaction among biological and social scientists in problem-oriented research; (ii) the use of community participatory approaches during the designing, planning and validation of technologies, and their dissemination; (iii) the need to enhance the capacity of both men and women in rice production and improved seed management; (iv) the need to anticipate and address constraints to the widespread adoption of the technologies, for example, the lack of supply of *Azolla* inoculum, seeds of new varieties at the right time, sunflower seeds and sources of good-quality irrigation water for the dry season; (v) the inclusion of both men and women farmers in evaluating adapted salt-tolerant varieties; (vi) the expansion of sunflower production as a crop suitable for saline areas, after rice; and (vii) the evaluation of additional crops that are adapted to these saline areas and have high market value.

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References

Ramasamy, C. and Selvaraj, K.N. (2006) Do drought tolerant rice and salinity tolerant rice offer a panacea for Indian farmers farming in fragile environments? *ABSP II Newsletter Quarterly* 1(2), 6.

Saha, S., Mahata, K.R., Singh, D.P., Paris, T.R. and Cueno, D.R. (2006) Baseline socio-economic surveys in selected coastal saline villages in Orissa, India. IRRI–ICAR–CRRI Collaborative Research Project. Challenge Program on Water and Food (CPWF) Project Number 7. Social Sciences Division, International Rice Research Institute, Philippines.

Scardaci, S.C., Eke A.U., Hill, J.E., Shannon, M.C. and Rhoades, J.D. (1996) Water and soil salinity studies on California rice. *Rice Publication No 2*. Cooperative Extension, University of California, Colusa, California.

Thiruchelvam, S. and Pathmarajah, S. (1999) An economic analysis of salinity problems in the Mahaweli River System H Irrigation Scheme in Sri Lanka. EEPSEA Research Report No rr1999082, Singapore.

Zolvinski, S. (2008) Qualitative impact assessment for coastal saline-affected villages in Orissa, India. Unpublished report. Social Sciences Division, International Rice Research Institute, Los Baños, Philippines.

25 Participatory Management of Coastal Resources: a Case Study of Baganchra–Badurgacha Subproject in the South-west of Bangladesh

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Abstract

Conflicts in the use of land and water resources for agriculture versus aquaculture constitute a key issue in the coastal zone of Bangladesh. Increasing areas of rice land are converted to aquaculture farms producing shrimp and fin fish which require brackish water. Powerful shrimp producers rent these lands owned mainly by small and medium farmers. The lands are abandoned after a few years when the profitability of these ventures declines. This rapid and unregulated exploitation generates conflict between shrimp producers and landowners, and causes eventual loss in the productivity of valuable land resources. The Local Government Engineering Department (LGED) demonstrated the effectiveness of participatory water resource management in addressing this problem and in enhancing sustainable development and management of the land and water resources in the coastal zone in the south-west of Bangladesh. The LGED implemented various subprojects, each covering 1000 ha or less, involving the development of water infrastructure in consultation with stakeholders. Local people are involved in subproject planning, implementation and operation and maintenance (O&M). This generates local enthusiasm for the subproject and facilitates the formation of water management associations (WMAs). Case studies reveal that the local people are key functionaries in the sustainable management of land and water and the WMAs are able to regulate water uses, provide a forum for resolving conflicts and play an important role in making relevant policies at the local level.

Introduction

The deltaic plain in Bangladesh encompasses about 3 million ha of coastal land that is subjected to tidal flooding. There are growing concerns about incompatible and unsustainable uses of this land, which potentially can yield high economic returns, provided the environment is managed properly. Tidal fluctuations of the water level determine crop production on this land. Mainly indigenous rainfed varieties of rice are grown in the monsoon season. In recent years, the rice areas have been converted extensively to traditional aquaculture, which gives higher returns than crop cultivation. This very old practice involves the trapping and growing of shrimps and fin fish in the tidal channels and low-lying intertidal areas. The local tiger prawn, most commonly used in shrimp farming, breeds on shallow banks in the open seas, where tides and current pick up their larvae and carry them inland to estuaries, ponds and lagoons. After growing quickly in the brackish water, they return to sea to repeat the cycle. Powerful shrimp producers from outside the area rent these lands from marginal, small and medium farmers to use them for short-term profits. Shrimp aquaculture requires saltwater flooding of these rice areas. After a few years of aquaculture, the increase in the salinity level of the cultivated soils impedes crop production, degrades biodiversity and compels farmers to leave their lands fallow. There has been a reduction in the area planted with *aman* rice in the monsoon by more than 21% from 1984/85 to 2004/05 (BBS, 1987, 2008). The diversity of trees, weeds and aquatic plant species has also reduced gradually (Karim, 2006). As a result, conflicts between rice farmers and shrimp producers have become more frequent in recent years (MOEF, 1999; WARPO, 2004). It is important to find a process to prevent this rapid exploitation of lands for shrimp production in order to settle conflicts that have developed in the coastal zone (Brandon, 1998). It is argued that the situation could be resolved if local communities were given the opportunity to decide for themselves what is in their best interests in the management of water through exposure to better alternative uses of such land in the saline–freshwater interface zone, particularly given recent developments in brackishwater farming technology. The present study provides an overview of the current state of the coastal zone in Bangladesh and examines, by means of a case study, the effectiveness of local stakeholder involvement in building a consensus over the use of land and water that ensures equitable access to these resources.

Approach and Methods

The account of the present status of the coastal zone provided in this chapter is based on secondary information sources. The case study undertaken is on the Small Scale Water Resources Development Sector Project (SSWRDSP) implemented by the Local Government and Engineering Department (LGED) of Bangladesh. Information for the case study was collected through field visits, land use assessments using land use maps, beneficiary household surveys and interviews using structured questionnaires, group discussion and annual impact monitoring from 1997 to 2007. The beneficiary households were surveyed in 2003 and 2006. Each survey covered 20 households consisting of five from each of the four categories of large (more than 3 ha), medium (1–3 ha), small (0.5 to less than 1 ha) and landless (less than 0.5 ha) farms. Non-governmental organization (NGO) fieldworkers were actively involved in the survey. Subproject status, infrastructure and costs and pre-subproject data on land utilization, cropped area and yield levels and fisheries production were collected from secondary sources. These included the project final report and subproject appraisal and feasibility reports.

The coastal zone of Bangladesh

Biophysical description

Lands subject to tidal flooding extend over most of the southern part of Bangladesh (Fig. 25.1). The country has 710 km of continuous coastline along the Bay of Bengal (WARPO, 2003). Heavy tidal clays dominate the low-lying landscape traversed by innumerable tidal rivers and creeks (UNDP/FAO, 1988). Under the influence of changes in sea level in the Bay of Bengal, the tidal reach extends as far in as 150 km. The combination of high winds (with speeds up to 225 km/h) accompanied by sea swells can cause tidal surges to reach as high as 9 m. Diurnal water level fluctuation and the corresponding incoming and outgoing tidal flows are the forces that drive ecosystem processes and human activities in the coastal zone. Tidal water in the rivers remains saline throughout the year in the south-west, but is saline in the dry season only in the northern parts of Khulna District. The seasonal flooding depth is normally less

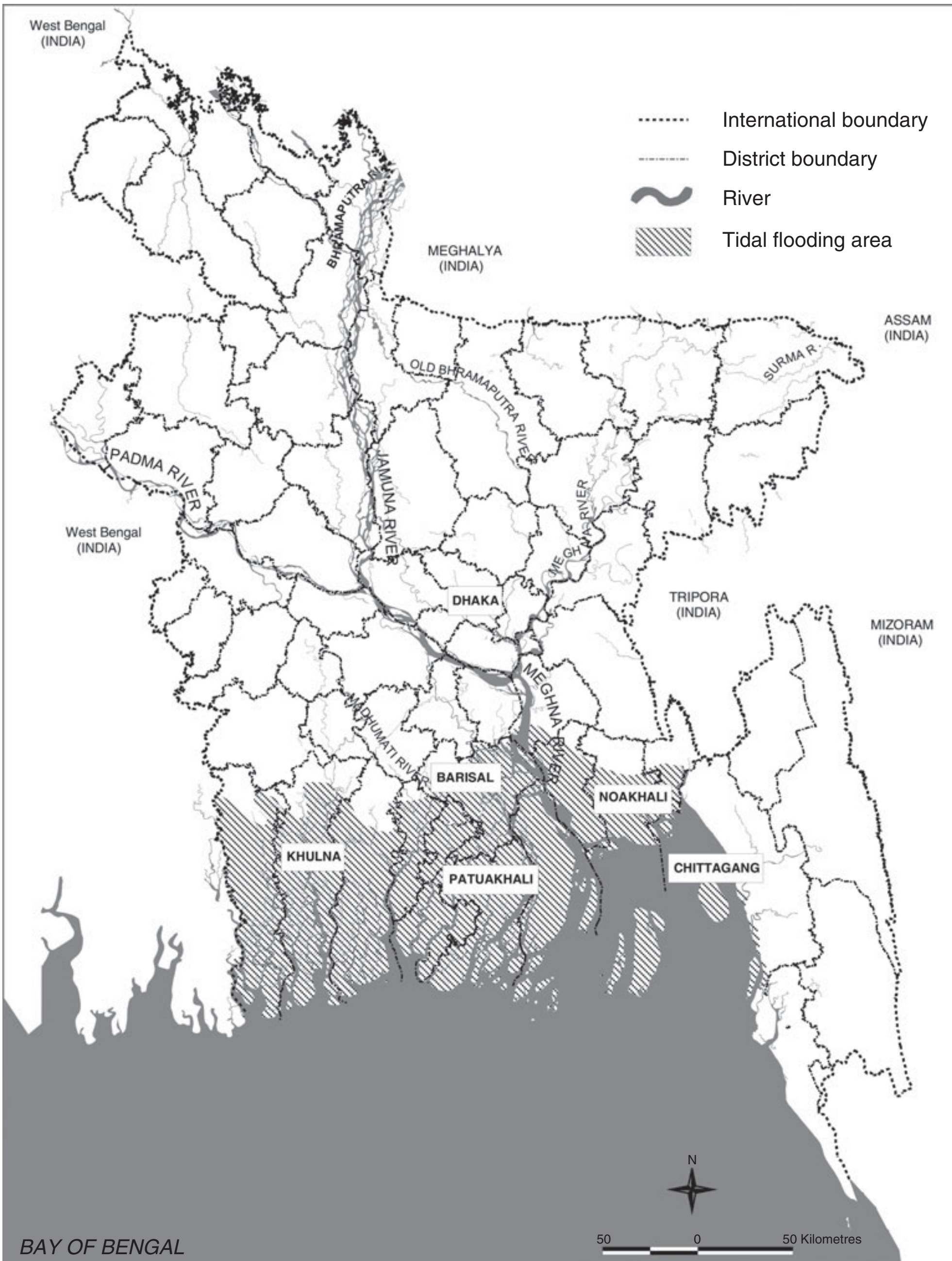

Fig. 25.1. Tidal affected area in Bangladesh.

than 1 m. Soils are saline during the dry season, but the salinity drops during the rainy season, especially on land protected by embankments (Brammer, 1997). The Bangladesh Water Development Board has constructed a series of embankments and polders to provide tidal flood protection and thereby enable crop production.

Land tenure

The practice of sharecropping is common whereby absentee landowners lease their holdings to tenants for crop cultivation and shrimp farming, or engage landless labourers in cattle/buffalo herding (Brammer, 1997). Exceptions occur in the northern parts of Barisal and Chittagong districts where more owner-cultivators operate small farms. A land reclamation project study in Noakhali District reported that more than two-thirds of the households were landless (BWDB, 1987). Of all owner-operated farms, small-scale holdings of < 1 ha accounted for 21%, whereas medium- and large-scale holdings of > 1 ha constituted 4%. Medium and large farmers own 50% of the land and live mainly outside the polder area. The small-scale farmers own 7% of the land, but cultivate another 24% through sharecropping. Sharecropping accounts for 60% of the cultivated land owned by absentee landowners and medium- and large-scale farmers. Lands are also cultivated by contractors who either recruit local labour or bring in migrant labour. Such land tenure arrangements provide little or no incentive for tenant farmers to intensify crop and shrimp production. The government owns land in low-lying areas that is leased to interested parties. These lands, which abound in natural fish populations, traditionally have been a source of livelihood for local fishermen. Recent conversion of these areas into aquaculture farms has created social problems among communities in the area whose access to the natural resources and supply of domestic water is disrupted. Small farmers become virtually landless when their rice fields become uncultivable because of inundation with saltwater from adjacent aquaculture farms.

Cropping system

Crop cultivation covers about two-thirds of the coastal zone. Locally adapted *aman* rice is the principal crop, transplanted in the monsoon season and harvested in the dry season. Vegetables, chilli, peas or sesame follow the main rice crop on the margins of low-lying lands in the dry season. Limited areas are suitable for crop cultivation during the dry season because of soil salinity build-up.

Fisheries

In recent years, aquaculture has expanded rapidly because of its profitability and demand from the export market. In the past, about 52,000 ha of coastal land were under traditional aquaculture, producing shrimp and fin fish (UNDP, 1988a) in rotation with rice cultivation. With increasing demand, traditional aquaculture has expanded within and outside the polders. Shrimp production has also expanded into cropped land that has been inundated with brackish water. The current total aquaculture area is estimated at 141,000 ha, producing 100,800 t and accounting for about 5% of the total annual fish production (inland capture and culture plus marine fisheries) in the country (BBS, 2005). The shrimp and fin fish yields associated with traditional aquaculture are generally low. Furthermore, this system is beset with the problem of unpredictable production, which depends on the availability as well as abundance of natural shrimp recruited from the wild. The presence and abundance of natural competitors and predators of the shrimp also influences the survival, growth and quality of shrimp. Wild seeds are collected in a crude way by scooping along shallow banks and, in the process, the less desirable varieties or undesirable fish and shrimp species are destroyed, hence affecting their natural population adversely (UNDP, 1988a) and exacerbating the problem of declining fisheries resources (Berg *et al.*, 1998). This situation has changed with the availability of hatchery-raised shrimp fry.

Forests

Mangroves constitute the dominant vegetation of the tidal forest in the coastal zone. Mahmood (1986) reported that natural mangrove forest occupied about 587,000 ha and planted mangrove forest about 24,000 ha. The coastal zone accounts for approximately 30–50% of total government forestry production. Large-scale conversion of the coastal land area into shrimp ponds has resulted in the destruction of the mangrove forests. Private ownership or granting user's rights to fishers within these forests has resulted in a decrease in natural fish catches (UNDP, 1988b).

Strategies and plans

The Bangladesh government recognizes the importance of an integrated approach for water resources management in response to growing water demands. The National Water Policy emphasizes participatory inputs into the planning and implementation of water management infrastructure for agricultural use (MWR, 1999). The policy also emphasizes rational multipurpose water use without compromising the integrity of the aquatic ecosystem. The national agricultural policy supports bottom-up planning through people's participation and its implementation at the village level to ensure maximum utilization of land (MOA, 1999). The strategic plan targets appropriate land use for the production of rice, pulses, spices and oilseeds on 2.9 million ha in the coastal zone. Fisheries development strategies emphasize the improvement of aquaculture extension and development of hatcheries as an important support industry for the culture of shrimp and other aquatic species (MOFL, 1998). The Department of Fisheries has prepared an aquaculture extension action plan. Committees have been formed at the divisional, district and subdistrict levels to implement regulations relating to shrimp culture and to mitigate constraints to facilitate shrimp production. The integrated forest management plan aims to prevent adverse impacts on mangroves and integrating traditional land use activities. The national environmental management action plan introduced a participatory mechanism to identify the principal environmental issues in the country (NEMAP, 1995). The sustainable environmental management programme has embarked on institution-based participatory ecosystem management activities (MOEF, 1992).

There is also active NGO participation at the grassroots level. A survey conducted by the Bangladesh Bureau of Statistics (BBS, 1999) identified 329 local and regional NGOs in the coastal districts. A number of NGOs work with fisheries communities (WARPO, 2003) and their activities include dissemination of government policies on fishery and fishing community management, and the organization of issued-based forums.

Two related issues faced by the coastal communities are those concerning land and water use and impacts on the quality of these resources.

Salinity intrusion

Salinity intrusion, both through surface and underground water, is a major concern in the coastal zone (UNDP, 1989). The boundary of the 2000 mmhos/cm salinity threshold for rice varies with season. In the driest month (March), 100 subdistricts in the coastal zone are considered unsuitable for rice cultivation because of the high salinity of the water. The establishment of the coastal embankment system, consisting of more than 100 polders, has been fairly successful in limiting the ingress of saltwater into the cropped fields (Mahbullah, 1988). Currently, two factors contribute to the expansion of the saline-affected area. First, the low flow of the Ganges River because of the diversion at the Farakka barrage in neighbouring India has caused an increase in the extent of saltwater intrusion during the dry season (MPO, 1986; Hossain, 2003). Second, shrimp cultivation in brackish water has subjected the adjacent rice fields to increasing salinity. The salinity-affected area increased from 3438 km^2 in the pre-diversion period (1967–1975) to 11,478 km^2, including 5700 km^2 of mangrove forest (BWDB, 1999).

Aquaculture versus rice

The national conservation strategy report identified six major land use conflicts in rural areas (IUCN/MOEF, 1992). Two of these conflicts, namely agriculture versus shrimp culture and capture fisheries and forestland versus shrimp and capture fisheries, occur in the coastal zone. By the late 1980s, an estimated 120,000 ha of rice land had been converted to seasonal or annual aquaculture (UNDP, 1989). The area reached more than 141,000 ha by early 2005 (BBS, 2005). In view of the emerging problems of land degradation through unsustainable and indiscriminate use by shrimp operators for short-term gains, the government now discourages year-round brackishwater aquaculture and private landowners hesitate to commit investment of a permanent nature. The agricultural sector review (UNDP, 1988a) recommended that agricultural use should be given priority over brackishwater aquaculture where cultivation was feasible. However, in areas where aquaculture and rice cultivation alternate seasonally, the yield of rice is declining rapidly, whereas aquaculture provides higher net returns, even in comparison with modern rice varieties.

In brackishwater areas having potential for aquaculture development, semi-intensive systems using more feed and improved cultural practices could raise net returns by five times compared with the traditional practice of shrimp culture. This potential can be harnessed only if aquaculture receives adequate support for growth as an agro-industry. Adoption of semi-intensive methods can increase production as well as generate employment. However, it is important to ensure that in creating conditions favourable for aquaculture, the interests of small-scale farmers are not compromised. The brackishwater areas targeted for aquaculture development are either under private or public ownership. The privately owned lands are small in size. Land belonging to several owners is procured or leased for making a brackishwater aquaculture farm, locally called a *gher*. The small-scale landowners are poorer than the *gher* operators, who can finance such ventures. When the landowners refused to lease out their lands for aquaculture in the areas where rice production was feasible, the *gher* operators would flush out the adjoining areas with saltwater and compel the landowners to lease out their land at nominal rates. Intensified aquaculture may be encouraged if equity issues can be solved effectively.

Prospects

The settlement of conflicts between aquaculture (which salinizes land) and crop farming (which requires prevention of saltwater flooding) is crucial for the sustainable management of coastal resources in Bangladesh. The implication of shrimp farming versus crop farming for local employment opportunities and for economic benefits existing within the coastal zone is significant. Local management of water resources and understanding of technical aspects of the interaction between agriculture, forest conservation, aquaculture and aquatic ecology are important for the sustainable management of coastal resources. This should be complemented by a series of measures to optimize land use and enhance environmentally friendly development with the adoption and implementation of the policy objectives of the government.

Experience from combined aquaculture and rice production in a Dutch-assisted project in polder 22 in Khulna District indicates that, where salinity levels are suitable for rice production, allowing brackish water on to the land for aquaculture in the early monsoon period (February–June) does not necessarily reduce the yields of the successive rice crops in the following monsoon period (Mahbullah, 1988). If this is possible in a relatively large area, then this combination may be practised in the smaller areas where the institutionalization of stakeholders' participation in the management of water resources would be easier. This can be demonstrated by the following case study in a subproject implemented by the LGED under the SSWRDSP to support the national policies for coastal resources management. The SSWRDSP is financed by the Bangladesh Government, with the Asian Development Bank and the International Fund for Agricultural Development providing co-financing loans. The Government of the Netherlands provided a grant for technical assistance. The beneficiaries also contribute to the subprojects' construction operation and maintainence costs. SSWRDSP constructed 451 subprojects, of which 108 were in the coastal zone (SSWRDSP, 2003; SSWRDSP-2, 2007). The subprojects intensify land use, increase agricultural, fisheries and forest production and maintain the traditional ecosystems.

Case Study

South-west of Bangladesh

The ecology of this area is suitable for raising shrimp. It allows landowners to trap the brackish waters that shrimp thrive in and then, after a good harvest, clean their fields so they can start anew. With nature's blessing and the government's support, hundreds of shrimp farms, each covering about 100 ha, have emerged around this area. The farms used to be swamplands but are now banked, drained and shaped like polders. These new farms are marked with guard towers, built to keep out the fishermen and other locals. The shrimp farm operators often intimidate surrounding landowners by inundating their land with brackish water, forcing them to cultivate shrimp and then buying the product cheaply from them, hence doubling their profits. Displaced tenants, sharecroppers and fieldworkers subsist by searching for wild shrimp fry in the river. There are two different worlds: one outside the levee, the other inside. On the outside, women and children skim the river for shrimp fry. The estate pays Taka1000, or about US$15, for every 1000 fry, which are transferred to the big saline ponds constructed inside the levee. This had been a practice until the ban on wild shrimp fry fishing in the early 2000s.

Running a tiger prawn farm is a high maintenance activity. For a 100 ha shrimp farm, a staff of 20 workers needs to add or remove water continuously, using motorized pumps and sluice gates, to keep the saline level just right, and to apply antibiotics to fend off disease. They also need to feed carnivorous tiger prawn sacks of fishmeal pellets every day to help them grow to a marketable size. To maintain the right acidity level, lime is added regularly, along with oxygen being pumped into the ponds. Once the length of the biggest prawn reaches 30 cm, local women and children are brought in to collect them. Properly managed, a farm owner can harvest 15 t of prawn and gross for the season about ten times more than what he would gain from a rice crop. However, there are high risks associated with these production systems, which can result in the entire crop of prawn being lost.

Baganchra–Badurgacha villages

As in other south-western parts, the issue of shrimp farming versus rice production for food supply and employment opportunities to the local people persists in these two villages in Dumuria Subdistrict of Khulna District. During the 1997 subproject feasibility study by the LGED, the estimated population in the villages was 1395 and the number of households was 279 (SSWRDSP, 1997). About 66% of households were farmers, 15% fishers and 19% landless. Of all farm households, the marginal (owning less than 0.2 ha) comprised 27%, small (owning more than 0.2–1.0 ha) comprised 53%, medium (owning more than 1.0–2.0 ha) comprised 15% and large (owning more than 2.0 ha) comprised 4%. The villages cover 375 ha, of which 93% is cultivated land influenced by tidal water from the Ghangrail River to the south and west and the Teligati River to the north and east. About one-tenth of the cultivated land is medium lowland, where flooding depth ranges from 1 to 2 m, and the remainder is lowlands, where flooding depth is > 2 m.

Traditionally, a single crop of rice is grown annually. Tidal flooding from the adjoining rivers through two tidal *khals* (natural drainage channels), silt deposition from flood waters and imperfect drainage of saltwater has restricted crop production in the villages. Trapping and growing of shrimp and fish had been practised in the tidal channels and low-lying intertidal areas. This traditional practice was expanded into the low-lying rice area in the mid-1970s by five influential shrimp producers from a neighbouring subdistrict. They would rent land on condition that it would be released before the *aman* rice season started. The *aman* rice could be grown during July–December after shrimp farming in January–July. The landowners would receive some cash payments for the use of their lands. The shrimp producers were not satisfied with the use of land during the agreed period. After the shrimp farming ended in July, they would continue to use the land for white fin fish farming until the end of the monsoon season. This would delay or prevent landowners from growing rice on their land. When planted, the use of low-yielding indigenous varieties, tidal flooding and the increase in salinity level in the late monsoon season would reduce yield. The shrimp producers further constructed seasonal earthen dams in the water channels to regulate the flow of saltwater. However, they would charge the rice producers as much as 25% of the rice harvested on the land. On the other hand, the rent paid by the shrimp producer for the use of land was inadequate. Another problem was that flooding the shrimp farms with saltwater was changing the suitability of land for crop production, vegetation and livestock grazing and thus generated frequent conflicts between the rice farmers and the influential outsiders who operated the shrimp ponds, depriving the former from cultivating their own land.

Subproject development

On 20 November 1996, the *upazila* (subdistrict) office of the LGED at Dumuria received a proposal from the people in Baganchra and Badurgacha villages for control of tidal flooding on their lands. The proposal was reviewed and recommended by the subdistrict development coordination committee. It was forwarded through the LGED district office at Khulna to the SSWRDSP management office at the LGED headquarters. The SSWRDSP carried out a reconnaissance visit and subsequently completed a feasibility study. When the proposal was found to be cost-effective for the construction of a subproject, the LGED subdistrict and district offices promoted a cooperative venture among the local people in the villages. The subproject construction started in the dry season in 1998. Re-excavation of two drainage channels linked to adjacent rivers and one tributary channel with a combined length of 4.5 km was completed in 1999 to improve drainage of flood water. In the following year, two one-vent tidal regulators were constructed and 14.8 km embankments were re-sectioned to control tidal flooding. Two sluices allow fingerlings to enter into the re-excavated channels during the monsoon season when salinity levels are low. The sluices have been designed with low head to ease fish movement and migration. An O&M shed was also constructed in the subproject area. The constructions required Taka9.86 million (US$170,000).

Beneficiary organization

In 1997, the LGED socio-economist and community organizer brought local stakeholders together to form a WMA after the subproject was found to be feasible. An NGO facilitator was employed to strengthen the WMA. The WMA was registered with the Department of Cooperatives the following year as the Baganchra–Badurgacha Subproject Water Management Cooperative Association (WMCA). The WMCA membership covered 279 households that would benefit directly or indirectly from the subproject. The beneficiary landowners contributed 3% and 1.5% of the costs of the earthworks and hydraulic structures, respectively. The total number of households, along with the amount of land they owned in the subproject area, were identified and listed. The contribution from the beneficiaries was then collected by the WMCA on the basis of the land owned by each individual beneficiary and deposited in a joint account by the LGED and WMCA. With 482 members, including 153 women, the WMCA has developed its own capital of Taka435,000 (US$6,400) with shares and savings by its members and has introduced a micro-credit programme using the fund. Since its formation, the WMCA has provided loans to 378 men and 159 women. The average size of each loan was Taka1310 (US$19). The cumulative credit distribution reached Taka706,000 (US$10,400), with an 88% recovery rate. The landless households mainly benefited from the micro-credit programme. In Bangladesh, informal credit accounts for 33–67% of the total volume of rural borrowings (IFAD, 1992). The rates of interest in the informal credit sector exceed 100%. Landless households receive more than 90% of their funds from non-institutional sources, as compared with 62% by medium and large farm households (Mahbub and Afsar, 1988).

Subproject water management

The WMCA operates water control structures in consultation with landowners. The LGED, local stakeholders and local government institution (union council) signed a lease agreement to confirm that the WMCA was satisfied with the infrastructure and accepted responsibility for subproject O&M. The agreement was signed in 2001, 1 year after the physical construction had been completed, to allow for a trial O&M period during which defects were identified and rectified. The WMCA prepared annual O&M plans and budgets and mobilized local resources for the maintenance costs. Annually, the WMCA spends Taka57,000–150,000 (US$850–2200) for the O&M. The LGED constructed an O&M shed on 0.23 ha of land purchased by the WMCA. Agricultural, fisheries and O&M subcommittees were formed to oversee aquaculture, crop production and O&M activities. The LGED delivered comprehensive training courses to WMCA management committee and subcommittee members, with support from the agricultural extension and fisheries departments.

Subproject impact

The subproject implementation and formation of the WMCA helped landowners to re-establish their rights on their own lands. They have established small fish farms on their own holdings. The outsider shrimp growers moved to the public lands. The combination of subproject operation and tidal water management by the participation of landowners increased land use intensity and adoption of improved farming practices (Table 25.1).

The landowners have adjusted the timing of rice production after shrimp and fin fish (Fig. 25.2). They plough their lands in February and subsequently inundate by tidal water flow. Indigenous fin fish and shrimp species enter the land with brackish water. Shrimp postlarvae are stocked in the water and are grown from February to July. During April–July, rainwater decreases the salinity level in the water. In August, *aman* rice seedlings are transplanted when white fin fishes are still present. The fish are harvested in September. The rice is harvested in November.

The area where rice is grown in the monsoon season has increased by 19%. Modern varieties, which were not grown prior to the subproject, now cover about 70% of the total rice area in the monsoon season. A decline in

Table 25.1. Changes in crop and fish production in the Baganchra–Badurgacha subproject area.

	Pre-subproject	Post-subproject	
Item	1997	2003	2006
Crop area (ha)			
Modern variety of *aman* (monsoon) rice	–	113.0	209.0
Local variety of *aman* (monsoon) rice	251.0	186.0	90.0
Modern variety of *boro* (winter) rice	–	–	107.0
Non-rice	3.0	10.2	10.2
Crop production (t)			
Modern variety of *aman* (monsoon) rice	–	440.7	877.8
Local variety of *aman* (monsoon) rice	351.4	446.4	243.0
Modern variety of *boro* (winter) rice	–	–	524.3
Non-rice	39.3	98.9	63.2
Crop yield (t/ha)			
Modern variety of *aman* (monsoon) rice	–	3.9	4.2
Local variety of *aman* (monsoon) rice	1.4	2.4	2.7
Modern variety of *boro* (winter) rice	–	–	4.9
Non-rice	13.1	9.7	6.2
Aquaculture area (ha)			
Shrimp and prawn	299.0	299.0	299.0
Fin fish	170.0	230.0	299.0
Aquaculture production (t)			
Shrimp and prawn	30.5	37.7	44.6
Fin fish	38.1	85.8	126.2
Aquaculture yield (kg/ha)			
Shrimp and prawn	102.0	126.0	149.0
Fin fish	224.0	373.0	422.0

Months	Climate season[a]	Crop season[a]				Land use: Lowlands	Land use: Highlands
June	Monsoon	Kharif I/ Aus	Kharif II/ Aman			Shrimp + fin fish	Prawn + fin fish
July							
August						Fin fish Aman rice	
September							
October	Post-monsoon				Rabi	Aman rice	
November				Boro			
December	Dry						Boro rice
January							
February						Shrimp + fin fish	
March	Pre-monsoon	Kharif I/ Aus					
April							
May							Prawn + fin fish

[a]WARPO 2000.

Fig. 25.2. Land use calendar.

soil salinity allows farmers to grow irrigated *boro* (winter) rice on higher ground. Prawn raised at the same time as the *boro* rice crop has replaced shrimp cultivation on this land. Shallow tube wells have been installed to irrigate the crops. Rainwater is also conserved in the internal channels and ponds are used to raise *boro* rice seedlings during the early winter season. Timely transplantation, decrease of salinity in soils and inputs use at recommended rates have increased rice yield levels. Annual rice production has increased from 351 to 1120 t. With the introduction of *boro* rice in the winter season, annual rice production has increased to 1645 t. The low salinity level in the water has also enabled an increase in non-rice crop production. Annual fin fish production has increased by 88 t, whereas shrimp and prawn production has increased by 14 t.

A survey conducted on beneficiary households in 2003, 2 years after the completion of the subproject construction, showed that the sub project had contributed to the re-establishment of livelihoods of the many displaced small farmers and had increased farm incomes (Table 25.2). On average, farm household income increased by 78% from aquaculture and by 22% from crop production. Among the four types of households, the small farms maximized their incomes from rice production and the other farms from aquaculture. The small farm households benefited more from increasing rice area and deploying additional family labour to produce the crop. The medium farm households brought 90% of their cultivated land under aquaculture compared to 10% by the large farm households. They also produced more vegetables and spices for the market, deploying more family labour for crop production. The landless farm households benefited from increased labour demand and gaining access to land and water resources through sharecropping.

Table 25.2. Improvements in farming enterprises and annual farm incomes for the implementation of Baganchra–Badurgacha subproject.

Description	Type of farm[a]				
	Large	Medium	Small	Landless	Average
Increase in flood-free cropland (%)	49	84	77	89	61
Increase in sharecropping land (ha)	–	2	< 1	1	1
Increase in rice + aquaculture (% of land)	10	90	–	–	42
Increase in cropped area (%)					
Modern variety transplanted *aman* rice	4	20	8	17	9
Local variety transplanted *aman* rice	–	68	90	83	27
Non-rice crops	–	–	–	–	–
Increase in family labour use (person-day)					
Modern variety transplanted *aman* rice	15	16	4	4	10
Local variety transplanted *aman* rice	–10	19	21	16	14
Non-rice crops	1	3	–	1	1
Increase in hired labour use (person-day)					
Modern variety transplanted *aman* rice	–	1	–	–	< 1
Local variety transplanted *aman* rice	–	17	9	15	11
Additional employment (person-day)					
Agricultural labour	–	–	–	120	120
Fisheries labour	–	–	–	147	147
Increase in wage rate (Taka/person-day)	20	21	20	20	20
Increase in crop production (kg)					
Modern variety transplanted *aman* rice	1,080	1,512	253	1,000	883
Local variety transplanted *aman* rice	4,653	1,328	1,300	1,080	1,861
Non-rice crops	30	330	80	80	170
Increase in household income (Taka[b])					
Rice production (Taka[b])	27,333	12,000	4,500	1,500	10,206
Non-rice production (Taka[b])	–	2,000	–	–	588
Aquaculture (Taka[b])	64,333	97,800	833	2,333	40,824

[a]Large farm owning > 2.0 ha of land, medium-sized farm owning 1.0–2.0 ha of land, small farm owning 0.2–1.0 ha of land, and landless < 0.2 ha of land; [b]Taka1 = US$0.016.

Increases in labour demand and wage rates suggest an improvement in livelihoods in the subproject area. The labour requirement per hectare was 109 person-days to produce an indigenous rice variety and 140 person-days to produce a modern rice variety, whereas aquaculture required 230 person-days/ha. The BIDS study (Khuda, 1985) suggests that the landless and small farm households benefit mainly from the increased labour demand. According to the study, the landless can spend only 4% of their time on the family farm producing a rice crop. Thus, landless households always seek outside employment. On the other hand, small farmers spend 91% and medium and large farmers spend 100% of their time on the family farm. The higher wage rates benefited the farm labourers, whose purchasing power increased. With one day's wage, a labourer could purchase more than 6.0 kg of rice, as compared to less than 5.0 kg prior to the subproject.

A beneficiary household survey undertaken in 2006 showed that, except for the landless, all the farm households brought their total cultivated land under aquaculture. The landless farmers produced shrimp and fin fish on 72% of the sharecropping land. All the farm households earned more from aquaculture. The share of net income from aquaculture was 90% for small farms, 78% for medium farms, 63% for large farms and 75% for landless households.

The subproject provided varied opportunities to increase farm income. Figure 25.3 shows that farm incomes are higher for the various rice–aquaculture systems than for aquaculture alone and that the adoption of improved farming practices, particularly the modern rice varieties, further increased farm income. The highest return was obtained from

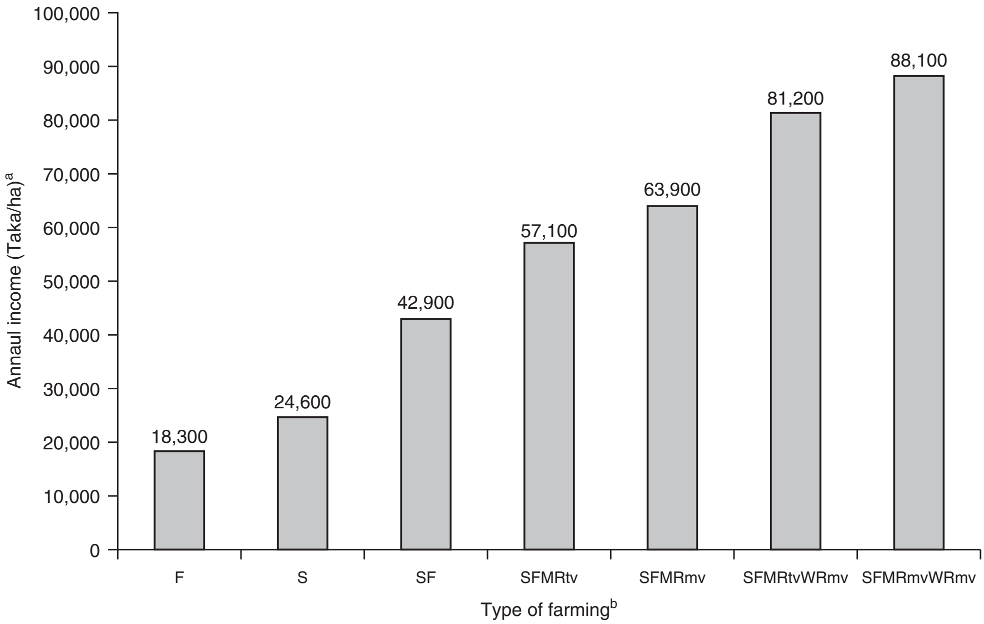

Fig. 25.3. Multiple opportunities to increase farm income. [a]Taka68 = US$1; [b]F, fin fish; S, shrimp; SF, shrimp and fin fish; SFMRtv, shrimp and fin fish in rotation with monsoon rice crop using traditional variety; SFMRmv, shrimp and fin fish in rotation with monsoon rice crop using modern variety; SFMRtvWRmv, shrimp and fin fish in rotation with monsoon rice crop using traditional variety and winter rice crop using modern variety; SFMRmvWRmv, shrimp and fin fish in rotation with monsoon and winter rice crops using modern variety.

the production of shrimp and fin fish in rotation with two rice crops using modern varieties of rice.

A small farm household owning a minimum of 0.2 ha of land can earn Taka33,000 (US$506) annually from shrimp and fish farming in rotation with double rice crops. With this income from the land, the farm household can meet 90% of its food requirements. The household consumption expenditure in the rural area is Taka5165 (US$79)/month (BBS, 2006). Food accounts for 59% of the total consumption expenditure. On this basis, more than two-thirds of farm households in the subproject area are able to attain a level of production that will satisfy the family's minimum food requirements.

Participatory process

The participatory process adopted by SSWRDSP in the subproject development was a combination of two parallel but interrelated processes: one that addresses 'institutional' matters and the other that addresses 'technical' matters. The institutional matters included subproject identification by the local people and submission through the local government institution, analysis to establish social and environmental acceptability, the formation of a WMA and preparation of subproject infrastructure, O&M and land and water utilization plans. The technical matters included subproject processing, analysis to establish technical and economic feasibility, engineering design and construction and a 1-year trial operation. The whole cycle of subproject development was completed in three stages.

Stage 1: Identification and feasibility

In consultation with local stakeholders, the local government institution initiated the subproject proposal. The subdistrict level coordination committee, comprised of officials of various government agencies, approved the proposal.

The project management office examined the proposal during a multidisciplinary field reconnaissance. This was followed by a participatory rural appraisal and feasibility study. A district level inter-agency project evaluation committee, comprising members of the local government institution and development agencies, examined the proposed subproject infrastructure.

Stage 2: Design and institutional establishment

Subproject design was prepared and the process of establishing the WMA was initiated under a legal framework. The NGO facilitator created awareness, promoted membership enrolment and assisted in the collection of beneficiary contributions. The project management office undertook engineering design work in consultation with stakeholders and solicited their approval. This process culminated in the signing of a formal implementation agreement by the WMA, local government institution and implementation agency. To sign the implementation agreement, the association achieved the enrolment of the majority of beneficiary households, collected beneficiary contributions and deposited the contribution in a joint account held by the implementation agency and the WMA. The approach of the project was that local stakeholders were at the forefront of the investment process. This approach was set in place deliberately so that local stakeholders would understand clearly that they owned the completed infrastructure and that they were responsible for maintaining it.

Stage 3: Construction and first year O&M

The subproject infrastructure was handed over to the WMA 1 year after completion. The WMA formed the O&M subcommittee and prepared schedules, beneficiary lists and maps, and plans comprising operating guidelines, maintenance and resource mobilization were developed. The project provided on-the-job training to help the WMA.

Conclusions

Participatory water management in the Baganchra–Badurgacha subproject area increased and stabilized agricultural and fisheries production. The access of the local people to land and water improved through increased productivity. The stakeholders' participation strengthened the role of the local people in subproject O&M. They were integrated into the mainstream of the economic production system. The Baganchra–Badurgacha subproject reflects the type of impact the LGED has had on many other communities in subprojects established under the SSWRDSP throughout the coastal zone in Bangladesh. It demonstrates how the beneficiaries of a given hydrological system can be included in the bounds of the responsible entity for the O&M function, which is critical to sustainability of the water infrastructure. The beneficiaries can assume greater responsibilities for the water utilization plan and the WMA as a local institution can provide services through self-financed entities. Involving local stakeholders in water resources management through WMAs is effective in generating and securing compliance with rules for the use of water, which is a common resource. Devolution of responsibilities to the stakeholders externalizes O&M expenditures to communities from the government fund. The WMA's interaction with local government agencies providing support services results in productive uses of water resources. Furthermore, the combination of sustainable water resources management and the adoption of improved technologies increases farm incomes. Landowners are able to devise production systems that are rational and optimal. Landless households benefit from additional employment. The development of innovative strategies helps achieve these. The strategies include subproject selection with smaller areas for optimizing the balance between maximizing benefits and minimizing damages and institutionalization of the stakeholders' participation, ensuring their involvement in subproject implementation and ownership of subproject infrastructure for O&M.

In Bangladesh, many of the earlier water resources management activities, including flood control, drainage and irrigation (FCDI), were not productive. The performances of FCDI systems often failed to meet expectations (Chowdhury, 1988). There has been a serious lack of adequate maintenance and a widespread failure of infrastructure (MPO, 1991). The major reasons identified were design constraints and inadequate inputs from the target beneficiaries. The FCDI projects failed to address issues related to local stakeholders' participation and the distribution of responsibility between national and local governments in the process of implementation (EIP, 2000). Consequently, the project objectives for sustainable water resources management were rarely achieved. The SSWRDSP is an example of promoting stakeholder participation and contributes immensely to improving rural water resources management in Bangladesh and in other Asian countries.

References

BBS (Bangladesh Bureau of Statistics) (1987) *1987 Yearbook of Agricultural Statistics of Bangladesh*. Bangladesh Bureau of Statistics, Dhaka.

BBS (Bangladesh Bureau of Statistics) (1999) Report on survey of private and non-profit institutions in Bangladesh, 1997–98. Bangladesh Bureau of Statistics, Dhaka.

BBS (Bangladesh Bureau of Statistics) (2005) *2004 Yearbook of Agricultural Statistics of Bangladesh*. Bangladesh Bureau of Statistics, Dhaka.

BBS (Bangladesh Bureau of Statistics) (2006) Preliminary report on household income and expenditure survey 2005. Bangladesh Bureau of Statistics, Dhaka.

BBS (Bangladesh Bureau of Statistics) (2008) *2006 Yearbook of Agricultural Statistics of Bangladesh*. Bangladesh Bureau of Statistics, Dhaka.

Berg, U.I.G., Dunn, T.P. and Welcomme, R.L. (1998) Inland fisheries. In: Biswas, A.K. (ed.) *Water Resources: Environmental Planning, Management and Development*. McGraw Hill, New York, pp. 439–476.

Brammer, H. (1997) *Agricultural Development Possibilities in Bangladesh*, 1st edn. University Press Limited, Dhaka.

Brandon, C. (1998) Environmental degradation and agricultural growth. In: Faruqee, R. (ed.) *Bangladesh Agriculture in the 21st Century*, 1st edn. University Press Limited, Dhaka, pp.109–117.

BWDB (Bangladesh Water Development Board) (1987) *Feasibility Study on the Sandwip Cross-dam Development Scheme* Vol. II, *Annex A, Economic and Social Studies*. Land Reclamation Project, Bangladesh Water Development Board, Dhaka.

BWDB (Bangladesh Water Development Board) (1999) Report on the salinity and tidal hydraulics, morphology and hydrology, geo-hydrology and soil and agriculture of the Ganges dependent areas of Bangladesh. Directorate of Ganges Studies, Bangladesh Water Development Board, Dhaka.

Chowdhury, Y.A. (1988) *Institutional Analysis: BWDB and BADC* Vol. V*: Institution*. UNDP/ASR, Dhaka.

EIP (Early Implementation Project) (2000) *Learning Lessons: 20 Years of EIP Experience*. EGIS, MWR, Dhaka.

Hossain, A.N.H. (2003) State of water resources in Bangladesh. In: *Sessions Papers. The Third World Water Forum, Kyoto*. Ministry of Water Resources, Dhaka.

IFAD (1992) The state of world rural poverty. In: Jajairy, I., Alamgir, M. and Panuccio, T. (eds) *An Inquiry into Its Causes and Consequences*. Intermediate Technology Publications, International Fund for Agricultural Development, London.

IUCN/MOEF (1992) *The National Conservation Strategy of Bangladesh 1991 (revised in 1992)*. International Union for Conservation of Nature and Natural Resources/Ministry of Environment and Forest, Dhaka.

Karim, M.R. (2006) Brackish-water shrimp cultivation threatens permanent damage to coastal agriculture in Bangladesh. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 61–71.

Khuda, B.E. (1985) Pattern of employment in a rural area of Bangladesh. Bangladesh Institute of Development Studies Vol XIII, No 2. Dhaka.

Mahbub, H. and Afsar, R. (1988) Credit for women's involvement in economic activities in rural Bangladesh. BIDS Report 105. Bangladesh Institute of Development Studies, Dhaka.

Mahbullah (1988) *Impact of Coastal Polders on Agriculture Productivity: Evidence from Five Coastal Villages*. Government of the People's Republic of Bangladesh, Dhaka.

Mahmood, N. (1986) Effects of shrimp farming and other impacts on mangroves in Bangladesh. Paper presented at the Workshop on Strategies for the Management of Fisheries and Aquaculture in Mangrove Ecosystems, 23–25 June 1986, Bangkok.

MOA (Ministry of Agriculture) (1999) *National Agriculture Policy*. Ministry of Agriculture, Government of the People's Republic of Bangladesh, Dhaka.

MOEF (Ministry of Environment and Forests) (1992) *National Environmental Policy*. Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka.

MOEF (Ministry of Environment and Forests) (1999) *Toward Sustainable Development. The National Conservation Strategy of Bangladesh*. Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka.

MOFL (Ministry of Fisheries and Livestock) (1998) *National Fisheries Policy*. Ministry of Fisheries and Livestock, Government of the People's Republic of Bangladesh, Dhaka.

MPO (Master Plan Organization) (1986) *National Water Plan Volume 1, Master Plan for Irrigation and Water Development*. Master Plan Organization (now Water Resources Planning Organization [WARPO]), Ministry of Water Resources, Government of Bangladesh, Dhaka.

MPO (Master Plan Organization) (1991) *Evaluation of Historical Water Resources Development and Implications for National Water Plan*. Master Plan Organization (now WARPO), Dhaka.

MWR (1999) *National Water Policy*. Ministry of Water Resources, Government of the People's Republic of Bangladesh, Dhaka.

NEMAP (1995) *National Environmental Management Action Plan*. Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka.

SSWRDSP (1997) Baganchra–Badurgacha Subproject: combined summary appraisal report and summary IEE report. Small-Scale Water Resources Development Sector Project, Local Government Engineering Department (LGED), Dhaka.

SSWRDSP (2003) Small-Scale Water Resources Development Sector Project, project final report. Local Government Engineering Department (LGED), Dhaka.

SSWRDSP-2 (2007) Second Small-Scale Water Resources Development Sector Project, project quarterly report, July 2007. Local Government Engineering Department (LGED), Dhaka.

UNDP (1988a) A review of some aspects of fisheries subsector by Aminul Islam. In: *Bangladesh Agricultural Sector Review*. United Nations Development Program, Dhaka, pp. 110–172.

UNDP (1988b) Forestry sub-sector by Bahauddin Chowdhury. In: *Bangladesh Agricultural Sector Review*. United Nations Development Program, Dhaka, pp. 1–27.

UNDP (1989) Land use in Bangladesh: selected topics. Haroun Er Rashid. In: *Bangladesh Agricultural Sector Review*. United Nations Development Program, Dhaka, pp. 106–155.

UNDP/FAO (1988) Land resources appraisal of Bangladesh for agricultural development. Report 2. Agricultural regions of Bangladesh. United Nations Development Program/Food and Agriculture Organization of the United Nations, Dhaka.

WARPO (2000) *Draft Development Strategy Volume No 4, Annex C: Land and Water Use*. Water Resources Planning Organization, Ministry of Water Resources, Government of the People's Republic of Bangladesh, Dhaka.

WARPO (2003) Delineation of the coastal zone and NGOs in the coastal zone. Working papers, integrated coastal zone management plan project. Water Resources Planning Organization, Ministry of Water Resources, Dhaka.

WARPO (2004) *Framework Regional Strategy and Priority Action and Programmes. Southwest Area Integrated Water Resources Management Project. Phase 1 (Interim) Report*, Volume 1. Asian Development Bank, Bangladesh Water Development Board and Water Resources Planning Organization, Dhaka.

26 Learning to Build Resilient Coastal Communities: Post-tsunami Recovery in Sri Lanka and Indonesia

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Abstract

Vulnerability to natural hazards and other environmental risks is frequently discussed at a conceptual/theoretical level but rarely investigated systematically. This study identifies the key factors, as documented in the literature and supported by substantiated primary data, that have contributed to social vulnerability associated with the 2004 Indian Ocean tsunami in Sri Lanka and Indonesia. A review of the post-tsunami literature was conducted and a total of 382 documents was selected for a detailed meta-analysis. Of these documents, only 101 contained primary data with an explanation of the methodology used to assess vulnerability, and only 40 contained substantiated vulnerability insights. In the selected literature, limited attention is paid to the process by which knowledge is generated. For instance, 'fact finding' and 'verification' missions undertaken by many organizations rarely include descriptions of the underlying processes contributing to social vulnerability. In the absence of relevant data and substantiated arguments, it is possible to obtain only a limited understanding of who is vulnerable to hazards, the reasons for their vulnerability and what measures might be most appropriate and effective in reducing vulnerability. Consequently, it is not surprising that new and unexpected vulnerabilities have emerged during the longer-term post-disaster recovery process. Some 75% of the vulnerabilities identified in the literature have emerged during the recovery process, and the delivery of aid and other external interventions have been identified in the selected literature as the drivers of vulnerability for approximately 50% (51 of 103) of the vulnerability insights documented in the literature. The lack of understanding of social vulnerability and the resulting contribution of the post-tsunami relief and recovery activities to the exacerbation of existing and the emergence of new vulnerabilities highlight an urgent need for actors to learn how to base aid delivery and livelihood interventions on a clear consideration of vulnerable groups and the underlying causes of their vulnerability. Social learning theory is used to analyse the way the 'recovery community' operates and to highlight the current challenges in building resilience. We suggest that an alternative perspective is needed for actors in post-disaster recovery, namely that of being enablers of vulnerable people's recovery, self-organization and coping.

Introduction

Vulnerability analysis in practice: understanding who is vulnerable

Vulnerability to natural hazards and other environmental risks is frequently discussed at a conceptual/theoretical level but is rarely investigated systematically. Vulnerability analysis aims to shed light on how multiple complex and interacting factors contribute to human vulnerability in different contexts (e.g. Lindskog *et al.*, 2005). As part of a larger effort of the Stockholm Environment Institute's (SEI) Risk, Livelihoods and Vulnerability Programme to synthesize learning on social vulnerability to the 2004 Indian Ocean tsunami and other coastal hazards (see also Zou and Thomalla, 2008), this study intended to improve the capacity to conduct vulnerability assessments to support more sustainable post-disaster recovery efforts.

There have been numerous desk-based studies on the 2004 tsunami. The Tsunami Evaluation Coalition (TEC) conducted a number of extensive thematic reviews (Telford *et al.*, 2006), CARMA International (2006) reviewed tsunami communications in the media and numerous reviews have focused on specific technical, sectoral or policy concerns, including drinking water (Clasen *et al.*, 2006) and human rights (Action Aid, 2005). However, no systematic review of the literature from a vulnerability perspective exists.

Vulnerability and capacity assessments undertaken by SEI in Sri Lanka in collaboration with the International Federation of Red Cross and Red Crescent Societies (IFRC) and the Sri Lankan Red Cross Society (SLRCS) raised concerns that new vulnerabilities were emerging during the post-tsunami recovery process, most notably among poor and marginalized social groups (Miller *et al.*, 2006). Although it is acknowledged that a multitude of organizations and individuals has contributed to the debate on relief and recovery in the aftermath of the tsunami, generating an impressive body of literature, it is expected that a review of the literature from a vulnerability perspective could yield significant insights to the current state of tsunami recovery and the application of vulnerability analysis in practice. Accordingly, this study identifies the key factors, as documented in the literature and supported through substantiated primary data, that have contributed to social vulnerability associated with the 2004 Indian Ocean tsunami in Sri Lanka and Indonesia.

Vulnerability, as a body of work, also reflects several broad theoretical contributions ranging from geophysical, human ecology, political economy, constructivism, political ecology and sustainability science (Eakin and Luers, 2006; McLaughlin and Dietz, 2008). Each varies epistemologically and methodologically in the emphasis given to environmental, social, economic and political forces in shaping the causes of vulnerability. A diverse range of vulnerability concepts exists in the scientific literature, reflecting different theoretical areas and the contributions of a number of disciplines (Wisner *et al.*, 2004; Adger, 2006); each approach emphasizes different dimensions of vulnerability. Specifically, the Turner *et al.* (2003) vulnerability framework, which emerges from sustainability science, distinguishes three dimensions of vulnerability: (i) exposure to stresses, perturbations and shocks; (ii) the sensitivity of people, places and ecosystems to the stress or perturbation, including their capacity to anticipate and cope with the stress; and (iii) the resilience of the exposed people, places and ecosystems, that is, their ability to recover from the stress and to buffer themselves against and adapt to future stresses and perturbations. Although this body of work has increasingly presented insights into the complex nature of the social–ecological systems in which vulnerable groups are situated, the large number of definitions and concepts leads to confusion and limited application in operational settings. It is beyond the scope of this study to go into detailed scientific discussion of the conceptual relationship between these different concepts of vulnerability and the relationship between vulnerability and resilience (see, for example, Galoppin, 2006). Instead, we focus on one commonly agreed feature regarding vulnerability, namely that it explains the underlying causal structures of a negative outcome by focusing attention on vulnerable groups as the basis of this analysis. A vulnerability perspective is thus distinguished from many other approaches to hazards and environmental change in that it links social groups with causal factors and consequent risks/outcomes and considers changes over time, such as preparedness, coping, recovery and adaptation.

This chapter contributes to the literature that is particularly concerned with vulnerability in post-disaster contexts, primarily the manner in which knowledge about vulnerability is generated through assessments and other studies. It confirms an earlier observation by anthropologist Oliver-Smith that:

> Disasters commonly result in rapid local, state, national, or international aid. This convergence of people and goods, often foreign or strange to the local population, may ultimately be as great a source of stress and change as the disaster agent and destruction themselves.
>
> (Oliver-Smith, 1996, p. 313)

Methodology

Document search

The documents selected for inclusion in this review were retrieved from a large volume of literature on the tsunami through a comprehensive document search. Only documents that contained primary data and substantiated arguments produced within 2 years of the tsunami were included. The search was based on coarse scale keywords of 'tsunami' and 'Indonesia' or 'Sri Lanka', employing nine academic search engines, as well as Google and Google.scholar. Furthermore, 17 online directories and 32 web portals of research institutions, United Nations agencies, civil society organizations, development banks and relief and development agencies and governments were searched.

Meta-analysis

An analysis of the key factors that contributed to social vulnerability to the 2004 Indian Ocean tsunami in Sri Lanka and Indonesia documented in the selected literature was conducted employing a meta-analysis methodology that was based on earlier applications of such methods in sustainability science (see, for example, Zou and Thomalla, 2008). To enable an analysis with specific relevance for understanding social vulnerability to hazards, it was considered explicitly that social groups were part of larger social–ecological systems where proximate and underlying causes contribute to people's vulnerability and tend to be embedded in one or several of the dimensions composed of social, institutional, ecological and physical processes (Gunderson and Holling, 2002).

In this study, we considered the social vulnerability and coping capacity of identified vulnerable groups, focusing on substantiated arguments that were supported by primary data. 'Data' was considered here to be information derived from an agency's or researchers' direct interaction with a social group or their environment. It was interpreted in a broad sense, including both quantitative and qualitative information, regarding all dimensions of a vulnerable group's livelihood situation. 'Substantiated' means that the document must include both a clear methodology and a coherent vulnerability argument.

Vulnerability was interpreted as referring to a social group's (a vulnerability unit's) experience of a stress (risk/outcome) when exposed to one or several stressors (causal factor). This means that vulnerability is associated with: a vulnerable subject; a causal factor; and an increased risk or actualization of a negative outcome (Table 26.1). In the detailed analysis of each selected document, specific social groups considered by the authors to be vulnerable (e.g. displaced people) were documented and the links to a causal factor and a risk/

Table 26.1. Glossary for concepts employed in the analytical framework.

Term	Definition
Vulnerability	The combined existence of a vulnerable group, a risk and a causal factor
Vulnerable group/unit	A defined social group which is seen as experiencing an increased risk because of the influence of a causal factor
Causal factor	A factor which leads to a detrimental outcome for the vulnerability unit, or an increased risk of this happening
Risk	A change which is perceived (by an agency or researcher) as harmful to a vulnerable group
Resilience	Capacity of a social group or social–ecological system to cope with the influence of a causal factor and avoid the harmful outcomes of a risk

outcome identified. One example is the statement that displaced people are vulnerable to the erosion of their livelihood opportunities because of ‘hasty efforts’ to relocate people in the recovery (Shanmugaratnam, 2005). Such an argument, consisting of the three linked notions, was defined as a ‘vulnerability insight’.

Coding and aggregation

Vulnerability insights were coded and categorized according to a number of criteria, which, beyond the identification of vulnerability, included information on each document, data as well as suggestions on building resilience. For identified vulnerable social groups, the insights were grouped into basic social categories to allow for selection of the most commonly identified factors for each group. Risks and causal factors were grouped into what was seen as naturally emerging types from the terminology of the authors and were later aggregated further into human, social, institutional, ecological–physical and economic, and livelihood types. Examples of each risk and cause relationship are provided to show the process of coding and aggregation of insights (Table 26.2). Although other finer distinctions could be made, it was decided to distinguish between three chronological types of vulnerabilities, using the notional phases of recovery employed by the TEC (Table 26.3).

Qualitative analysis and social learning

The investigation of the underlying causes contributing to the emergence of new social vulnerabilities was based on a qualitative analysis, relaxing the analytical framework used initially, and comparing a range of arguments made in the literature on the basis of various perspectives. In the analysis of the obstacles currently preventing the disaster risk reduction community from addressing the needs of vulnerable groups adequately and the underlying factors contributing to vulnerability in Sri Lankan and Indonesian coastal communities, the framework for social learning proposed by Wenger (1998) was used. Here, it was considered that learning by agents of the recovery depended on four composite pillars: (i) belonging to a community of practice; (ii) learning by doing; (iii) meaning and sense making, which build on experience; and (iv) identity development. Thus, people live, exist and learn as social beings in interaction with others. This interaction takes place in a community of practice, where the involved actors take part in a systemic process of negotiating meaning. In contributing to collective action in the recovery process, social learning was perceived as ‘the process of co-creation of knowledge, which provides insight into the causes of, and the means required to transform a situation’ (SLIM, 2004, p. 1). For more details about the methodology, please refer to Larsen *et al*. (2008).

Findings

Do we know who is vulnerable?

Of the 382 documents selected from the search, only 101 contained primary data with an explanation of the methodology used to assess vulnerability, and only 40 contained substantiated vulnerability insights. The analysis revealed that instead of paying explicit attention to vulnerable groups, organizations/researchers frequently applied quite institutionalized approaches that reflected a sense-making perspective of ‘damage’, ‘needs’ and ‘priority issues’. A vulnerability perspective is rarely applied and central to their analysis or approach to recovery (Table 26.4).

Many organizations do not publish online and some of the ‘grey literature’ lacks basic information such as date, author and affiliation, and this prevents their use as credible sources. Because of excellent web-portal access to reports from Sri Lanka, it was easier to obtain relevant information from Sri Lanka than from Indonesia. In the identified literature, 22% of the insights referred to Indonesia, 75% to Sri Lanka and 3% to the region or both countries.

Of 51 documents published in peer-reviewed journals, only 11 included primary data on social groups. Similarly, although the TEC review on needs assessments drew on a total of 8000

Table 26.2. Process of coding and aggregation of vulnerability insights. One example of a substantiated vulnerability insight is listed for each risk category and the corresponding cause indicated. A similar procedure was followed for other causes and social groups. The insights were coded in accordance with the message as interpreted from the larger text/document. Aggregation of risks was conducted according to the following categories. *Human*: psychological damage, health problems; *Social*: abuse, conflict, destruction of social capital, marginalization; *Economic*: financial problems; *Ecological–physical*: degradation of physical assets, loss of land, disaster exposure, food problems, resource problems, problems of water and sanitation; *Livelihoods*: livelihood damage. Aggregation of causes according to the following categories: *External intervention*: aid; *Human*: psychological; *Social*: conflict, gender, marginality, psychological, loss of relatives; *Institutional*: policy, land tenure, corruption, health services; *Economic*: financial, trade, poverty; *Ecological–physical*: water and sanitation, biophysical, salination, disaster exposure, living conditions; *Livelihoods*: livelihoods.

Risk aggregation	Risk coding	Vulnerability insight	Cause coding	Reference
Human	Psychological damage	Displaced, experiencing depression and fear because of uncomfortable living conditions in camps	Living conditions	Mashni *et al.* (2005)
	Health related	Risk of communicable diseases for displaced in overcrowded temporary camps	Aid	Sida *et al.* (n.d.)
Social	Abuse	Women exposed to sexual violence because of living conditions in temporary camps	Aid	Action Aid (2005)
	Conflict	Increasing conflict over limited coastal resources among fishers because of false claims and unfair benefit distribution	Aid	Sellamuttu and Milner-Gulland (2005)
	Destruction of social capital	Social disruption for women because of under-representation in decision making	Marginality	Yamada *et al.* (2006)
	Marginalization	Double victimization of tsunami survivors because of involuntary resettlement	Policy	BDG (2005)
Economic	Financial problems	Households in certain occupations are more at risk of losing their jobs after the tsunami	Marginality	Birkmann *et al.* (2006)
Ecological–physical	Degradation of physical assets	Squatters are not allowed to rebuild because lacking land ownership	Land tenure	Birkmann *et al.* (2006)
	Loss of land	Land grabbing and loss by displaced people because of failed procedures during land and property restitution claims	Aid	AI (2006)
	Disaster exposure	Communities are exposed to coastal communities because of change of sand dunes and vegetation by infrastructure projects	Biophysical	Tanaka *et al.* (2006)
	Food problems	Families cannot meet food demands because of loss of livelihoods	Livelihoods	WFP (2005)
	Resource problems	Increased competition among fishermen as consequence of provision of coastal fishing vessels	Aid	Sida *et al.* (n.d.)
	Problems of water and sanitation	Insufficient clean water leads for displaced people because of shortage of reservoirs and bowsers in camps	Aid	UNICEF *et al.* (2004)
Livelihoods	Livelihood damage	Unemployment for displaced people as camps are placed far from work opportunities	Aid	Action Aid (2005)

Table 26.3. Phases of vulnerability during and after the tsunami 25 December 2004 (adapted from Scheper *et al.*, 2006).

Vulnerability category	Origin
Disaster vulnerability	Factors contributing to vulnerability associated with the tsunami (relief)
Immediate vulnerability	Factors contributing to vulnerability associated with emergency phase (recovery)
Emerging vulnerability	Factors contributing to vulnerability associated with recovery (development)

Table 26.4. A non-exhaustive list of prevalent sense-making perspectives in the literature. Although perspectives other than the explicit vulnerability analysis (7) can contain certain vulnerability insight (e.g. 5 and 6), they often lack specification of whom is vulnerable and why (e.g. 1 and 2) or are tailored to audience or purposes which do not enable attention to vulnerability (e.g. 3 and 4).

Number	Sense-making perspective – looking for:	Examples from the literature
1	Needs	HRCSL *et al.* (2005); LTTE (2005)
2	Damage and impacts	CGI (2005); AusAid and Care International (2005)
3	Lessons and planning priorities	Care *et al.* (2005); Fritz Institute (2005)
4	Top priorities and recovery 'issues'	GoI (2005); OCHA and UNEP (2005)
5	Human rights violations	Action Aid (2005); HRC and EWC (2005)
6	Psychosocial impacts	Mattock (2005)
7	Vulnerability and risks	Birkmann *et al.* (2006); Miller *et al.* (2006)

documents (de Ville de Goyet and Morinière, 2006), very few of these contained primary data.

Vulnerability findings tend to be widely generalized and assumed to be relevant in the context of vulnerable groups, but few specific links to these contexts are made. For instance, the Asian Development Bank (ADB) (2005a, p. 1) noted that: '[D]espite the unprecedented scale of loss of human life, homelessness, and displaced populations, the macroeconomic impact of the disaster will be limited and marginal.'

Such a claim disconnects the macroeconomic context from the livelihoods and realities of vulnerable groups who comprise that very economy, and may contribute to the creation of a mismatch between the data generated and the recommendations made. Similarly, claims are made regarding the impact on trees and timber demand (Greenomics Indonesia and WWF, 2005), which are of limited value to inform an understanding of vulnerability because of a lack of attention as to how and to what extent such concerns for environmental sustainability are related to differentiated social sustainability and vulnerability.

In the selected literature, limited attention is paid to the process by which knowledge is generated. The 'fact finding' and 'verification' missions undertaken by many organizations rarely include descriptions of the underlying process contributing to vulnerability. Instead, there is a tendency to present recommendations, the credibility of which depends on the reputation of the authors or publishers. Many reports that appear to be based on substantial work provide no detailed discussion of the methods used to derive the insights, and this limits considerably the value and application of the presented data and arguments. Similar conclusions have been made by the TEC (de Ville de Goyet and Morinière, 2006) and the Environmental Foundation Ltd of Sri Lanka (EFL, 2005). In the absence of relevant data and substantiated arguments, such reports contribute little to our understanding of who is vulnerable, the reasons for their vulnerability and what measures might be most appropriate and effective in reducing vulnerability and building resilience.

Aid delivery as a cause of the emergence of new vulnerabilities during recovery

When recovery does not aim explicitly to reduce existing vulnerabilities, it is not surprising that new, unexpected vulnerabilities emerge. Seventy-five per cent of the vulnerabilities identified in the literature have emerged during the recovery process, as opposed to 19% during immediate disaster relief and 6% during the disaster emergency phase (see Table 26.2 for definitions). The delivery of aid and other external interventions was identified as the causes of vulnerability for close to 50% (51 of 103) of vulnerability insights documented in the literature. This is similar to findings of other studies on post-disaster recovery, as reviewed by Oliver-Smith (1996).

The complete data set from our analysis (Figs 26.1, 26.2 and 26.3) indicates that social and institutional drivers dominate both the causes and outcomes of the identified vulnerabilities. Although it is not a new observation that socio-economic factors create hazard vulnerability (e.g. Miller *et al*., 2005), it is significant that socially constructed factors lead to more than 50% of the vulnerabilities identified in the selected literature. Most assessments to date have focused on sectoral aspects, leaving broader and more integrated livelihood issues aside (de Ville de Goyet and Morinière, 2006). Few documents have been concerned with emerging vulnerabilities and the social/institutional dimensions of hazard vulnerability. The selected literature distinguishes between 11 distinct (but not exclusive) vulnerable groups (Fig. 26.4). These are described according to

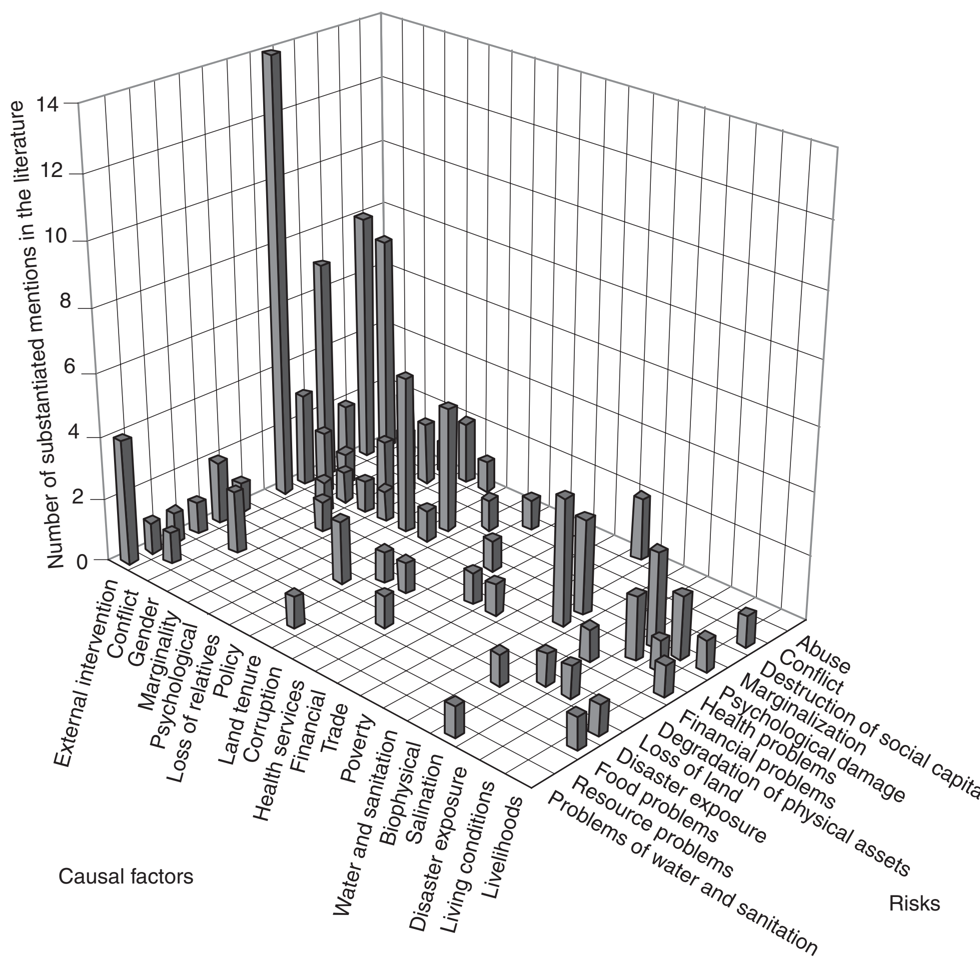

Fig. 26.1. Synthesis of the vulnerabilities in Sri Lanka and Indonesia after the 2004 tsunami.

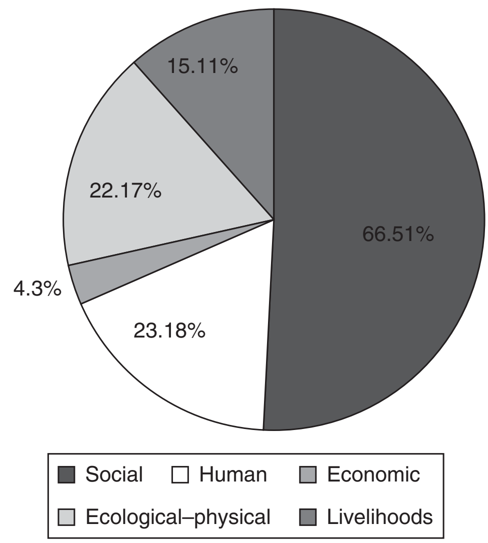

Fig. 26.2. Aggregation of risks identified in the literature.

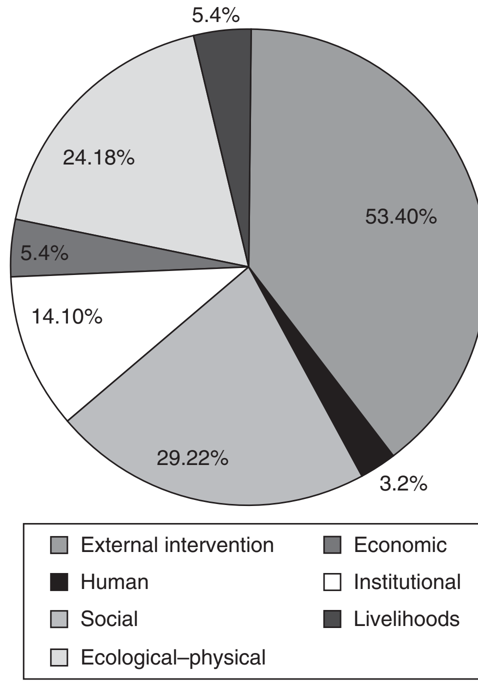

Fig. 26.3. Aggregation of causes identified in the literature.

social characteristics (women, children, families), livelihoods (farmers, fishermen, coastal communities) and the degree of victimization (displaced people, patients, victims of other disasters). It is not clear the extent to which such categories were identified a priori or were based on factors that emerged from the studies. Some groups, including displaced people, women and fishermen (Fig. 26.5), were described as being affected more adversely from external interventions than others. They experienced a range of new stresses during the recovery, the most important being health problems, then conflict and then abuse (Fig. 26.6).

However, there is no standardized description of these social groups and the same people could be included in several groups, depending on the perspective of the observer. Traditional livelihoods, such as farming and fishing, received considerably more attention than livelihood strategies in emerging sectors such as tourism, and more attention than entrepreneurs engaged in a variety of service sectors. Only three documents drew attention to the vulnerabilities of entrepreneurs engaged in small-scale businesses and trading, highlighting how their livelihoods had been eroded because the tsunami obstructed the flow of goods from the coast and inland. Birkmann *et al*. (2006) discussed the vulnerability of daily paid labourers and mobile fish sellers. People working in the tourism sector largely were not considered a vulnerable group in any of the selected documents, but recent research by Calgaro and Lloyd (2008) provided an analysis of the vulnerability of tourism-dependent communities to environmental shocks.

Why do new vulnerabilities emerge?

Although the literature conveys a generally high degree of awareness of the potential risks associated with the post-disaster recovery process among actors, there seems to be little consideration of specifically who is vulnerable and why. Understanding social vulnerability demands an investigation of the underlying causes and a questioning of the political ecology that determines who defines the risk and who benefits in the recovery. Participatory vulnerability assessment methodologies aim to allow communities themselves, rather than external ‘experts’, to identify and prioritize the

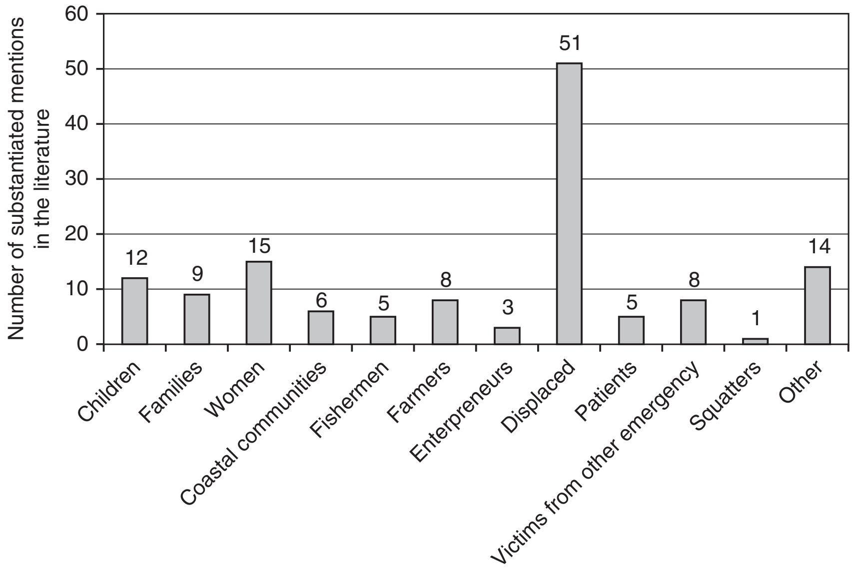

Fig. 26.4. Vulnerable groups as identified in the literature.

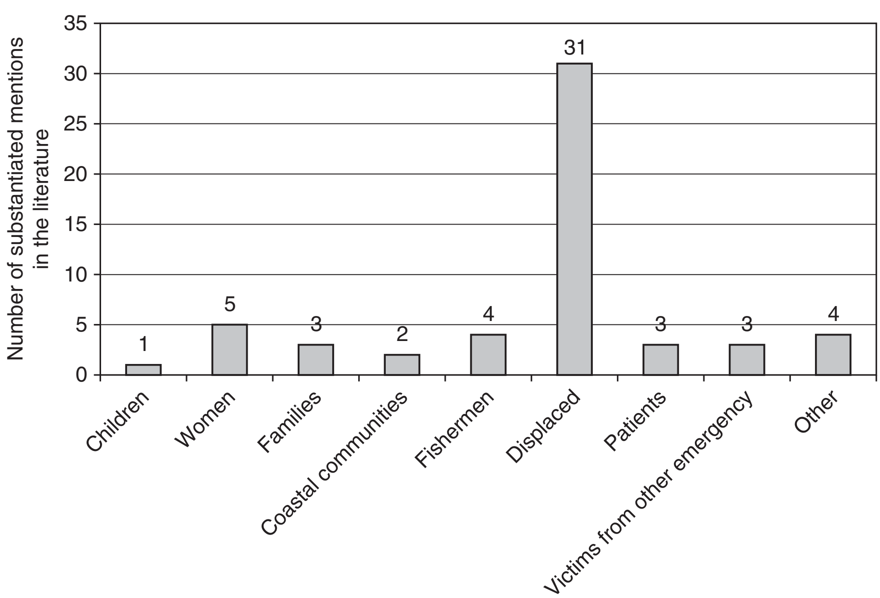

Fig. 26.5. Vulnerable groups exposed to new risks during the post-tsunami recovery.

key risks they perceive and confront. Constructivist (see Douglas and Wildavsky, 1982) and political ecology perspectives (see Watts and Bohle, 1993; Wisner *et al.*, 2004) on vulnerability emphasize the roles culture and power play in the representation of people as 'vulnerable', and the underlying causes. A closer look at the three most important emerging vulnerabilities identified, namely health risks, abuse of women and competition over fisheries, helps us to understand better the detrimental effects of poorly planned recovery efforts.

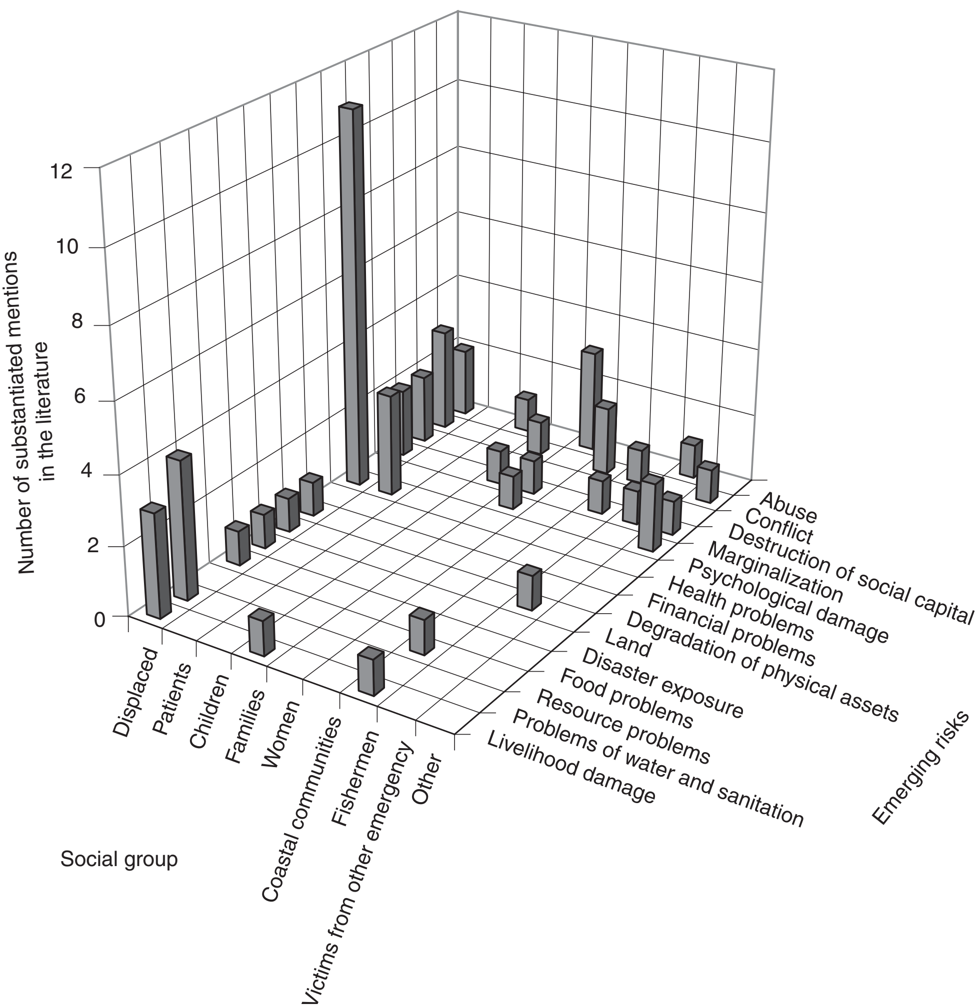

Fig. 26.6. New emerging risks for the identified vulnerable groups during recovery.

Health risks emerging during displacement were primarily caused by: (i) the lack of access to clean water and sanitation; (ii) the positioning of camps in areas exposed to mosquitoes and coastal hazards and far away from livelihood sources; and (iii) the fact that shelters intended for short-term habitation were used as longer-term dwellings (Action Aid, 2005). The gender-motivated violence was most severe in transitory camps where men had opportunities for abusive contact with women and girls because protective mechanisms were absent and the proper functioning social network necessary to help women recover did not exist (Forum Asia, 2005). People depending on fishing faced difficulties in rebuilding their livelihoods because aid focused uncritically on the supply of boats and fishing gear. The indiscriminate provision of boats and fishing gear led to the destabilization of communities and the emergence of resource conflicts and jealousy. Compensation schemes lacked coordination among aid donors, resulting in unclear differentiation with regard to fishing activity and resource use. This situation led to disproportional aid and overcompensation, which in turn exacerbated competition at the local level (see Shanmugaratnam, 2005).

These issues could be considered as symptoms of inadequate planning, delays in reconstruction, poor coordination between agents and a lack of dialogue and action with vulnerable groups in addressing the underlying causes of their vulnerabilities. This created a vicious cycle of increasing dependency of the displaced, who, as explained by Action Aid (2005, p. 25), 'have to cope with geographical, social, cultural and political settings they know little about, and with limited support structures'. The term 'double victimization' (BDG, 2005) captures this predicament, where the labelling and treatment of those affected as merely 'displaced' contributes to their detachment from their identity, social networks and livelihoods. Their resulting marginalization in the relief phase leads to further stresses associated with the recovery and access to aid and is likely to lead to psychological distress and have long-term impacts on their future options, including access to education (see DMIP, 2004).

The failure to address gender issues adequately in disaster relief and recovery has been discussed extensively in the research community, in international bodies and in civil society organizations (ICRC, 2005; Purvis, 2005), but this awareness has seldom been translated into action. ADB notes that, 'there has been a general failure to perceive women not only as victims of the disaster, but also as key actors in shaping the recovery' (ADB, 2005b, p. 6). Although, as expressed by the Association of Women's Rights in Development, the tsunami recovery is seen by some as a catalyst for social change, the reality can be very different: aid delivery is perceived as unjust by some beneficiaries and some changes in coastal zone management policies are deeply contested and not debated openly (see HRC-SL *et al.*, 2005). The coastal buffer zone policy in Sri Lanka has led to considerable uncertainties (which contributed to the delays), as well as forced resettlement or eviction from prior legal or de facto property and is associated with significant claims of widespread corruption among government officials and relief agencies (see Sarvananthan, 2005). However, few authors investigate these important contested issues explicitly and, as a result, there is not enough information available to address them meaningfully in the recovery.

Similarly, ecological restoration projects are based on contested views of their real value for disaster mitigation. For example, the 'Recommendations for Action' issued at the Asian Wetland Symposium in 2005 advocate ecological restoration for the creation of 'bio-shields' to give protection against future coastal hazards (GEC *et al.*, 2005). Danielsen *et al.* (2005) argue that mangroves and coastal vegetation can provide a significant buffer to coastal hazards. However, others argue that such measures are likely to have only a limited effect in the face of large-scale hazards such as the 2004 tsunami and that human modifications of coral reefs have not contributed to the magnitude of the damages observed on land (see Baird *et al.*, 2005). This reinforces the need for grounded, rigorous and context-specific studies to assess the value of coastal ecosystems in reducing the impacts of coastal hazards.

Newly emerging vulnerabilities must also be seen in the context of the past several decades of top-down coastal zone policy planning. Increasing development in highly exposed coastal environments and ecologically sensitive ecosystems, such as flat and low-lying land, particularly river deltas, estuaries and islands, has increased considerably people's exposure to coastal hazards like tropical cyclones, tidal surges, tsunamis and coastal erosion (see Zou and Thomalla, 2008).

Learning to build resilience: obstacles in the recovery community

The documented shortfalls of the post-tsunami relief and recovery work and the emergence of new vulnerabilities highlight the urgent need for actors to learn how to base aid delivery and livelihood interventions on a clear consideration of vulnerable groups and the underlying causes of their vulnerability. But what are the obstacles for learning how to build more resilient coastal communities? To reflect on this question, we use social learning theory, to provide a perspective that is different from the conventional approaches applied in the ongoing recovery debates regarding coordination and accountability and participation, which mostly emphasize regulatory governance mechanisms and dimensions of power (see Bennett *et al.*, 2006). However, the hierarchical decision-making structure assumed in these approaches is not always present, since humanitarian work is supported largely by a 'voluntary ethos' in which 'every organization defines its own threshold of autonomy and the extent to which it will be coordinated by others' (Bennett *et al.*, 2006, p. 23). Social learning theory is useful for analysis when the interactions among recovery actors are governed by a diverse set of relationships that continually are being redefined. It helps us to consider the question of 'who should control the chaos created by the multiplicity of players' (Bennett *et al.*, 2006, p. 23) and to determine how the people and organizations involved can establish common mechanisms for collective action. Taking a social learning perspective, the 'chaos' can be considered as a 'community of practice' (as used by Wenger, 1998), which develops and improves its actions through continual mutual learning. We therefore need to consider the existing community of practice in tsunami recovery and the reasons that prevent it from addressing the needs of vulnerable groups and thus end up having such detrimental effects on tsunami-affected communities. Such understanding is crucial if new initiatives such as the joint UN and ProVention Consortium Hyogo Framework for Action 2005–2015 are to act as platforms for more constructive multi-stakeholder processes for building resilience. Other attempts to discuss aspects of learning in the recovery process complement some of the insights presented here (see IFRCRC, 2006), but these sources rarely address the learning process explicitly per se. Below, we present the four pillars of social learning in the context of the current recovery community.

(I) Practice: operationalizing vulnerability analysis for dialogue and action

'Learning as doing' brings attention to the frameworks and perspectives that are employed by agencies and researchers engaging in recovery activities (adapted from Wenger, 1998, p. 5).

One of the key findings from this analysis is that a vulnerability perspective is rarely used to guide relief and recovery work and that few substantiated vulnerability arguments are presented in the literature. Although the search carried out by the authors may have missed some documents, it is significant that only three of the 101 documents containing primary data were based on formal vulnerability analyses: Birkmann *et al.*, 2006; Miller *et al.*, 2006; SEI and IFRC/SLRCS, 2006. This might be explained by the fact that mainstreaming vulnerability thinking into the disaster risk reduction community has gained momentum only recently through the Hyogo Framework for Action 2050, and that limited progress in translating theoretical vulnerability concepts into operational activities has been made so far. However, several efforts to operationalize vulnerability and resilience concepts in practice were found: the vulnerability and capacity assessments undertaken by the Red Cross Movement; the United Nations University vulnerability assessments (Birkmann *et al.*, 2006); and the US-IOTWS (Indian Ocean Tsunami Warning System) Program's Coastal Community Resilience (CCR) Program (USAID, 2006).

One of the reasons for the low uptake of these scientific concepts in policy and practice is that such theoretical frameworks are perceived as too complicated and difficult to apply. They also tend to place additional demands on data collection and consultations that may not be considered feasible in times of urgency. Yet, recent methodological innovations in vulnerability and capacity assessment (VCA) (see Hamza, 2006) have gone some way in addressing these concerns and allowing for easier operationalization of vulnerability analysis.

(II) Community: politicized aid provides little space for dialogue and collective action

'Learning as belonging' emphasizes the community's social configuration in which the recovery takes place and the formation of space in which worthwhile activities are defined and pursued (adapted from Wenger, 1998, p. 5).

An essential dimension of being in a community of practice is that meaning is negotiated continuously. When actors employ diverse perspectives and frameworks for sense making, it is important to have mechanisms that enable them to communicate across potential barriers. However, the mechanisms that determine the ability of the recovery community to reconfigure continuously and adapt are undermined frequently by the highly politicized agendas of different actors. This was also one of the key findings of Calgaro and Lloyd (2008) in the context of recovering tourism-dependent communities in Thailand. Numerous allegations of corruption, nepotism, inefficiency and exclusion demonstrate that aid is 'a resource controlled by competing political interests and thereby a politicized issue in and of itself' (Frerks and Klem, 2005, p. 19). Many publications indicate that organizations are under tremendous pressure to get their message out and to demonstrate action instead of seeking a convergence towards a collective goal. In a situation of limited and contested information (see also Sarvananthan, 2005), much unsubstantiated and unverified information is taken as fact and reaches broad audiences via news items, agencies' own evaluations and media statements. The severe public pressure to be accountable and to spend donated money rapidly and in a transparent and effective way creates an extremely competitive environment between actors. This pressure leads to turf wars in which territories are staked out and in which limited incentives exist for actors to monitor and evaluate openly their own work or the work of others. Such concerns have prompted recent calls to establish a global disaster response fund.

(III) Meaning: early warning misses links to community experience

'Learning as experience' highlights 'meaning' as a way of talking about the changing ability of actors and researchers to make sense of their experiences, existences and actions in the recovery process (adapted from Wenger, 1998, p. 5).

Because of its enormous impact, geographical scale and public awareness, the 2004 tsunami stands out from prior disasters such as Hurricane Mitch and the Bangladesh cyclone of 1991 from which the global disaster risk reduction community draws experience. In many organizations, high staff turnover and low institutional memory limit their ability to capitalize on recovery experience (see Miller *et al.*, 2005). One of the most important manifestations of the current mode of collective sense making of the recovery is the focus on establishing an early warning system (EWS) in the Indian Ocean. The aim of developing a large-scale EWS was based on the assumption that it was the absence of warnings that had failed to prevent the disaster (ADPC, 2004). This triggered an 'international data-collection effort in the affected countries' in order to improve the tsunami models in the region (Bhattacharjee, 2005, p. 22). When emphasizing such a large-scale disaster risk reduction strategy, analyses and arguments are made for national and regional level decision making that are not directly applicable at the local level. Sector aggregated data cannot inform community action directly as it lacks a differentiation of social groups and an understanding of their different vulnerability contexts. This sense-making perspective takes the 2004 tsunami as the point of departure for understanding how resilience against future hazards can be built during post-tsunami recovery. However, this analysis and those of others (Adger *et al.*, 2005) show that the underlying vulnerabilities of social groups affected by the disaster are linked inextricably to the pre-disaster situation. If the development of the EWS is based on one-way information flow to the communities, the risk perceptions, knowledge and experiences of these communities are unlikely to be considered in the design of the system and local agents of recovery and preparedness are unlikely to play an active role.

(IV) Identity: from controllers to enablers of vulnerable groups coping

'Learning as becoming' proposes that the recovery work changes the self-perception of the people and organizations involved. This includes attention to the developing histories and identities of organizations while they are engaged in joint learning (adapted from Wenger, 1998, p. 5).

An emphasis on the actions of aid workers rather than the affected communities themselves does not easily accommodate emerging appreciations that communities themselves are the drivers of recovery and that women are often key agents in the recovery, rather than simply being a vulnerable group (OCHA, 2005). Unfortunately, the view that those affected by disasters are passive victims still very much dominates in the media. This is likely to reinforce the perception that people are in a situation of powerlessness and marginalization, and this reduces their coping capacities.

With the increasing application of participatory approaches and the acknowledgment of the right of the people affected by the tsunami to lead their own recovery (see EC and IOM, 2005), it follows that actors and researchers will also have to reconsider their own role in the recovery. To support this process best, it must be appreciated that being assessed does not necessarily mean being consulted when there is a danger that the assessment may serve the assessor more than the assessed (de Ville de Goyet and Morinière, 2006). In order not to slow down the recovery process, consultation must be based on an open dialogue with realistic and meaningful participation and not only serve as a means to effective project implementation (ACSD, 2005).

When discussing vulnerability, one needs to specify who is vulnerable and what they are vulnerable to. Because of this subjective characteristic of vulnerability, arguments are only valuable if they represent the perspective of the individual or group to which they relate. When the goal is to 'build back better', as envisaged by many United Nations agencies, the question therefore is: who defines what is better? As long as the information underpinning the recovery process is produced overwhelmingly by outside 'expert' observers and for decision makers at higher levels of government who are highly removed from the realities on the ground, we will be unable to identify and understand the perceptions of vulnerability and resilience of those most likely to be affected by hazards and to support them to act in the spaces of opportunity created by the recovery process.

Conclusions

The main conclusion from this study is that the literature on the recovery from the 2004 tsunami in Sri Lanka and Indonesia is characterized by a lack of relevant vulnerability data and substantiated arguments. This situation results in a limited understanding of social vulnerability, inappropriate interventions and a failure to ensure that recovery builds more resilient coastal communities. The majority of the vulnerabilities identified in the literature have emerged during the recovery process, triggered by intervention and aid delivery of external actors. In this chapter, we have analysed the ability of the recovery community to learn to build resilience – giving emphasis to the knowledge production process of assessments and other studies. A number of challenges arising from the nature of this recovery community, including limitations in operational vulnerability assessments, perpetuation of unsubstantiated facts in a politicized aid environment and dominance of technical and external interpretations in the post-disaster sense-making process were suggested.

Arguably, disaster risk reduction should place less emphasis on interventions that are controlled from the outside and do more to enable those affected by disaster to help them to recover. The Asian Coalition for Housing Rights expressed this when it entitled a special issue of their newsletter 'Housing *by* People' (our emphasis) (ACHR, 2005). Learning cannot be controlled centrally – it emerges from the collective and mutually dependent acts of donors and researchers, communities and government. In order to learn to build resilience in the coastal communities, an alternative perspective may be necessary for actors in the recovery: that of being enablers of vulnerable people's recovery, self-organization and coping. Such a perspective is likely to support resilient coastal communities better in the future.

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References

ACHR (Asian Coalition for Housing Rights) (2005) Housing by people in Asia. Newsletter of the Asian Coalition for Housing Rights 16 August (http://www.achr.net/000ACHRTsunami/Download%20TS/ACHR%20Tsunami%20Newsletter.pdf, accessed 6 June 2009).

ACSD (Asian Civil Society Declaration on Post-Tsunami Challenges) (2005) Resources available for rehabilitation must be used to help rebuild just and equitable societies. Press release. Asian Forum for Human Rights and Development (Forum-Asia), Bangkok.

Action Aid (2005) Tsunami response – a human rights assessment (http://www.actionaid.org/docs/tsunami_human_rights.pdf, accessed 6 June 2009).

ADB (Asian Development Bank) (2005a) An initial assessment of the impact of the earthquake and tsunami of December 26, 2004 on South and Southeast Asia. ADB, Manila.

ADB (Asian Development Bank) (2005b) Rebuilding Sri Lanka: assessment of tsunami recovery implementation. ADB, Manila.

Adger, N. (2006) Vulnerability. *Global Environmental Change* 16, 268–281.

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R. and Rockström, J. (2005) Social-ecological resilience to coastal disasters. *Science* 309, 1036–1039.

ADPC (Asian Disaster Preparedness Center) (2004) *Lessons Learned from the Tsunami Event December 26, 2004: Case of Sri Lanka*.

AI (Amnesty International) (2006) Sri Lanka waiting to go home – the plight of the internally displaced. AI, London.

AusAID and Care International (2005) Rapid assessment of Western Islands of Aceh 09 to 14 January 2005 (Pulau Simeulue, Kepulauan Banyak and Aceh Singkil). Draft report.

Baird, A.H., Campbell, S.J., Anggoro, A.W., Ardiwijaya, R.L., Fadli, N., Herdiana, Y., Kartawijaya, T., Mahyiddin, D., Pardede, A.M.S.T., Pratchett, M.S., Rudi, E. and Siregar, A.M. (2005) Acehnese reefs in the wake of the Asian tsunami. *Current Biology* 15(26), 19–26.

BDG (Bilateral Donor Group) (2005) Summary report: bilateral verification mission to tsunami-affected districts in Sri Lanka, January to February 2005. BDG, Colombo.

Bennett, J., Bertrand, W., Harkin, C., Samarasinghe, S. and Wikramatillake, H. (2006) Coordination of international humanitarian assistance in tsunami-affected countries. Tsunami Evaluation Coalition, London.

Bhattacharjee, Y. (2005) In wake of disaster, scientists seek out clues to prevention. *Science* 307, 22–23.

Birkmann, J., Fernando, N., Hettige, S., Amarasinghe, S., Jayasingam, T., Paranagama, D., Nandana, M.D.A., Nassel, M., Voight, S., Grote, U., Engel, S., Schraven, B. and Wolferts, J. (2006) Rapid and multidimensional vulnerability assessment in Sri Lanka at the local level. Source No 7/2007, UNU Institute for Environment and Human Security (UNU-EHS), Bornheim, Germany.

Calgaro, E. and Lloyd, K. (2008) Sun, sea, sand and tsunamis: examining disaster vulnerability in the tourism community of Khao Lak, Thailand. *Singapore Journal of Tropical Geography* 29(3), 288–306.

Care International Indonesia (2006) CARE tsunami response: two years in Aceh. Care International Indonesia, Jakarta.

Care, United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (2005) Draft field report: rapid environmental impact assessment – Sri Lanka tsunami. Unpublished. OCHA, Benfield Hazard Research Center, London.

CARMA International (2006) The CARMA report on western media coverage of humanitarian disasters. CARMA International, London.

CGI (Consultative Group on Indonesia) (2005) Indonesia – preliminary damage and loss assessment. The December 2004 Natural Disaster. CGI, Jakarta.

Clasen, T., Smith, L., Albert, J., Bastable, A. and Fesselet, J.-F. (2006) The drinking water response to the Indian Ocean tsunami, including the role of household water treatment. *Disaster Prevention and Management* 15(1), 190–201.

Danielsen, F., Sørensen, M.K., Olwig, M.F., Selvam, V., Parish, F., Burgess, N.D., Hiraishi, T., Karunagaran, V.M., Rasmussen, M.S., Hansen, L.B., Quarto, A. and Suryadiputra, N. (2005) The Asian tsunami: a protective role for coastal vegetation. *Science* 310, 643.

de Ville de Goyet, C. and Morinière, L.C. (2006) *The Role of Needs Assessment in the Tsunami Response*. Tsunami Evaluation Coalition, London.

DMIP (Disaster Management and Information Programme) (2004) Portrait of a disaster. Rapid assessment report of the effects of the tsunami crushes in Sri Lanka. DMIP, Nugegoda, Sri Lanka.

Douglas, M. and Wildavsky, A. (1982) *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. University of California Press, Berkeley, California.

Eakin, H. and Luers, A.L. (2006) Assessing the vulnerability of social–environmental systems. *Annual Review of Environment and Resources* 31, 365–394.

EC (European Commission) and IOM (International Organization for Migration) (2005) Settlement and livelihoods needs and aspirations assessment of disaster-affected and host communities in Nias and Simeulue. EC and IOM, Brussels.

EFL (Environmental Foundation Ltd) (2005) Comments on the UNDAC rapid environmental assessment of Sri Lanka, 9 February 2005. EFL, Colombo.

Forum Asia (Asian Forum for Human Rights and Development) (2005) Draft report untitled. Unpublished.

Frerks, G. and Klem, B. (2005) Tsunami response in Sri Lanka. Report on a field visit from 6–20 February 2005. Disaster Studies, Wageningen University, Wageningen, the Netherlands.

Fritz Institute (2005) Recipient perceptions of aid and aid effectiveness: rescue relief and rehabilitation in tsunami-affected Indonesia, India and Sri Lanka.

Galoppin, G.C. (2006) Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change* 16, 293–303.

GEC (Global Environment Centre), AWS 2005 Secretariat, Japan, Wetlands International, Ramsar Secretariat (2005) The tsunami and coastal wetlands – recommendations for action. Report on Special Session on Tsunami and Coastal Wetlands, Asian Wetland Symposium, 9 February 2005, Bhubaneswar, India.

GoI (Government of Indonesia, Ministry of Environment) (2005) Rapid Environmental Impact Assessment – Banda Aceh, Sumatra. GoI, Jakarta.

Greenomics Indonesia and WWF (World Wide Fund for Nature) (2005) Implementation design – timber for Aceh program. Final draft, Jakarta.

Gunderson, L.H. and Holling, C.S. (2002) *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington, DC.

Hamza, M. (2006) Vulnerability and capacity assessment methodology, SEI Tsunami Programme. Unpublished project document, Oxford.

HRC (Human Rights Center) and EWC (East–West Center) (2005) *After the Tsunami. Human Rights of Vulnerable Populations*. University of California, Berkeley, California.

HRCSL (Human Rights Commission Sri Lanka), Colombo University Community Extension Centre, United Nations Development Programme (UNDP) (2005) The report on people's consultations on post-tsunami relief, reconstruction and rehabilitation in Sri Lanka. HRCSL, Colombo.

ICRC (International Committee of the Red Cross) (2005) Sri Lanka – north-east livelihoods – assessment report. Unpublished.

IFRCRC (International Federation of Red Cross and Red Crescent Societies) (2006) Tsunami two-year progress report. IFRCRC, Geneva, Switzerland.

Larsen, R.K., Miller, F. and Thomalla, F. (2008) Vulnerability in the context of post 2004 Indian Ocean tsunami recovery: lessons drawn for building more resilient coastal communities. A synthesis of documented factors contributing to tsunami-related vulnerabilities in Sri Lanka and Indonesia. SEI Risk, Livelihoods and Vulnerability Programme Working Paper. Stockholm Environment Institute, Stockholm.

Lindskog, E., Dow, K., Axberg, G.N., Miller, F. and Hancock, A. (2005) When rapid changes in environmental, social and economic conditions converge: challenges to sustainable livelihoods in Dak Lak, Vietnam. Stockholm Environment Institute, Stockholm.

LTTE (Liberation Tigers of Tamil Eelam, Planning and Development Secretariat) (2005) *Post-Tsunami Reconstruction Needs Assessment for the NorthEast (NENA), Sri Lanka*. LTTE, Sri Lanka.

McLaughlin, P. and Dietz, T. (2008) Structure, agency and environment: toward an integrated perspective on vulnerability. *Global Environmental Change* 18(1), 99–111.

Mashni, A., Reed, S., Sasmitawidjaja, V., Sundhagul, D. and Wright, T. (2005) *Multi-Agency Evaluation of Tsunami Response: Thailand and Indonesia*. CARE International and World Vision International, Atlanta, USA.

Mattock, J.L. (2005) *Resource Loss and Psychosocial Distress: An Application of the Conservation of Resources (COR) Model to the 2004 Asian Tsunami in Sri Lanka*. University of Northumbria, Newcastle, UK.

Miller, F., Thomalla, F. and Rockström, J. (2005) Paths to a sustainable recovery after the tsunami. *Sustainable Development Update* 5(1), 2–3.

Miller, F., Hamza, M., Lonsdale, K., de la Rosa, E. and Rozable, N. (2006) Galle vulnerability and capacity assessment report. Stockholm Environment Institute, Stockholm.

OCHA (United Nations Office for the Coordination of Humanitarian Affairs) (2005) Post-tsunami update. United Nations activities in support of the relief and recovery efforts of the Sri Lankan government and its people. Post-tsunami update July/August. OCHA.

OCHA (United Nations Office for the United Nations Coordination of Humanitarian Affairs) and UNEP (United Nations Environment Programme) (2005) *Indian Ocean Tsunami Disaster of December 2004*. UNDAC Rapid Environmental Assessment in the Democratic Socialist Republic of Sri Lanka. Joint UNEP/OCHA Environment Unit, Geneva, Switzerland.

Oliver-Smith, A. (1996) Anthropological research on hazards and disasters. *Annual Review of Anthropology* 25, 303–328.

Purvis, J. (2005) The December 2004 tsunami and the wider issue of making poverty history. *Women's History Review* 14(1), 5–6.

Sarvananthan, M. (2005) *Post-Tsunami North & East Sri Lanka: Swindlers Hold Sway*. PPID Working Paper Series (Working Paper 4), Point Pedro, Sri Lanka.

Scheper, E., Parakrama, A. and Smruti, P. (2006) *Impact of the Tsunami Response on Local and National Capacities*. Tsunami Evaluation Coalition, London.

SEI (Stockholm Environment Institute) and IFRC/SLRCS (International Federation of Red Cross and Red Crescent Societies and Sri Lanka Red Cross Society) (2006) Matara vulnerability and capacity assessment report. 22–30 September 2006, Talalla Central GNs, Devinuwara DS, Matara District, Sri Lanka.

Sellamuttu, S.S. and Milner-Gulland, E.J. (2005) *The Importance of Community Participation and Empowerment in Post-Tsunami Rehabilitation – A Case Study from the Hambantota District in Sri Lanka*. Paper presented during the 4th PEP Research Network General Meeting, 13–17 June 2005, Colombo.

Shanmugaratnam, N. (2005) Tsunami victims' perceptions of the proposed buffer zone and its implications in eastern Sri Lanka. Norwegian University of Life Sciences, Aas, Norway.

Sida (Swedish International Development Agency Cooperation), Department for International Development (DFID), Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) (n.d.) Hambantota district verification mission, 13–15 February. Unpublished.

SLIM (2004) Introduction to SLIM publications for policy makers and practitioners. SLIM Policy Briefing (http://slim.open.ac.uk, accessed 6 June 2009).

Tanaka, N., Sasaki, Y., Mowjood, M.I.M., Jinadasa, K.B.S.N. and Homchuen, S. (2006) Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. *Landscape and Ecological Engineering* 3(1), 33–45.

Telford, J., Cosgrave, J. and Houghton, R. (2006) Joint evaluation of the international response to the Indian Ocean tsunami: synthesis report. Tsunami Evaluation Coalition, London.

Turner, B.L. II, Kasperson, R.E., Matsone, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A. and Schiller, A. (2003) A framework for vulnerability analysis in sustainability science. *PNAS* 100(14), 8074–8079.

UNICEF (United Nations Children's Fund), US Agency for International Development (USAID), World Food Programme (WFP), United Nations Refugee Agency (UNHCR), Department for International Development (DFID) (2004) Rapid situation and initial needs assessment (RSINA) for the government of Sri Lanka (GoSL) and UNDP/OCHA in tsunami-affected districts. Unpublished.

USAID (United States Agency for International Development) (2006) US Indian Ocean tsunami warning system (IOTWS) program. Concepts and practices of 'resilience': a compilation from various secondary sources. USAID, Bangkok.

Watts, M.J. and Bohle, H.G. (1993) The space of vulnerability: the causal structure of hunger and famine. *Progress in Human Geography* 17(1), 43–67.

Wenger, E. (1998) *Communities of Practice. Learning, Meaning, and Identity*. Cambridge University Press, Cambridge, UK.

WFP (World Food Programme) (2005) Tsunami emergence food security assessment. Overview of preliminary findings. WFP, Rome.

Wisner, B., Cannon, T., Blaikie, P. and Davis, I. (2004) *At Risk: Natural Hazards, People's Vulnerability and Disasters*. Routledge, London.

Yamada, S., Gunatilake, R.P., Roytman, T.M., Gunatilake, S., Fernando, T. and Fernando, L. (2006) The Sri Lanka tsunami experience. *Disaster Management & Response* 4(2), 38.

Zou, L. and Thomalla, F. (2008) A synthesis of insights on the causes of social vulnerability to coastal hazards in South-east Asia. SEI Risk, Livelihoods and Vulnerability Programme Working Paper, Stockholm Environment Institute, Stockholm.

27 Social Vulnerability to Coastal Hazards in South-east Asia: a Synthesis of Research Insights

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Abstract

Several decades of research on natural hazards have produced a large range of insights on the complex and interacting factors contributing to hazard vulnerability. Despite these insights and the efforts of the disaster risk reduction and humanitarian communities, reducing vulnerability to coastal hazards remains a challenge facing many communities worldwide and particularly in South-east Asia. This chapter presents preliminary findings of a comprehensive and systematic analysis of 128 peer-reviewed scientific articles, focusing on causal factors and structures of social vulnerability to coastal hazards and the key recommendations put forward for reducing vulnerability. The review presents findings from Bangladesh, India, Indonesia, Malaysia, Philippines, Sri Lanka, Thailand and Vietnam. A meta-analysis methodology is applied and includes the development of a coding system, statistical characterization and synthesis. The analysis is restricted to peer-reviewed journal articles and is based on a review of the main conceptual frameworks on hazard vulnerability. A total of 336 causal factors and 227 recommendations are identified and categorized, and their interrelationships analysed. There are several key findings. First, there is a clear gap between the conceptual/theoretical literature and the empirical case studies; few case studies refer to or apply a particular conceptual framework for analysing hazard vulnerability. Second, generalized patterns or causal structures of vulnerability can be established. However, a multitude of factors interact in complicated ways and at multiple scales and interpretations of their interactions to produce hazard vulnerability are different in different environmental, historical and social contexts. Third, there are considerable mismatches between the identified vulnerability factors and the recommendations for vulnerability reduction.

Introduction

Natural hazards have always been an important part of human history and remain one of the main challenges for human well-being and sustainable development in many parts of the world. Between 1980 and 2000, some 75% of the world's population lived in areas affected at least once by an earthquake, a tropical cyclone, a flood or a drought (UNDP, 2004). Among these regions, South and South-east Asia suffer disproportionately from the impacts of natural disasters (Bildan, 2003).

Compared with other parts of the world, Asia experiences the majority of severe disasters. Between 1993 and 2002, hydrometeorological hazards accounted for 90% of reported disasters, 86% of the number of people killed and 99% of the number of people affected by disasters (Table 27.1).

Table 27.1. Distribution of natural disaster impacts by continent: 1993–2002.

	Reported disasters (%)	People reported killed (%)	People reported affected (%)	Estimated damage in US$ (%)
Africa	15.60	3.11	5.48	0.39
Americas	26.30	12.53	1.90	24.24
Asia	37.60	78.79	91.09	57.73
Europe	15.02	5.05	0.90	16.00
Oceania	4.56	0.53	0.63	1.64
Total	2935	531,159	2496.2 million	654.6 billion

Emergency Events Database, Centre for Research on the Epidemiology of Disasters (CRED), Université Catholique de Louvain – Ecole de Santé Publique, Belgium.

Figure 27.1 shows the ratio of the percentages of the number of reported disasters, the number of people killed and affected and the estimated damage in Asia compared with the rest of the world between 1995 and 2004. Although the percentages of disasters reported and people affected were relatively stable, there were high interannual variations in the number of lives lost and the estimated economic damage. However, the number of people killed and the estimated damages show a decreasing trend until about 2002–2003, and since then they have been increasing again.

The continuing high socio-economic losses arising from natural disasters indicate that hazard vulnerability in South and South-east Asia remains high and that current efforts are not sufficient to reduce vulnerability significantly.

Several decades of research have led to an improved understanding of the complex and interacting factors that contribute to the construction of social vulnerability to natural hazards (Kasperson and Kasperson, 2001, 2005; White *et al.*, 2001; Pelling, 2003; Turner *et al.*, 2003; Bankoff *et al.*, 2004; Birkmann, 2006). However, despite these insights, a

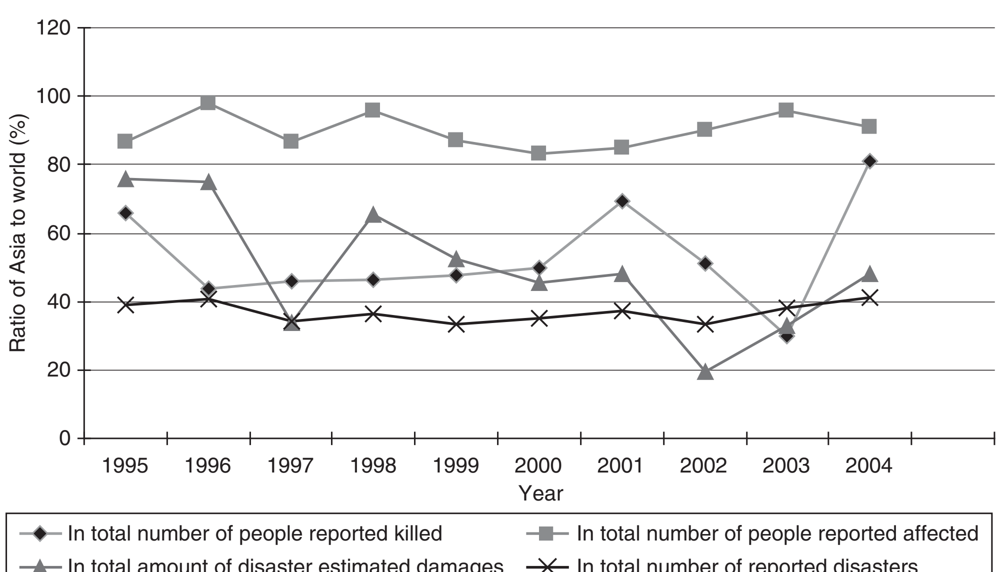

Fig. 27.1. Natural disaster impact ratio of Asia compared to the rest of the world (1995–2004). Emergency Events Database, Centre for Research on the Epidemiology of Disasters (CRED), Université Catholique de Louvain – Ecole de Santé Publique, Belgium.

growing awareness of natural hazards among the general public through extensive media coverage (Berz *et al*., 2001; White *et al*., 2001) and the efforts of the disaster risk reduction and humanitarian communities (e.g. International Decade for Natural Disaster Reduction (IDNDR), Yokohama Declaration 1994 and the Hyogo Framework for Action 2005–2015) to reduce hazard vulnerability to the impacts of natural disasters have grown significantly over the past several decades (Yodmani, 2004) and remain a considerable challenge to poverty reduction and sustainable development in many countries around the world.

This chapter provides a summary of the key findings of a recent report (Zou and Thomalla, 2008) in which a comprehensive systematic analysis of the scientific literature on social vulnerability to coastal hazards in South and South-east Asia was conducted. The objectives of this work were to identify the causal factors contributing to social vulnerability to coastal hazards, to analyse the complex interactions between them and to review the recommendations made for reducing hazard vulnerability. By drawing out key lessons learned from several decades of research experience, we identified current gaps in knowledge, as well as gaps in the translation and application of scientific knowledge in policy and practice.

A Meta-analysis of Coastal Hazard Vulnerability

The results of a single study can be influenced by characteristics of the study setting, the sampled population, timing, locations and the subjective bias of the researchers. Therefore, some general trends and underlying principles can only be deduced across a large body of case studies or empirical studies.

The purpose of meta-analysis is to combine findings from separate but largely similar studies. According to some researchers, such studies may be suitable for the application of a variety of analysis techniques (e.g. common literature review, formal statistical approaches) for combining, comparing, identifying or selecting common elements, relevant results and cumulative properties from a broad set of individual cases (Matarazzo and Nijkamp, 1997). Meta-analysis plays an important role in the dissemination of knowledge and in determining the direction of subsequent research, policies and practice (Sandelowski *et al*., 1997).

Meta-analysis has now become a widely accepted research tool, encompassing a range of procedures used in a variety of disciplines, such as psychology, labour economics, environmental science and transportation science (Gaarder, 2002; Yu, 2002; Greenaway and Witten, 2004; Travisi *et al*., 2004). There are, however, few uses of this methodology in the field of natural hazard research.

Meta-analysis involves a critical examination of multiple accounts of phenomena to review similarities and differences among them (Nijkamp and Pepping, 1997–1998). This analysis requires the establishment of an analytic strategy and coding system to categorize data and to interpret findings in relation to predefined research questions. The following seven steps describe the process of undertaking a meta-analysis: (i) formulating the guiding research questions; (ii) choosing an appropriate conceptual framework; (iii) developing a literature search strategy; (iv) collecting case studies; (v) coding information from individual case studies; (vi) formulating and describing the object under investigation; and (vii) synthesizing the data collected from individual case studies (Matarazzo and Nijkamp, 1997; Glasmeier and Farrigan, 2005).

Using the Turner *et al*. (2003) multidisciplinary framework for assessing vulnerability in coupled socio-ecological systems as a basis for this analysis, we systematically reviewed 128 documents. These included 120 articles (including place-based case studies and theoretical and conceptual discussion papers) published in peer-reviewed scientific journals and eight journal editorials or communications. The literature search included documents published between 1970 and March 2006 and was defined thematically by hazard type (coastal flood, storm surge, tsunami, tidal wave, hurricane and marine-related infectious disease) (Adger *et al*., 2005) and geographically by South and South-east Asia (Bangladesh, India, Indonesia, Malaysia, Philippines, Sri Lanka, Thailand and Vietnam). A methodology for documenting and coding information extracted from the large amount of literature was developed in order to deconstruct the statements identified in the collected documents into a set of characteristics with coherent forms of description. To prevent the exclusion of relevant information throughout the coding process, the system was updated continuously as new information became available. The selected documents were analysed statistically to reveal information on the types of studies undertaken, the spatial scale of analysis, country or regional focus, hazard types, disaster risk management phases, conceptual approach and research methodology.

Results and Discussion

Results of meta-analysis

Contributing factors to coastal hazard vulnerability

We identified a total of 361 individual causal factors contributing to coastal hazard vulnerability. In contrast to similar syntheses of the factors contributing to particular phenomena undertaken in other fields of research (Geist and Lambin, 2002; Misselhorn, 2005), we did not distinguish between 'underlying drivers' and 'proximate factors', or 'indirect drivers' and 'direct drivers'. This way of categorizing factors introduces the problem of deciding whether a particular cause is direct or indirect. This is difficult because vulnerability is a characteristic of all people, ecosystems and regions confronting environmental or socio-economic stresses, and is driven by multiple interacting and cumulative impacts of various factors operating at different spatial and temporal scales (Turner *et al*., 2003).

We identified two ways in which researchers have looked at vulnerability to coastal hazards. One is to consider how vulnerability is affected by a wide range of socio-economic factors and the other is to focus on the effects on the vulnerability of different interventions aimed at reducing disaster risk. In the first, society is regarded as the object of analysis. Here, human activities and interactions between the natural environment and social development are considered. In the second, the approaches, strategies and actions in different phases of the disaster risk reduction cycle are considered and their effectiveness in reducing vulnerability discussed. In line with these two approaches, we described the identified causal factors as either socio-economic factors (Table 27.2) or disaster risk management factors (Table 27.3). Of the 361 identified factors contributing to vulnerability, 287 relate to socio-economic issues and 74 relate to disaster risk management issues. Individual causal factors were then assigned to major categories, subcategories and factor groups. We defined nine major categories of factors relating to socio-economic characteristics and four major categories of factors relating to disaster risk management. The latter correspond with the phases of the disaster risk management cycle (Hodgkinson and Stewart, 1991; Helbing and Kuhnert, 2003).

Figure 27.2 shows the number of individual factors in each major category, their causal relationships and the number of times these links have been identified in the selected literature. The statistical analysis shows that factors relating to 'geography and environment' are considered to be the most important in contributing to vulnerability to coastal hazards. The fact that they were mentioned more than twice as many times as the next highest category also implies that these factors were perceived to be far more important than any other. The most frequently mentioned factors in this category were climate change, changing rainfall patterns, low-lying coastal land and sea-level rise.

The second and third most often mentioned factors belonged to the categories 'human conditions and basic rights' and 'demography'. Within the category 'human conditions and basic rights', the most frequently mentioned cause was individual poverty, followed by lack of access and entitlements, national poverty and inequality. The most important demographic factors were population growth, population density and migration.

The dynamics of the demography and livelihood factors are partially driven by issues

Table 27.2. Social-economic factors contributing to coastal hazards vulnerability.

Major categories	Subcategories		Groups
Human condition and basic rights			National poverty Individual poverty Access to resources Power relations Inequality
Development	Agriculture activity		Trend of agriculture intensity Crop diversity Land availability for agriculture
	Land use		Land use policies Urban development Industrial development Physical changes to the natural landscape
Macroeconomy			Market liberalization Globalized economy Labour and products market Structure of economy
Livelihood			Resource distribution Social networks
Infrastructure			Transportation Coastal flood protection Housing and shelters Basic services River channels and reservoirs Others
Institutions	Policies		Social welfare policies Communication of policies Participation in policy making processes Political bias in decision making
	Organizations	Structure	Hierarchy of managing body Cooperation between agencies Government resources
		Characteristics	Institutional culture Bureaucracy
	Others		Political situation Technological solutions Documented knowledge and experience Government capacity
Social culture and behaviour	Perceptions and behaviour		Religious perceptions Perception from past experience Cultural norms Individual behaviour Cultural and language differences
	Social structure		Conflicts or strife Traditional networks Community structure Household structure
Demography			Population density Migration Gender Children Population structure
Geography and environment			Environmental characteristics Geographical characteristics Environmental changes by human activities

Table 27.3. Factors contributing to coastal hazard vulnerability relating to disaster risk management.

Major categories	Groups
Mitigation	Planning and preparedness
	Assessment
	Knowledge management
Early warning	Dissemination of warnings
	Development of early warning systems
	Perceptions of warnings
	Poor communication of warnings
	Information and knowledge
Response	Response plans
	Available resources
	Governmental actions
	Cooperation and assistance
	Knowledge and experience
Post-disaster recovery	Medical service
	Outside assistance
	Aid distribution
	Institutional perception and behaviour
	Action of affected people
	Knowledge and information

relating to access to natural resources. Some people choose to live in marginal and hazardous areas because it is easier for them to gain access to resources there compared to other places (Thompson and Sultana, 1996; Gupta and Sharma, 2006). With growing social and environmental changes, many important natural resources are increasingly threatened. These resources are important in building community-level coping capacity and resilience to natural hazards.

The interactions between poverty, inequality and lack of entitlements were mentioned frequently in the selected literature. The research of Blaikie *et al*. (1994) shows that disasters are largely socially constructed. Entrenched political ideologies and power structures regulate access to resources and form the root factors of hazard vulnerability, as they exacerbate the dynamic pressures acting on communities and leading to unsafe conditions within a fragile environment and local economy (Tompkins and Hurlston, 2005).

Access to entitlements is based on the political representation of different groups. The limitation of access to entitlement, such as shortcomings of the underlying social welfare and insurance and credit systems aggravate inequality. For example, in India, most of the losses resulting from natural disasters are not insured and therefore many people receive no financial compensation for the loss of life of family members or loss of their livelihoods (Atmanand, 2003). This lack of access to insurance and compensation aggravates vulnerability to future hazards.

Recommendations to reduce vulnerability

We identified a total of 227 individual recommendations relating to many different aspects of vulnerability and disaster risk reduction. These were grouped into eight major categories, each of which contained a number of groups of recommendations (Table 27.4). We did not apply the same categories we used to organize the different factors of vulnerability (Tables 27.2 and 27.3) because many of the recommendations focused on the higher policy level and did not correspond directly with the identified factors of vulnerability.

These eight categories of recommendations on how to reduce vulnerability did not receive equal attention in the selected literature. The category 'institutions and policies' accounted for 48% of the number of recommendations and 54% of the number of times mentioned.

Recommendations in the category 'infrastructure', which relates to the construction of

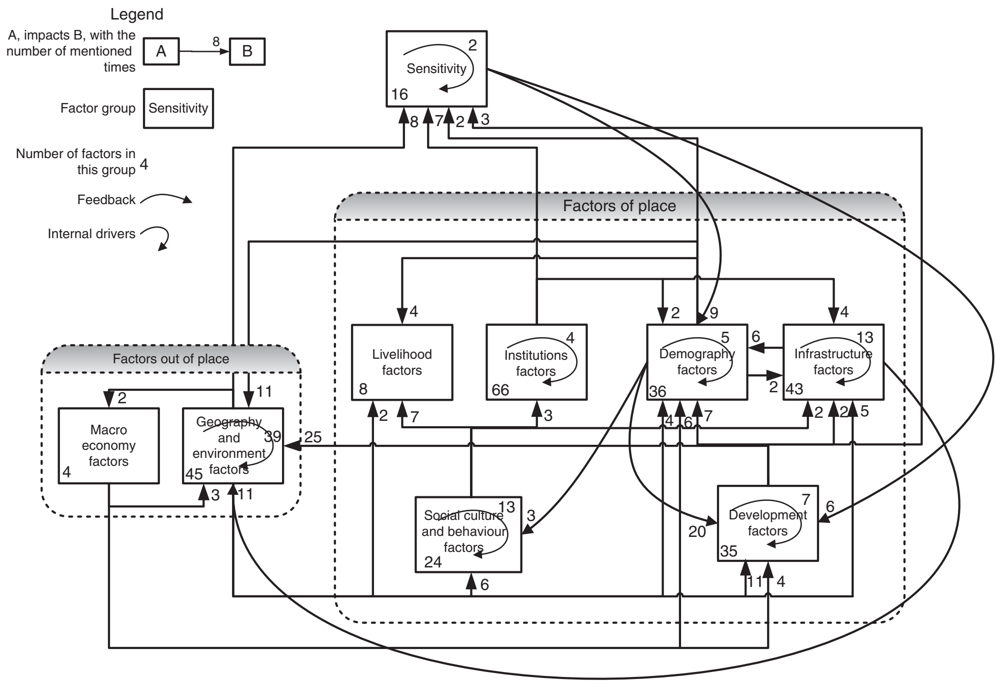

Fig. 27.2. The causal relationships between the different categories of factors contributing to vulnerability.

flood protection infrastructure, shelters and housing, transportation and the management of waterways and reservoirs, were the second most mentioned.

The category 'institutions and policies' consisted of 11 groups of recommendations that spanned a wide range of issues (Table 27.4). The group 'micro level and livelihood' included the most individual recommendations (15), followed by the groups 'cooperation' and 'government organization', with 14 and 13 recommendations, respectively.

The category 'community and household' is different from that of the subgroup 'micro level and livelihood' in the category 'institutions and policies' because it is concerned with community-based ('bottom-up') disaster risk reduction strategies, whereas the 'institutions and policies' recommendations target local authorities and institutions on the implementation of vulnerability reduction policies ('top-down' approaches).

In terms of the number of individual recommendations (8) and the number of times these were mentioned in the literature (20), recommendations in the category 'community and household' received the least amount of attention of all categories.

Key findings

Even though the loss of human life has been reduced significantly over the past several decades through the implementation of various disaster risk reduction strategies, there is an increasing trend in terms of the number of reported natural disasters, the number of people affected and the overall socio-economic impacts of these disasters. The reduction of social hazard vulnerability therefore remains a key international challenge to date. Considering the wealth of research on natural hazards, environmental risks and human vulnerability and well-being, as well as the practical experience gained in disaster risk reduction efforts worldwide, it seems surprising that the endeavours of researchers, decision makers and practitioners to reduce hazard vulnerability have had such limited success. The insights gained in this analysis help to explain why this might be the case.

Table 27.4. Categories of recommendations to reduce vulnerability to coastal hazards identified in the selected literature.

Categories	Groups of recommendations
Sociocultural	Education
	Traditional coping strategies
	Others
Institutions and policies	Guidelines
	General policies
	Micro level and livelihood
	Insurance, welfare and other measures
	Development
	Government organization
	NGOs and other institutions
	Cooperation
	Information and communication management
	Investments
	Others
Recovery	Plans
	Aid distribution
	Monitoring
	Redevelopment
	Local facility
Infrastructure	Flood protection
	Transportation
	Housing and shelters
	Waterways and reservoirs
Environment	Protocols and plans
	Reforestation
	Development control
	Sea-level rise reduction
	Ecosystem restoration
	Water quality
Community and household	Protocols and plans
	Credit system
	Local organization and structure
Early warning	Construction of early warning system
	Dissemination of warnings
	Cooperation
	Mass communication
Assessment	Risk assessment
	Needs assessment
	Capability and liability assessment
	Livelihood assessment
	Impact assessment
	Protocols and guidelines

The most important causes of vulnerability to coastal hazards

The majority of the top 20 most frequently mentioned factors in the selected literature were related to demography. Population growth was the highest ranking single cause of coastal hazard vulnerability. Population density, migration and habitation of marginal and hazardous areas were also frequently mentioned factors. Demography affected almost all other factors of vulnerability. The second most important factors were issues relating to human conditions and basic rights, particularly national and individual poverty, lack of access to resources, and inequality. Human conditions and basic rights issues were seen to influence many other causes of vulnerability strongly. Poverty, lack of access to resources and inequality were considered in turn to be important drivers of demographic processes, particularly migration (Fig. 27.3).

Increasing influence of regional and global processes

In the past several decades, globalization and the liberalization of international trade have led to the establishment of new population dynamics around the world. As economies are ever more interconnected and interdependent, coastal communities are affected increasingly by processes occurring on larger scales (Adger *et al*., 2005). For example, in regions where people are highly dependent on the production of cash crops for their livelihoods, such as coffee and rubber, their hazard vulnerability is affected strongly by fluctuations in the global market prices of those commodities (Lindskog *et al*., 2005).

Population dynamics

Migration is considered one of the most important factors contributing to hazard vulnerability. It is one of the main causes of the overexploitation of natural resources, environmental degradation and the exacerbation of existing inequalities and tensions over access to resources. Migration includes large-scale population flows between countries or world regions and smaller-scale

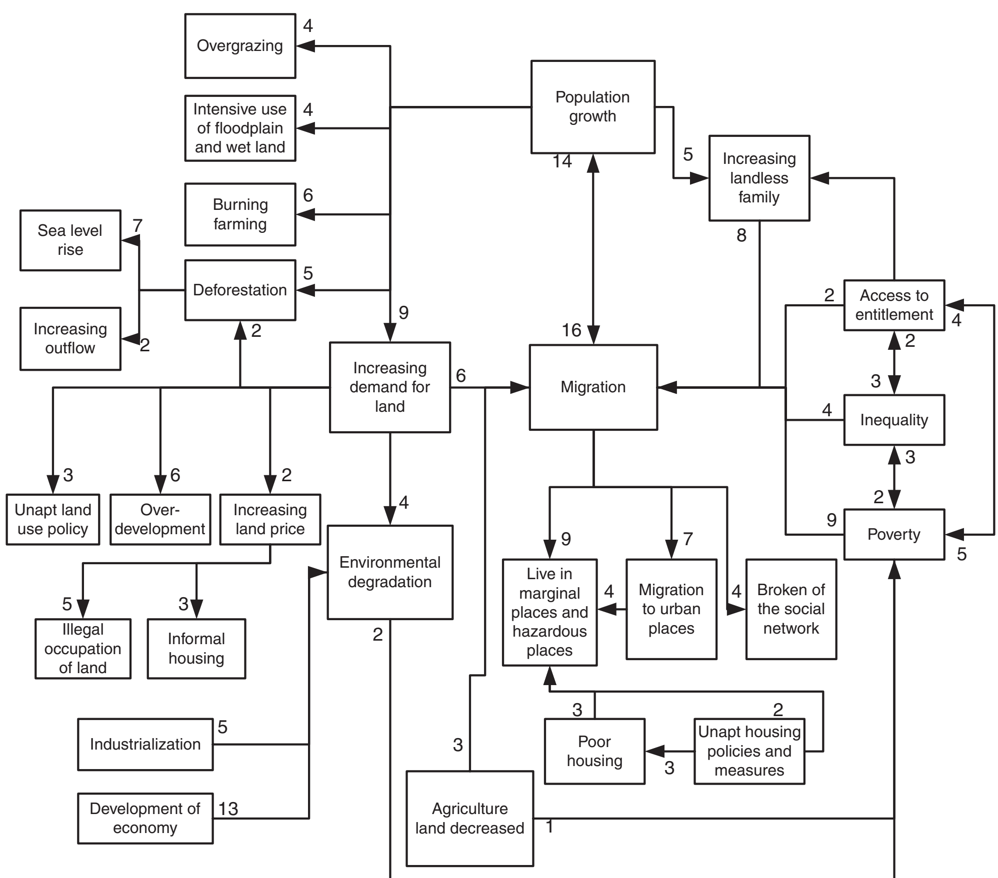

Fig. 27.3. Conceptual map of the relationships between demographics, land use and environmental degradation in creating vulnerability to coastal hazards.

population flows, such as migration from an inland mountain area to a coastal area in the same country (Lindskog *et al*., 2005), and can be temporary or permanent. Global population dynamics are often regarded as 'economic migration'. This type of migration typically includes production and consumption patterns that involve different industries. Tourism is a typical example causing temporary (seasonal) movement of large numbers of people across regions. Although this movement is short term, it represents a significant part of population dynamics. The 2004 Indian Ocean tsunami highlighted the vulnerability of tourists, and the people working in the tourism sector, to coastal hazards (Calgaro, 2005). Because of the relative short duration of their stay, tourists rarely acquaint themselves with the potential hazards at their target destinations. Their poor knowledge of local hazard characteristics and institutions and procedures for disaster risk management make tourists particularly vulnerable. Also, early warning information tends to be less accessible to international tourists because frequently the warnings are not communicated in a language they understand and because tourists are difficult to reach as a result of their high mobility. Many of these issues also affect international economic migrants seeking employment in the expanding manufacturing industries in the rapidly developing economies in South and South-east Asia. Market liberalization and economic globalization create opportunities and growth in the region and many countries aim to provide a better investment environment by creating special industrial zones. These zones are frequently located along the coast and separate investors and foreign employees from local communities. People living and working in these zones tend to have more limited access to hazard warnings than people in well-established local communities.

A third kind of migration occurs at national, subnational and local scales where poor people living in rural communities move to other rural communities or urban areas to gain better access to natural resources, employment opportunities and education. For example, in the 1980s, the Kinh residents in some villages in the Dak Lak Province in Vietnam migrated to make a better living by trading in fertilizers and insecticides (Lindskog *et al*., 2005). Many poor people move to coastal areas to obtain access to common-pool coastal and marine resources (Shakur, 1998; Brenner, 2001). This migration to the coast leads to population growth and increasing population density in coastal areas. This in turn increases the demand on coastal resources and leads to overgrazing, slash and burn farming, deforestation and intensive use of flood plains and wetlands. The increasing demand for land also leads to higher land prices, overdevelopment and inappropriate land use policies, with far-reaching consequences in many other areas.

Development

Factors in the categories 'development' and 'infrastructure' are linked closely to socio-economic processes. The countries considered in this study are all developing and transitional countries where economic development is of high priority and socio-economic changes are occurring rapidly. Most documents on a particular country focus on Bangladesh, India and Vietnam. This can be explained by the fact that these countries are located in highly exposed geographic locations that suffer the physical impacts of frequent and severe tidal surges and tropical storms. Furthermore, these countries have a high socio-economic vulnerability because they are highly dependent on agricultural production and are characterized by high levels of national and individual poverty and extremely uneven access to resources. Traditional small-scale and subsistence farming is being replaced increasingly by large-scale commercial agricultural production. Crop diversification and intensification, as well as land use changes through industrial development and urbanization are in many places leading to profound changes in the geography and environment. Infrastructure development, such as the construction of flood embankments, artificial channels and reservoirs, transform the environment and affect ecosystem functioning and ecosystem services.

The role of institutions in creating and perpetuating vulnerability

Institutions determine both explicitly and implicitly the power structure within a given society and hence the distribution of social and natural resources. A disaster can therefore be understood as the product of a cumulative set of decisions taken over long periods of time (Comfort *et al.*, 1999). Our analysis indicates that factors relating to institutions affect almost all other causes of vulnerability to coastal hazards, ranging from the choice of development pathways and practices to demographical dynamics and poverty and marginalization. Institutional structure and characteristics are defined to some extent by social culture. Social culture consists of people's perceptions and social structure, both of which are the results of longer-term historical processes. It involves aspects such as religion, history, values and social norms. These kinds of informal institutions have a profound effect on hazard vulnerability. For example, some researchers (Atmanand, 2003; Takeda and Helms, 2006) noted that bureaucracy, fear of competition, local protectionism and corruption prevented outside aid from reaching those with the greatest need. Some considered institutional learning as an important process to reduce vulnerability (Thompson and Sultana, 1996), but we found no specific recommendations on how such a learning process could be better supported.

Cooperation and power relations

The extent and effectiveness of cooperation between different actors is determined not only by the need to share information but also by the expectations and intentions of the different stakeholders and the power relations between them. There are many discussions about the connotations and structures of power, and their core is an understanding of the application of action, knowledge and resources to resolve problems and to further interests (Few, 2002). Thus, the distribution of power can be considered as the underlying structure of society and this structure influences many aspects of social systems, including cooperation.

Cross-level cooperation is often motivated either by the potential benefits to particular stakeholders or the high costs of not undertaking them. The gains from such interactions are often uneven (Adger *et al.*, 2005). The essence of this kind of cooperation between decision makers and communities is the linkage between resource users on the one hand and regulators and government agencies on the other (Anderies *et al.*, 2004). In traditional top-down management approaches, a regulatory framework is imposed on resource users, with little or no decision making power for them and civil society. Good cooperation between the government authorities and civil society enables everyone, including poor and marginalized people, to play a role in making decisions about the allocation of resources and in overseeing government decision-making processes (Carney, 1999). This involves the decentralization of power and control over resources, a process that requires the willingness of national governments to reduce their own power.

The most important recommendations to reduce vulnerability

Increase hazard awareness and knowledge

Increasing hazard awareness and knowledge was the most frequently made recommendation to reduce hazard vulnerability. Individual recommendations included calls to increase the awareness of potential hazards, establish appropriate response and coping strategies and conduct periodical emergency drills. Such measures tended to be targeted particularly at poor people living in rural coastal communities and people who had migrated recently to coastal areas. The main suggested channels for achieving these aims were school programmes and media campaigns. Some researchers such as Shakur (1998) and Haque (2003) argued the importance of increasing general literacy in reducing hazard vulnerability.

Improve early warning systems and evacuation procedures

Many researchers, including Mushtaque *et al.* (1993) and Kelly and Adger (2000), considered effective early warning systems a key component of disaster preparedness and response. Thus, many recommendations in this area focused on the improvement of risk assessment methodologies and early warning systems. There was a clear emphasis, however, on improving the technological 'hard' elements of such systems, with little consideration of the 'soft' components such as appropriate mechanisms for the communication and dissemination of early warning information to end-users and the linkages with community-based disaster preparedness activities.

Improve communication and cooperation

Our analysis revealed a strong need to improve cooperation and communication between the many different actors operating in areas and sectors relevant to reducing hazard vulnerability. This need refers to both vertical and horizontal cooperation. Vertical cooperation refers to cooperation between authorities and communities and includes the sharing of information, as well as the sharing of control over power and resources through the participation of local communities in the decision-making process. Horizontal cooperation refers to cooperation between different government authorities and between such authorities with other stakeholders, such as non-governmental and civil society organizations and researchers.

Strengthen environmental protection and post-disaster rehabilitation

It is now widely acknowledged that the state of the environment is an important component of human well-being and sustainable development (Millennium Ecosystem Assessment, 2005). As our understanding of the interactions between human activities and natural processes in coupled human–environment systems improves, the calls for strengthening environmental governance and undertaking post-disaster rehabilitation of affected ecosystems become increasingly louder. Recent research indicates that human vulnerability and livelihood security are linked closely to biodiversity and ecosystem resilience (Holling and Meffe, 1996; Adger, 1999; Elmqvist *et al*., 2003; Adger *et al*., 2005). The role of resilient ecosystems in underpinning resilient social systems, and hence decreasing vulnerability to natural hazards, is related to the capacity of ecosystems to buffer the impacts of extreme events. Healthy ecosystems are also able to provide more options for communities to assist with livelihoods recovery following a disaster.

Conclusions

The analysis of the state of scientific understanding of the causes of hazard vulnerabilities and the recommendations put forward by researchers to reduce these vulnerabilities revealed important shortcomings in the relevance of existing scientific research in providing appropriate and relevant information for policy and practice (see also Thomalla *et al*., 2006). Gaps exist in particular in the application of conceptual thinking in vulnerability assessment, in the development of operational methodologies relevant for actors at the subnational level and in the formulation of concrete recommendations that address the systemic underlying causes of vulnerability.

Limited understanding of vulnerability patterns

A wealth of empirical case studies on risk and vulnerability has been undertaken at scales ranging from household to global level. The experience in undertaking such assessments is diverse and the findings are highly context and place specific (Turner *et al*., 2003). Because the characteristics of different locations can vary considerably, some researchers (Weichselgartner and Bertens, 2000; Cannon *et al*., 2003) argue that each disaster situation is unique. Also, the understanding of the causal structures and dynamics of vulnerability remains patchy and anecdotal, despite the advances of vulnerability research during the past two decades (Adger *et al*., 2005; Kasperson, 2006). Unfortunately, very few rigorous comparative studies that aim to synthesize this collective experience have been undertaken. Examples are the work of Misselhorn (2005) in the area of food insecurity in southern Africa and that of Geist and Lambin (2004), Lambin and Geist (2004) and Geist

(2005) in the area of land cover change. Recently, progress has been made in improving integrative analysis of vulnerability and human well-being in the context of environmental risks and change. The UNEP Global Environment Outlook (GEO)-4, Chapter 7 'Vulnerability of Human–Environment Systems: Challenges and Opportunities' (Jäger *et al.*, 2007) describes specific representative patterns of the interactions between environmental change and human well-being. These 'archetypes of vulnerability' aim to illustrate the basic processes whereby vulnerability is produced and to enable policy makers to recognize their particular situations within a broader context, providing regional perspectives and important connections between regions and the global context and insights into possible solutions. The GEO-4 archetype approach is inspired by earlier work on the 'syndromes of global change' that describes non-sustainable patterns of human–environment interaction and analyses the dynamics behind them (Lüdeke *et al.*, 1997, 2004; Schellnhuber *et al.*, 2004), but is broader as it includes opportunities offered by the environment to reduce vulnerability and improve human well-being (Jäger *et al.*, 2007).

With respect to coastal hazards, many studies have been undertaken during the past several decades and a considerable number of them focus on South-east Asia. However, there have been few attempts to investigate comprehensively the underlying factors and pathways through which social vulnerability to coastal hazards is constructed, and this is the first systematic review based on the analysis and comparison of a large number of case studies. One of the key aims of this analysis was to determine whether typical patterns of vulnerability could be identified in the context of coastal hazards in South-east Asia. It was found that, conceptually, linkages between different causes could be established (see Figs 27.2 and 27.3), but that many different interpretations of how these factors interact to produce vulnerability exist, depending on the scale of analysis and the specific environmental, historical and social contexts of the particular case. More research is therefore required to facilitate the systematic assessment of vulnerability across different sectors and geographical scales.

The most important underlying causes of vulnerability are ignored in recommendations

Many of the factors considered most important in creating hazard vulnerability relate to social structure and the underlying processes of societies that determine power relationships and access to resources. Poverty and marginalization are linked closely with vulnerability not just to hazards but to all kinds of environmental and socio-economic shocks and surprises. The extent of poverty, lack of entitlements and resource access and inequality are important indicators and drivers of vulnerability. Although not the only cause of vulnerability, poverty exacerbates it by driving many other causes of vulnerability, such as migration and population growth in high-risk coastal areas. Thus, many of the most important factors contributing to vulnerability to coastal hazards (demography, poverty and marginalization) are inherent characteristics of human society, affecting vulnerability through multiple pathways and processes. Addressing these factors requires challenging the existing structures and power relationships of today's societies.

Rather than using these issues as a starting point for developing strategies to reduce vulnerability, most of the recommendations are concerned with measures that enhance coping and responses to the hazard event itself. Although such recommendations make an important contribution to reducing the potential impacts of hazards, they do not address the underlying systemic causes of vulnerability. For example, improving hazard knowledge might help people living or working in exposed coastal areas to prepare for the impacts of potential hazards, but it does not address the reasons why these people have no choice but to live in such areas in the first place.

Lack of conceptual frameworks in guiding vulnerability case study analysis

There is a tremendous gap between conceptual and theoretical work on vulnerability and empirically based case studies. The selected documents included a large number of local case studies of coastal hazard vulnerability, but none of these employed a conceptual or theoretical framework to guide the analysis. Although references to ten different conceptual frameworks were identified in the literature, all of the documents in which they were mentioned focused either on a general theoretical discussion of hazard vulnerability (mostly at the global scale), or on a discussion of the concepts and theoretical underpinnings of vulnerability research. Since the purpose of undertaking a case study is to obtain a detailed understanding of the factors contributing to the vulnerability of local individuals, households or communities in order to identify potential entry points for policy intervention, the use of a conceptual framework is important to help identify all possible factors contributing to vulnerability and to map the interactions between them. There are very few links in the literature between theoretical thinking and the context-specific richness of experience and knowledge derived from local case studies.

Gaps between assessment, policy and practice

The links between vulnerability assessment and policy development are extremely weak, as most of the assessments are undertaken at national, regional and global levels that have limited relevance to decision makers at subnational scales. Ineffective communication between different stakeholders relating to all phases of the disaster risk reduction cycle was identified as one of the main factors contributing to vulnerability. Although many authors demonstrate the need to improve information sharing between different actors, to increase hazard awareness among the public and to improve the dissemination and communication of early warnings, most recommendations are so general that they are of limited value when formulating appropriate and effective disaster risk reduction strategies and policies. They frequently take the form of statements such as 'need to reduce poverty' or 'need to develop community-based recovery strategies' without providing concrete suggestions on how such measures could be realized in the context of practical operational activities. This indicates that there is an urgent need to improve and apply methods to assess vulnerability and to produce policy-relevant findings that inform disaster risk reduction efforts better. Although the concept of vulnerability is used widely among researchers, policy makers and practitioners, it is rarely defined or applied. The 'notion' of vulnerability needs to be formalized in order to support accurate communication within and between different communities and to eliminate misunderstandings that result from the use of ambiguous terminology (Ionescu *et al.*, 2005; Hinkel and Klein, 2007).

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References

Adger, W.N. (1999) Social vulnerability to climate change and extremes in coastal Vietnam. *World Development* 22(2), 249–269.

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R. and Rockström, J. (2005) Social–ecological resilience to coastal disasters. *Science* 309, 1036–1039.

Anderies, J.M., Janssen, M.A. and Ostrom, E. (2004) A framework to analyze the robustness of social–ecological systems from an institutional perspective. *Ecology and Society* 9(1), 18 (http://www.ecologyandsociety.org/vol9/iss1/art18/print.pdf, accessed 26 May 2009).

Atmanand (2003) Insurance and disaster management: the Indian context. *Disaster Prevention and Management* 12(4), 286–304.

Bankoff, G., Frerks, G. and Hillhorst, D. (eds) (2004) *Mapping Vulnerability: Disasters, Vulnerability and People*. Earthscan, London.

Berz, G., Kron, W., Loster, T., Rauch, E., Schimetschek, J., Schmieder, J., Siebert, A., Smolka, A. and Wirtz, A. (2001) World map of natural hazards – a global view of the distribution and intensity of significant exposures. *Natural Hazards* 23, 443–465.

Bildan, L.S. (2003) *Disaster Management in South-east Asia: An Overview, 2003*. Asian Disaster Preparedness Center, Bangkok, p. 44.

Birkmann, J. (2006) (ed.) *Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies*. United Nations University Press, Tokyo.

Blaikie, P., Cannon, T., Davis, I. and Wisner, B. (1994) *At Risk: Natural Hazards, People's Vulnerability and Disasters*. Routledge, London.

Brenner, N. (2001) The limits to scale? Methodological reflections on scalar structuration. *Progress in Human Geography* 25, 591–614.

Calgaro, E. (2005) Paradise in tatters: an analysis of the vulnerability of the tourism community of Khao Lak, Thailand to the 2004 Indian Ocean Tsunami. Stockholm Environment Institute Working Paper. Stockholm Environment Institute, Stockholm.

Cannon, T., Twigg, J. and Rowell, J. (2003) Social vulnerability, sustainable livelihoods and disasters. Report to DFID Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Support Office. Department for International Development (DFID), London.

Carney, D. (1999) Sustainable livelihoods approaches: progress and possibilities for change. Report to DFID Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Support Office. Department for International Development (DFID), London.

Comfort, L., Wisner, B., Cutter, S., Pulwarty, R., Hewit, K., Oliver-Smith, A., Wiener, J., Fordham, M., Peacock, W. and Krimgold, F. (1999) Reframing disaster policy: the global evolution of vulnerable communities. *Environmental Hazards* 1, 39–44.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B. and Norberg, J. (2003) Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1(9), 488–494.

Few, R. (2002) Researching actor power: analyzing mechanisms of interaction in negotiations over space. *Area* 34, 29–38.

Gaarder, B.M.M. (2002) Can population characteristics account for the variation in health impacts of air pollution? A meta-analysis of PM10-mortality studies (http://www.cserge.ucl.ac.uk/Gaarder%202002.pdf, accessed 26 May 2009).

Geist, H. (2005) *The Causes and Progression of Desertification* (Ashgate Studies in Environmental Policy and Practice). Ashgate, Aldershot, UK.

Geist, H.J. and Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52(2), 143–150 (http://www.freenetwork.org/resources/documents/2-5Deforestationtropical.pdf, accessed 26 May 2009).

Geist, H.J. and Lambin, E.F. (2004) Dynamic causal patterns of desertification. *BioScience* 54(9), 817–829.

Glasmeier, A. and Farrigan, T. (2005) Understanding community forestry: a qualitative meta-study of the concept, the process, and its potential for poverty alleviation in the United States case. *The Geographical Journal* 171(1), 56–69.

Greenaway, A. and Witten, K. (2004) A meta-analysis of community action projects. Report to a project funded by the Cross Departmental Contestable Fund through the Ministry of Health, New Zealand, Centre for Social and Health Outcomes Research and Evaluation.

Gupta, M. and Sharma, A. (2006) Compounded loss: the post-tsunami recovery experience of Indian island communities. *Disaster Prevention and Management* 15(1), 67–78.

Haque, C.E. (2003) Perspectives of natural disasters in East and South Asia, and the Pacific Island States: socio-economic correlates and needs assessment. *Natural Hazards* 29, 465–483.

Helbing, D. and Kuhnert, C. (2003) Assessing interaction networks with applications to catastrophe dynamics and disaster management. *Physica* A 328, 584–606.

Hinkel, J. and Klein, R.J.T. (2007) Integrating knowledge for assessing coastal vulnerability to climate change. In: McFadden, L., Nicholls, R.J. and Penning-Rowsell, E.C. (eds) *Managing Coastal Vulnerability*. Elsevier Science, Amsterdam, pp. 61–78.

Hodgkinson, P.E. and Stewart, M. (1991) *Coping with Catastrophe: A Handbook of Disaster Management*. Routledge, London.

Holling, C.S. and Meffe, G.K. (1996) Command and control and the pathology of natural resource management. *Conservation Biology* 10(2), 328–377.

Ionescu, C., Klein, R.J.T., Hinkel, J., Kavi Kumar, K.S. and Klein, R. (2005) Towards a formal framework of vulnerability to climate change. NeWater Working Paper 2, Potsdam Institute for Climate Impact Research, Potsdam, Germany.

Jäger, J., Kok, M.T.J., Mohamed-Katerere, J.C., Karlsson, S.I., Lüdeke, M.K.B., Dabelk, G.D.O., Thomalla, F., de Soysa, I., Chenje, M., Filcak, R., Koshy, L., Long Martello, M., Mathur, V., Moreno, A.R., Narain, V., Sietz, D., Naser Al-Ajmi, D., Callister, K., De Oliveira, T., Fernandez, N., Gasper, D., Giada, S., Gorobets, A., Hilderink, H., Krishnan, R., Lopez, A., Nakyeyune, A., Ponc, A.E., Strasser, S. and Wonink, S. (2007) *Vulnerability of Human–Environment Systems: Challenges and Opportunities*. Global Environment Outlook GEO-4, United Nations Environment Programme, Nairobi.

Kasperson, J.X. and Kasperson, R.E. (2001) International Workshop on Vulnerability and Global Environmental Change: a workshop summary, 17–19 May 2001. Stockholm Environment Institute, Sweden.

Kasperson, J.X. and Kasperson, R.E. (eds) (2005) *The Social Contours of Risk*. Earthscan, London.

Kasperson, R.E. (2006) Rerouting the stakeholder express. *Global Environmental Change* 16(4), 320–322.

Kelly, P.M. and Adger, W.N. (2000) Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Climatic Change* 47, 325–352.

Lambin, E.F. and Geist, H. (2004) Causes and pathways of tropical deforestation. In: de Dapper, M. (ed.) *Tropical Forests: A State of the Art at the Turn of the Century*. Royal Academy of Overseas Sciences, Brussels, pp. 59–65.

Lindskog, E., Dow, K., Axberg, G.N., Miller, F. and Hancock, A. (2005) When rapid changes in environmental, social and economic conditions converge: challenges to sustainable livelihoods in Dak Lak, Vietnam. Stockholm Environment Institute Report. Stockholm Environment Institute, Stockholm.

Lüdeke, M.K.B., Moldenhauer, O. and Petschel-Held, G. (1997) Rural poverty driven soil degradation under climate change: the sensitivity of the disposition towards the Sahel Syndrome with respect to climate. *Environmental Modeling and Assessment* 4(4), 315–326.

Lüdeke, M.K.B., Petschel-Held, G. and Schellnhuber, J. (2004) Syndromes of global change: the first panoramic view. *GAIA – Ecological Perspectives for Science and Society* 13(1), 42–49.

Matarazzo, B. and Nijkamp, P. (1997) Meta-analysis for comparative environmental case studies: methodological issues. *International Journal of Social Economics* 24(7/8/9), 799–811.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Misselhorn, A.A. (2005) What drives food insecurity in southern Africa? A meta-analysis of household economy studies. *Global Environmental Change* 15, 33–43.

Mushtaque, A., Chowdhury, R., Bhuyia, A.U., Choudhury, A.Y. and Sen, R. (1993) The Bangladesh cyclone of 1991: why so many people died. *Disaster* 17(4), 291–303.

Nijkamp, P. and Pepping, G. (1997–1998) Levies for sustainable agriculture? A meta-analytic exploration of different pesticide elasticities in agriculture. *Journal of Environmental Systems* 26(1), 1–25.

Pelling, M. (2003) *The Vulnerability of Cities: Natural Disasters and Social Resilience*. Earthscan, London.

Sandelowski, M., Docherty, S. and Emden, C. (1997) Focus on qualitative methods–qualitative meta-synthesis: issues and techniques. *Research in Nursing and Health* 20, 365–371.

Schellnhuber, H.J., Crutzen, P.J., Clark, W.C. and Claussen, M. (eds) (2004) *Earth System Analysis for Sustainability*. MIT Press, Cambridge, Massachusetts.

Shakur, T. (1998) Implications for policy formulation towards sheltering the homeless: a case study of squatters in Dhaka, Bangladesh. *Habitat International* 12(2), 53–66.

Takeda, M.B. and Helms, M.M. (2006) Bureaucracy, meet catastrophe: analysis of the tsunami disaster relief efforts and their implications for global emergency governance. *International Journal of Public Sector Management* 19(2), 204–217.

Thomalla, F., Downing, T.E., Spanger-Siegfried, E., Han, G. and Rockström, J. (2006) Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. *Disasters* 30(1), 39–48.

Thompson, P.M. and Sultana, P. (1996) Distributional and social impacts of flood control in Bangladesh. *The Geographical Journal* 162(1), 1–13.

Tompkins, E.L. and Hurlston, L.A. (2005) Natural hazards and climate change: what knowledge is transferable? Tyndall Centre Working Paper, Tyndall Centre for Climate Change Research, Norwich, UK.

Travisi, C.M., Florax, R.J.G.M. and Nijkamp, P. (2004) A meta-analysis of the willingness to pay for reductions in pesticide risk exposure. SEIV-Sustainability Indicators and Environmental Valuation (http://www.feem.it/NR/rdonlyres/F04024C9-2B72-45CC-ACA8-DEDE97CBCEAC/1228/10104.pdf).

Turner, B.L., Kasperson, R.E., Matsone, P.A., McCarthy, J.J., Corellg, R.W., Christensene, L., Eckleyg, N., Kasperson, J.X., Luerse, A., Martellog, M.L., Polsky, C., Pulsipher, A. and Schillerb, A. (2003) A framework for vulnerability analysis in sustainability science. *PNAS* 100(14), 8074–8079.

UNDP (2004) Reducing disaster risk: a challenge for development. A global report – UNDP. Bureau for Crisis Prevention and Recovery (BRCP), United Nations Development Programme, New York.

Weichselgartner, J. and Bertens, J. (2000) *Natural Disasters: Acts of God, Nature or Society? On the Social Relation to Natural Hazards*. MIT Press, Southampton, Massachusetts.

White, G.F., Kates, R.W. and Burton, I. (2001) Knowing better and losing even more: the use of knowledge in hazards management. *Environmental Hazards* 3, 81–92.

Yodmani, S. (2004) *Disaster Risk Management and Vulnerability Reduction: Protecting the Poor*. Asia and Pacific Forum on Poverty, Bangkok.

Yu, C.S. (2002) A GP-AHP method for solving rout decision making fuzzy AHP problems. *Computers and Operations Research* 29(14), 1969–2001.

Zou, L. and Thomalla, F. (2008) A synthesis of insights on the causes of social vulnerability to coastal hazards in South-east Asia. SEI Poverty and Vulnerability Report, Stockholm Environment Institute, Stockholm.

28 An Extended Hydrological Classification for Mangrove Rehabilitation Projects: a Case Study in Vietnam

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Abstract

Mangrove rehabilitation projects often fail to achieve their goals because hydrological aspects are not taken into account. This is understandable since the only hydrological tool available for such projects is the classification by Watson (1928), developed for mangrove forests in regions with a semi-diurnal tidal regime and a gradually rising elevation. Therefore, the possibilities for application seem rather limited. This study evaluates the Watson classification for mangrove forests in Vietnam, with planted and natural mangrove forests and rather irregular hydrological characteristics. During two fieldwork periods in spring 2004 and 2007, tidal regime, elevation profile, water levels in open water and in the mangrove forest, inundation characteristics and vegetation were measured. In Can Gio mangrove forest, the tidal regime is irregular semi-diurnal, which results in a highly variable level and frequency of high and low tides. This irregular tidal regime influences the inundation frequency strongly. Elevation measurements in the mangrove forests revealed a rather regular, gradually rising elevation profile in the forest close to the main creeks, and ridge-like structures and slightly lower basins behind such ridges deeper in the forest. The inundation characteristics in the zone with gradual rising profile were in line with expectations based on elevation. But in the zone with the irregular (micro) topography, direct surface discharge from the basins was impeded and therefore such basins were inundated considerably longer than estimated from their elevation. As a result, the inundation classes according to the Watson classification did not correspond very well with observed hydrological conditions. Therefore, an extended classification was developed that corresponded better to the actual hydrological conditions because it included the effects of an irregular tidal regime and an irregular elevation profile. This extended classification was tested on other locations in Can Gio. It can be concluded that the extended hydrological classification is a promising tool for predicting the natural development of the mangrove vegetation and determining the need for active management in the forest. Future mangrove rehabilitation projects might be more successful in restoring natural mangrove forests with a high biodiversity using this extended hydrological classification.

Introduction

Mangroves are highly productive but also extremely vulnerable ecosystems (Tabuchi, 2003). Over recent decades, changes in hydrological conditions, conversion to shrimp ponds, salt ponds or agricultural land, overharvesting of wood, and oil spills have reduced the world's mangrove forests to less than 50% of the original total cover (Kairo *et al.*, 2001). Also, natural disasters can have a devastating effect on mangroves, as can be seen, for instance, from the effects of the 26 December 2004 tsunami in Asia. Over the past decades, rehabilitation projects have been executed in deforested or degraded regions. However, attempts to restore mangroves often fail to achieve the stated goals or fail completely (Sanyal, 1998; de Leon and White, 1999; Lewis, 2005). Furthermore, monospecific mangrove plantations are sometimes presented as examples of successful mangrove rehabilitation but according to Lewis (2001), they do not fit the definition of ecological restoration.

Lewis (2005) argues that failures in attempts to restore mangroves can be attributed to the fact that hydrological aspects are ignored. Specific hydrological site characteristics frequently are not examined within the scope of mangrove restoration projects and according to Hughes *et al*. (1998), 'hydrology is the single most important determinant of the establishment and maintenance of specific types of wetland'. The impact of water on mangrove ecology includes the effect of the variable water levels in tidal regions, the intensity of wave action, the variation in salinity, the groundwater and the indirect effects of water on soil composition and the availability of light and oxygen (van Speybroeck, 1992; Hogarth, 1999; Ellison *et al*., 2000; Peterson and Baldwin, 2004).

The only common hydrological tool in mangrove rehabilitation projects is the general classification for mangrove forests by Watson (1928), where the tidal range is considered in five inundation classes, as shown in Table 28.1. Assignment to one of these classes is based on three classification criteria, namely 'tidal regime', 'elevation' and 'flooding frequency'. Watson indicated that the limits of the classes were chosen arbitrarily, so the classification could only be used for a rough comparison between different locations. Furthermore, he developed his classification for mangroves in areas with regular semi-diurnal tides and a gradually rising elevation, although only part of the mangrove forests worldwide met these conditions. Tides may show a large diurnal component and mangrove areas may have a significant microtopography, determining the physical processes in the system (Kjerfve, 1990; Lewis, 2005). Since no other (general) hydrological classification for mangroves has been developed, the Watson classification is still used in mangrove restoration projects and other mangrove management issues all over the world (Tomlinson, 1986; Hong and San, 1993; Hogarth, 1999; Lewis, 2005). The question arises whether this classification is generally applicable or whether additional hydrological information is needed.

This chapter examines the possibilities of applying the Watson classification for mangrove rehabilitation through the analysis of the hydrology in a specific mangrove area, and presents an extended classification, which is suitable not only for mangrove systems with regular semi-diurnal tides and a gradually rising elevation but also for mangrove systems with an irregular tidal regime and elevation profile. The Can Gio area in Vietnam is chosen as the

Table 28.1. Inundation classification of Watson and the South-east Asian mangrove species attributed to each class.

Inundation class	Tidal regime (flooded by)	Elevation (above admiralty datum)	Flooding frequency (times per month)	Vegetation (species)
1	All high tides	Below 244 cm	56–62	None
2	Medium high tides	244–335 cm	45–59	*Avicennia* spp., *Sonneratia*
3	Normal high tides	335–396 cm	20–45	*Rhizophora* spp., *Ceriops*, *Bruguiera*
4	Spring high tides	396–457 cm	2–20	*Lumnizera*, *Bruguiera*, *Acrosticum aureum*
5	Equinoctial tides	457 cm and above	< 2	*Ceriops* spp., *Phoenix paludosa*

Watson (1928); Tomlinson (1986); Hogarth (1999); Bosire *et al.* (2003).

major research site because this mangrove forest is extensive (over 40,000 ha; Vietnam MAB National Committee, 1998), the species composition is representative of mangrove forests in South-east Asia and the area has a history of mangrove destruction and reforestation.

Site Description

Vietnam has extensive mangrove forests in the southern part of the country (Hong and San, 1993). Can Gio District is located in the province of Ho Chi Minh City. It measures 35 km from north to south and 30 km from east to west (Tuan *et al.*, 2002). Part of Can Gio is shown in Fig. 28.1. Can Gio is the delta of the Saigon-Dong Nai river (Tri *et al.*, 2000), which discharges into the South China Sea. The creek system in Can Gio experiences an irregular semi-diurnal tidal regime (Hong and San, 1993). Figure 28.2 shows the tidal prediction for Vung Tau, located about 10 km east of Can Gio. The predominant semi-diurnal regime is variable over time and some days even shows a complete diurnal tidal regime. The maximum amplitude of the tides in Can Gio ranges from 3.3 to 4.1 m (Vietnam MAB National Committee, 1998).

In the first half of the 20th century, Can Gio was covered almost completely with natural mangrove forest with a high biodiversity. Dominating species were inter alia *Sonneratia alba*, *Avicennia* spp., *Rhizophora* spp., *Xylocarpus granatum*, *Ceriops tagal*, *Kandelia candel* and in higher areas *Phoenix paludosa* and *Excocaria agallocha*. Natural primary succession was determined principally by elevation. During the Second Indochina War (1963–1974), mangrove forests in southern Vietnam were defoliated with herbicides such as Agent Orange, causing the destruction of almost the complete mangrove cover. After 1978, rehabilitation projects were initiated in Can Gio and other mangrove regions by the Vietnamese government (Tuan *et al.*, 2002). Reforestation was undertaken in monoculture with *R. apiculata*, already the dominant species in the natural mangrove forests in Vietnam. After 25 years, little natural regeneration of other species had occurred; hence, the plantations did not develop into natural mangrove forests, probably to a large extent as a result of a lack of consideration of hydrological aspects. In 2000, parts of Can Gio were declared a Biosphere Reserve by UNESCO (Tuan *et al.*, 2002), which gave the area an international commitment to protect and increase biodiversity. In order to achieve this, a reliable classification for mangroves in relation to hydrology would be a helpful management tool.

Methods

For a number of selected locations in Can Gio, data on topography, water levels in open water and in the mangrove forest, flow characteristics (overland and creek flow) and vegetation development were gathered. This information was used to perform a detailed hydrological analysis of these locations, in order to compare the results with Watson's classification and assess the implications for vegetation development. These measurements were performed in 2004 and 2007.

Surveys were conducted in several transects with different edaphic and hydrological characteristics (Fig. 28.1). Transect A was located closest to the sea and had a length of 700 m measured from the Dong Tranh riverbank, and transect B was located somewhat further inland along the same river and had a length of 150 m. In this chapter, predominantly the survey in transect A is presented.

The piezometric head was measured over time by automatic pressure measuring devices. In transect A, the piezometric head was measured in the open water (site A0) and at increasing distances from the coastline into the mangrove forest (sites A1–A6). The measurement sites were related to vegetation zones and located at 10, 140, 200, 330, 460 and 680 m from the Dong Tranh riverbank (van Loon, 2005; van Huijgevoort and te Brake, 2007; van Loon *et al.*, 2007).

The elevation of the soil surface at the measurement sites was determined by comparing the water level data at high tide and by using laser levelling equipment. The average predicted water level in Vung Tau over the period from 22 March to 31 July 2004 was

Fig. 28.1. Map of the southern part of Can Gio with the location of transects A and B. Forestry Service, Can Gio.

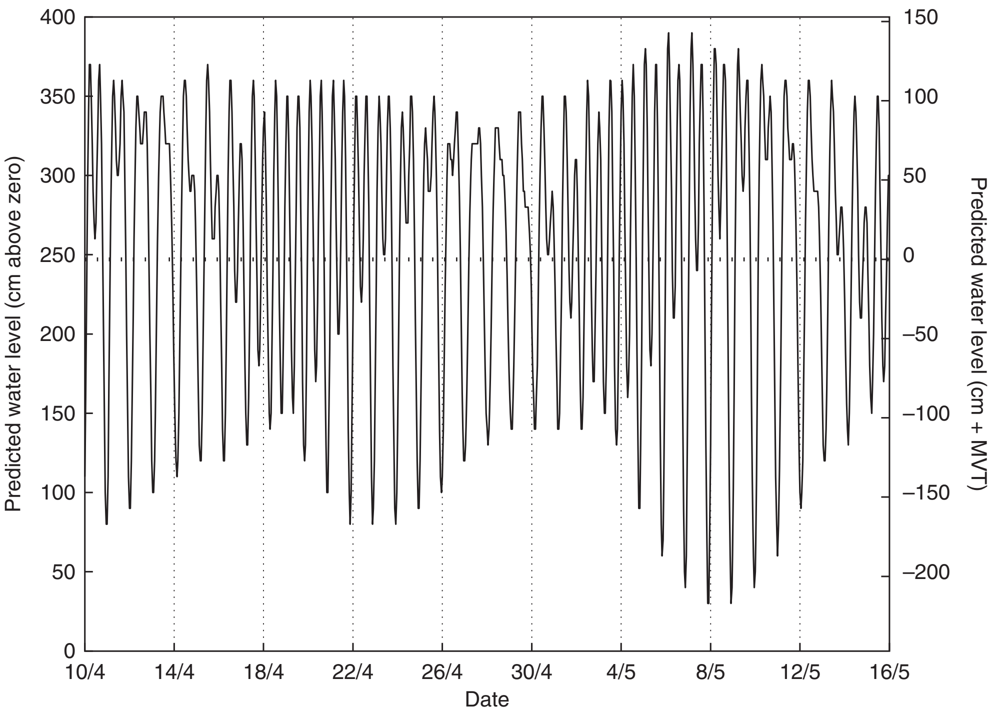

Fig. 28.2. Tidal prediction for the port of Vung Tau for the period 10 April to 16 May 2004. Left axis = the reference level of Vung Tau; right axis = the reference level MVT. Marine Hydrometeorological Centre, Hanoi, Vietnam.

chosen as the reference level: mean Vung Tau (MVT). MVT is comparable to standard mean sea level, but no information could be obtained on the actual level.

A vegetation analysis was performed along the transects using plots of 10 × 10 m with an interval of 50 m. Species composition, quality of the vegetation and status of natural regeneration were observed

Results and Discussion

Elevation and vegetation

Transect A was located in an actively sedimenting, expanding mudflat. Elevation measurements in the mangrove forest revealed a rather regular, gradually rising elevation profile in the forest close to the Dong Tranh riverbank and ridge-like structures and slightly lower basins behind such ridges deeper in the forest (Fig. 28.3). The ridge-like structures are expected to be natural levees related to the creek systems, as they are located parallel to the Dong Tranh river and to smaller creeks. The mudflat along the river was devoid of mangrove vegetation, except for some mangrove propagules (mostly dead *A. alba*). At the start of the vegetation, primary succession had resulted in a monospecific *Avicennia* zone with no undergrowth. The elevation profile in this zone was regular, rising gradually. At a distance of 150–200 m from the Dong Tranh riverbank, an abrupt change into a transition zone with many mangrove species and much undergrowth was observed. The vegetation was concentrated in patches and consisted of a natural regeneration with species like *Rhizophora* spp., *C. decandra*, *K. candel* and some full-grown solitary *A. alba* and *R. apiculata* trees. The change to the planted *Rhizophora* zone at about 300–

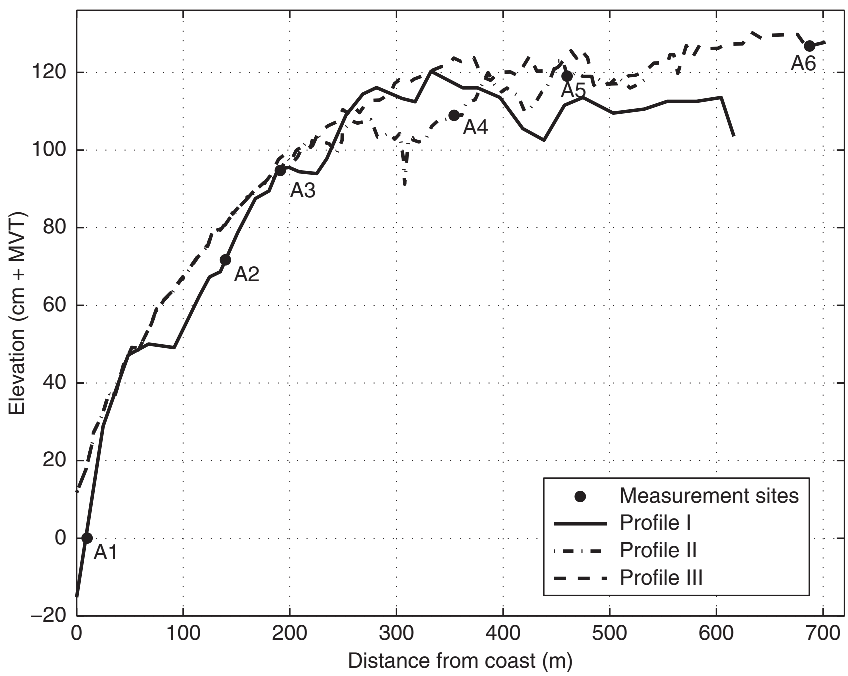

Fig. 28.3. Elevation profiles within transect A, including the location of the measurement sites.

400 m inland was more gradual, because other mangrove species appeared to have occupied patches in the plantation. At approximately 300 m from the Dong Tranh riverbank, the surface level gradient changed. From that point, the microtopography resulting from natural levees and basins was the dominant feature.

The other transects in the Can Gio area showed a similar topographical pattern. Ridges parallel to the coastline and basins further inland are also observed in other mangrove forests (e.g. Cahoon and Lynch, 1997). This leads to the conclusion that such an irregular topography appears frequently in mangrove systems.

Tidal influence

Rising tides propagate from the South China Sea (Fig. 28.1) northward into the Dong Tranh river. The observed tidal regime in the open water near transect A (A0) was comparable to that of Vung Tau (Fig. 28.2). Further propagation into the shallow creeks resulted in a deformation of the tide top and a time lag that increased in landward direction.

At rising tide, water enters the mangrove forest over the surface and through various small creeks. Details of some piezometric head measurements are displayed in Fig. 28.4a and b. A relatively constant piezometric head represents a situation with the water level below the soil surface. At sites A1, A2 and A3, the measured piezometric head followed the tide as soon as the tide level reached the surface level at that point. At A4, A5 and A6, the water level started rising later than expected according to the elevation of the sites. The ridges impeded direct overland flow from the open water to the observation sites, so the level of the open water had to rise above the highest point in the elevation profile, or the water had to enter the area through a subcreek. Such flow paths require more time than direct overland flow from the side of the river (Mazda *et al.*, 1997) and result in a lag in the reaction of the piezometric head to the tidal rise. This effect was also observed in other transects, with the observation sites

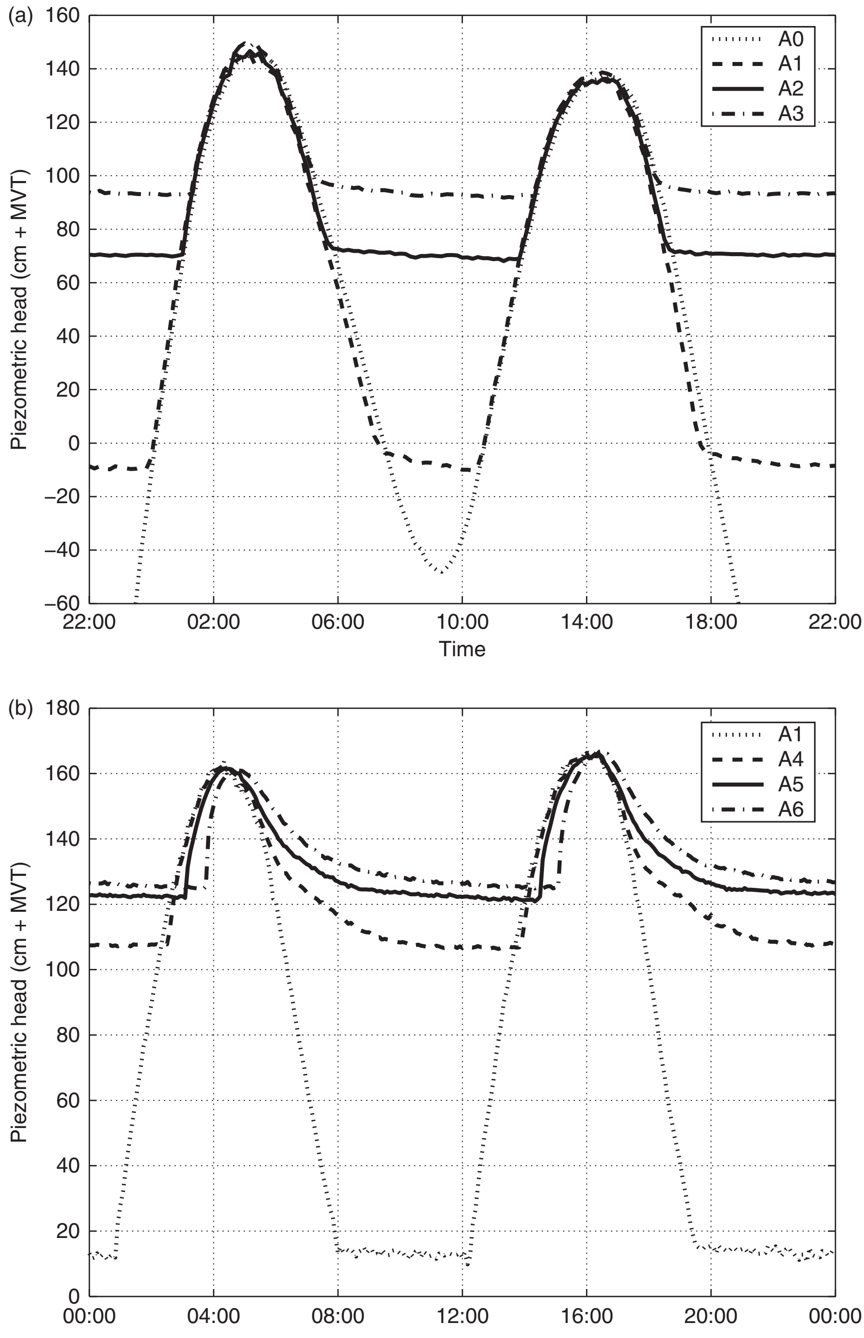

Fig. 28.4. (a) Detail of the piezometric head at measurement sites A0, A1, A2 and A3 on the morning of 6 May 2004; (b) detail of the piezometric head at measurement sites A1, A4, A5 and A6 on 22 March 2007.

behind the ridge in transect B showing a time lag of 60 min.

Ridge and basin structures not only have an effect during rising tide, but also when the tide falls. Piezometric heads measured in the area with the rather regular, gradually rising elevation profile (i.e. site A1, A2 and A3) followed, as expected, the open water tidal movement until the water level reached surface level. At that moment, an abrupt change to a relatively constant piezometric head was observed. In the area further from the Dongh Tranh riverbank where ridges and basins dominate the elevation profile, the piezometric head decreased only very gradually after high tide (Fig. 28.4). The ridges form a barrier to overland flow, so the water has to be discharged from the basin via subcreeks and through the soil, which is considerably slower than overland flow because of higher hydraulic resistance, small hydraulic gradients and longer flow routes. This basin effect has important implications for the duration of inundation and the wetness of the soil. These factors are, however, not taken into account by the Watson classification.

The inundation frequency was expected to decrease gradually inland. However, sites A1 and A2 showed a similar inundation frequency and the difference in elevation was 70 cm (Table 28.2). The reason for this similarity is the irregularity of the tidal regime. To explain this phenomenon, a detail of the predicted water level at Vung Tau is shown in Fig. 28.5. The tidal regime is changing gradually from diurnal to semi-diurnal and the varying amplitude of the tides causes a large variation in the water level of the high and low tide. The combination of this irregular level and the elevation of a site determine whether the site is reached by one or two high waters during one tidal cycle and, if inundated, the duration of the inundation. In Fig. 28.5, a site with elevation ‘1’ mostly experiences one long inundation per day, even when the tidal regime is semi-diurnal, so its inundation frequency is low. A site with elevation ‘3’ is reached by the highest high waters only, and therefore also has a low inundation frequency. A site with elevation ‘2’, however, is reached by many high waters, especially in the period of the change from diurnal to semi-diurnal tides, and vice versa. The classification criterion ‘flooding frequency’ in the Watson classification therefore yields inconsistent results in this respect.

From the inundation characteristics (Table 28.2), it is concluded that both the elevation profile and the inundation frequency are often not regular in mangrove forests. As both factors are important criteria in Watson’s classification, the hydrological conditions of a mangrove forest may not be represented correctly.

Watson hydrological classification

The Watson hydrological classification was tested for the measurement sites in transect A (Table 28.3). The parameter ‘tidal regime’ was determined by a qualitative evaluation of the water level data, the ‘elevation’ of the measurement sites was converted to height above admiralty datum and the ‘flooding frequency’ was adopted from inundation characteristics, as

Table 28.2. Assessment of the inundation characteristics of the various measurement sites, based on the piezometric head measurements in the mangrove forest.

Site	Elevation (cm + MVT)	Duration of inundation (min/ inundation)	Duration of inundation (min/day)	Percentage	Flooding frequency (times per month)	Maximum water level (cm above surface)
A0	–145.4	2547	1352	94	16	329.2
A1	0	549	773	54	42	146
A2	72	195	294	20	45	75
A3	95	141	156	11	33	55
A4	109.5	218	251	17	35	60.8
A5	121.5	222	118	8	16	48.4
A6	126.8	240	100	7	13	42.8

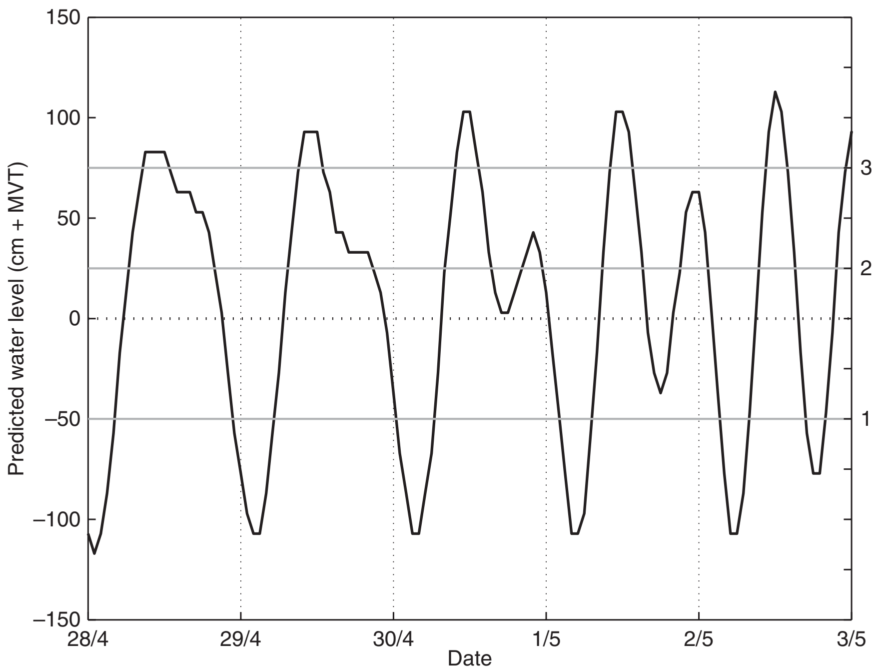

Fig. 28.5. Tidal prediction for the port of Vung Tau for the period 28 April to 3 May 2004 with three imaginary surface levels: 1 = –50 cm + MVT; 2 = 25 cm + MVT; 3 = 75 cm + MVT. Marine Hydrometeorological Centre, Hanoi, Vietnam.

Table 28.3. Inundation classes attributed to the measurement sites using the Watson classification of Table 28.1, including vegetation (*Av* = *Avicennia* spp.; *Rh* = *Rhizophora* spp.).

Site	Tidal regime	Class	Elevation (cm + MVT)	Class	Flooding frequency (times per month)	Class	Total class	Vegetation (species)
A0	All high tides	1	101.7	1	16	4	2	Open water
A1	All high tides	1	247	2	42	3	2	Mudflat – *Av*
A2	Medium high tides	2	319	2	45	2	2	*Av* – transition
A3	Normal high tides	3	342	3	33	3	3	Transition
A4	Normal high tides	3	356.5	3	35	3	3	Transition – *Rh*
A5	Spring high tides	4	368.5	3	16	4	4	Transition
A6	Spring high tides	4	373.8	3	13	4	4	*Rh* – zone

shown in Table 28.2. The inundation class of measurement site A0 is predicted better (class 1) when the criterion 'flooding frequency' is neglected (class 4). At measurement sites A1, A2 and A3, the Watson classification gives satisfactory results. In the area with the pronounced irregular microtopography, i.e. locations A4, A5 and A6, the Watson classification seems to give classes that are too high (too dry). The classification of Watson therefore seems to work unsatisfactorily in a situation with an irregular elevation profile.

Extended hydrological classification

Because the Watson classification could not be applied to sites with an irregular tidal regime and an irregular elevation profile, an adapted classification was developed (Table 28.4). The Watson classification was taken as a starting point because it had proven to be a valuable tool in mangrove management under rather homogeneous conditions. Our aim was to improve the Watson classification in such a way that it would be applicable in many more situations, and thus support the management of mangrove forests better.

In the original Watson classification, the parameter 'tidal regime' can be useful for a rough classification of locations only when no other, more detailed information on the conditions of the region can be obtained. This parameter is left unchanged in the extended classification. The parameter 'elevation' is converted to cm + mean sea level (MSL), because elevation is usually expressed with regard to this reference level. The parameter 'flooding frequency' is left unchanged and can be taken from an analysis of the water level either in open water or in the mangrove area. Furthermore, it was found that class limits for the parameters 'elevation' and 'flooding frequency' were not as strict as the Watson classification suggested. It is expected that a more general classification enables an easier and more realistic step from the field data to inundation classes, and consequently gives a more realistic prediction of mangrove regeneration.

In the areas with a regular tidal regime and a regular elevation profile, the parameters 'flooding frequency' and 'elevation' seem to be useful. However, in areas with an irregular tidal regime and/or an irregular elevation profile, 'duration of inundation' is expected to be the most important parameter. For mangrove forests with an irregular tidal regime, the parameter 'flooding frequency' cannot be used properly and when the elevation profile is irregular, the parameter 'elevation' should be used with great care. Because of obstructions to overland flow, e.g. by ridges or the dyke of a shrimp farm, locations behind such an obstruction can be wetter than locations with the same elevation not hindered by an obstruction. Therefore, a classification parameter 'duration of inundation (min/day and min/inundation)' is added to the classification.

The inundation classes for the measurement sites in Can Gio were determined again with the extended classification (Table 28.5). Sites A0–A3 had an irregular tidal regime, but did have a regular elevation profile (Fig. 28.3). Therefore, these locations were classified according to the parameter 'elevation'. The sites A4, A5 and A6 with a pronounced irregular microtopography can be classified best by using the 'duration of inundation'.

When the results of the extended classification (Table 28.5) are compared with the

Table 28.4. Inundation classification.

Inundation class	Tidal regime	Elevation (cm + MSL)	Flooding frequency (times per month)	Duration of inundation (min/day)	Duration of inundation (min/ inundation)	Vegetation (species)
1	All high tides	< 0	56–62	> 800	> 400	None
2	Medium high tides	0–90	45–56	400–800	200–400	*Avicennia* spp., *Sonneratia*
3	Normal high tides	90–150	20–45	100–400	100–200	*Rhizophora* spp., *Ceriops*, *Bruguiera*
4	Spring high tides	150–210	2–20	10–100	50–100	*Lumnitzera*, *Bruguiera*, *Acrosticum aureum*
5	Equinoctial tides	> 210	< 2	< 10	< 50	*Ceriops* spp., *Phoenix paludosa*

Table 28.5. Inundation classes attributed to the measurement sites using the new classification of Table 28.4.

Site	Tidal regime	Class	Elevation (cm + MVT)	Class	Flooding frequency (times per month)	Class	Duration of inundation (min/day)	Class	Duration of inundation (min/ inundation)	Class	Total class	Vegetation (species)
A0	All high tides	–	–145.4	1	16	–	1352	–	2547	–	1	Open water
A1	All high tides	–	0	2	42	–	773	–	549	–	2	Mudflat – *Av*
A2	Medium high tides	–	72	2	45	–	294	–	195	–	2	*Av* – transition
A3	Normal high tides	–	95	3	33	–	156	–	141	–	3	Transition
A4	Normal high tides	–	109.5	–	35	–	251	3	218	2	2.5	Transition – *Rh*
A5	Spring high tides	–	121.5	–	16	–	118	3	222	2	2.5	Transition
A6	Spring high tides	–	126.8	–	13	–	100	4	240	2	3	*Rh* – zone

(*Av* = *Avicennia* spp.; *Rh* = *Rhizophora* spp.).

results of the Watson classification (Table 28.3), the locations in the transition zone turn out to be wetter (lower inundation class).

Vegetation developments

Future vegetation developments in a mangrove forest can be predicted based on a more detailed analysis of the hydrological conditions. Such predictions and recommendations for management were formulated for the mangrove vegetation in Can Gio in the context of its status as a Biosphere Reserve. The extended hydrological classification of the sites was a valuable tool for that work.

In transect A, the *Avicennia* zone is only suitable for the species *A. alba* and *S. alba* (inundation class 2; Table 28.4). Because of sedimentation and coastal growth, newly exposed mudflat will change from class 1 to class 2 and will become available for colonization by *A. alba*. Hence, the *Avicennia* zone will extend in the coastal direction. Natural regeneration of *Avicennia* within this zone will only take place at the coastline and in gaps because of the high light requirements of this species (Youssef and Saenger, 1999). The transition zone (inundation class 3; Table 28.4) with its higher diversity will also move in the coastal direction because of sedimentation. The naturally regenerated *Rhizophora* spp. and *C. decandra* will, in the future, dominate this zone, but a diverse undergrowth of other species will continue to exist. In the *Avicennia* and transition zone, no active management will be necessary. In the monoculture *Rhizophora* zone, no significant changes can be expected, even though the hydrological conditions, according to the extended classification, are suitable for greater biodiversity. Light seems to be the limiting factor, since gaps caused by lightning or falling dead trees are partly occupied by other species. This process can be accelerated in the context of the restoration of the natural mangrove forest by active forest management. Gaps can be created in the *Rhizophora* plantation to allow natural regeneration of other species.

Conclusions

In Can Gio, the presence of a pronounced irregular microtopography alters the tidal flow in the mangrove forest considerably. The basin-like structures behind natural levees are inundated for longer periods than estimated from its elevation. Furthermore, the irregular tidal regime influenced the duration and frequency of inundation.

The case of Can Gio demonstrates that in some situations, the classification of Watson (1928) is not sufficient and a more detailed hydrological site characterization is essential. An extended classification has been developed, which is based on Watson's classification. In this extended classification, the duration of inundation is also taken into account. This classification gives promising results for the sites in the mangrove swamp in Can Gio. Additional measurements for validation of these findings have been performed in Can Gio and Ca Mau and will be presented soon. The findings should also be tested in many other mangrove regions around the world.

With such an extended hydrological assessment, it is possible to improve predictions in developments in the mangrove vegetation and to determine if and what active forest management is needed, and future mangrove rehabilitation projects are therefore expected to be more successful in restoring a natural mangrove forest. For the mangrove forest in Can Gio, based on the hydrological classification, active management is recommended only in regions where natural regeneration is hampered. Gaps can be created to allow other species to invade the monoculture *R. apiculata* plantation, which has hydrological conditions suitable for other species.

Acknowledgements

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References

Bosire, J.O., Dahdouh-Guebas, F., Kairo, J.G. and Koedam, N. (2003) Colonization of non-planted mangrove species into restored mangrove stands in Gazi Bay, Kenya. *Aquatic Botany* 76, 267–279.

Cahoon, D.R. and Lynch, J.C. (1997) Vertical accretion and shallow subsidence in a mangrove forest of south-western Florida, USA. *Mangroves and Salt Marshes* 1, 173–186.

de Leon, T.O.D. and White, A.T. (1999) Mangrove rehabilitation in the Philippines. In: Streever, W. (ed.) *An International Perspective on Wetland Rehabilitation*. Kluwer Academic Publishers, the Netherlands.

Ellison, A.M., Mukherjee, B.B. and Karim, A. (2000) Testing patterns of zonation in mangroves: scale dependence and environmental correlates in the Sundarbans of Bangladesh. *The Journal of Ecology* 88(5), 813–824.

Hogarth, P.J. (1999) *The Biology of Mangroves*. Oxford University Press, Oxford, UK.

Hong, P.N. and San, H.T. (1993) *Mangroves of Vietnam*. IUCN – The World Conservation Union, Bangkok.

Hughes, C.E., Binning, P. and Willgoose, G.R. (1998) Characterisation of the hydrology of an estuarine wetland. *Journal of Hydrology* 211, 34–49.

Kairo, J.G., Dahdough-Guebas, F., Bosire, J. and Koedam, N. (2001) Restoration and management of mangrove systems – a lesson from East African Region. *South African Journal of Botany* 67, 383–389.

Kjerfve, B. (1990) *Manual for Investigation of Hydrological Processes in Mangrove Ecosystems*. UNESCO/UNDP (United Nations Development Programme) Regional Project, Research and its application to the management of the mangroves of Asia and the Pacific (RAS/86/120). UNESCO, Paris.

Lewis, R.R. (2001) Mangrove restoration – costs and benefits of successful ecological restoration. In review, *Proceedings of the Mangrove Valuation Workshop*, Universiti Sains Malaysia, Penang, 4–8 April 2001. Beijer International Institute of Ecological Economics, Stockholm, Sweden.

Lewis, R.R. (2005) Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering* 24, 403–418.

Mazda, Y., Wolanski, E., King, B., Sase, A., Ohtsuka, D. and Magi, M. (1997) Drag force due to vegetation in mangrove swamps. *Mangroves and Salt Marshes* 1, 193–199.

Peterson, J.E. and Baldwin, A.H. (2004) Seedling emergence from seed banks of tidal freshwater wetlands: response to inundation and sedimentation. *Aquatic Botany* 78(3), 243–254.

Sanyal, P. (1998) Rehabilitation of degraded mangrove forests of the Sunderbans of India. Program of the International Workshop on Rehabilitation of Degraded Coastal Systems. Phuket Marine Biological Center, Phuket, Thailand, 19–24 January 1998, p. 25 (abstract).

Tabuchi, R. (2003) The rehabilitation of mangroves in Southeast Asia. In: *Proceedings of the International Symposium: Alternative Approaches to Enhancing Small-Scale Livelihoods and Natural Resources Management in Marginal Areas – Experience in Monsoon Asia*. United Nations University, Tokyo, pp. 121–128.

Tomlinson, P.B. (1986) *The Botany of Mangroves*. Cambridge University Press, Cambridge, UK.

Tri, N.H., Hong, P.N. and Cuc, L.T. (2000) Report of the UNESCO-MAB Regional Workshop on 'Establishment of Mangrove Biosphere Reserve in Can Gio, Southern Vietnam and Biosphere Reserve Network Initiative for Southeast Asia' held in Ho Chi Minh City, 6–11 November 1998. Cartographic Publishing House, Ho Chi Minh City, Vietnam.

Tuan, L.D., Oahn, T.T.K., Thanh, C.V. and Qui, N.D. (2002) *Can Gio Mangrove Biosphere Reserve*. Oxfam America, Hanoi.

van Huijgevoort, M.H.J. and te Brake, B. (2007) Hydrological characterization of mangrove forests in Can Gio and Ca Mau, Vietnam. MSc thesis, Department of Environmental Sciences, Wageningen University, the Netherlands.

van Loon, A.F. (2005) Water flow and tidal influence in a mangrove-delta system, Can Gio, Vietnam. MSc thesis, Department of Environmental Sciences, Subdepartment Water Resources, Wageningen University, the Netherlands.
van Loon, A.F., Dijksma, R. and Van Mensvoort, M.E.F. (2007) Hydrological classification in mangrove areas: a case study in Can Gio, Vietnam. *Aquatic Botany* 87(1), 80–82.
van Speybroeck, D. (1992) Regeneration strategy of mangroves along the Kenya coast: a first approach. *Hydrobiologia* 247, 243–251.
Vietnam MAB National Committee (1998) Can Gio Mangrove Biosphere Reserve. Draft Biosphere Reserve Nomination Form, Ho Chi Minh City, Vietnam.
Watson, J.G. (1928) Mangrove forests of the Malay Peninsula. *Malayan Forest Records* 6, Forest Department, Federated Malay States, Kuala Lumpur.
Youssef, T. and Saenger, P. (1999) Mangrove zonation in Mobbs Bay – Australia. *Estuarine, Coastal and Shelf Science* 49, 43–50.

29 Coastal Transects Analysis of Chao Phraya Delta, Thailand

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Abstract
The consequences of coastal degradation can be devastating, particularly in highly populated and sensitive areas such as deltas. Innovative approaches and tools are required to minimize these impacts and for sustainable management. The high complexity, diversity, dynamics and large-scale characteristics of many coastal areas around the world have led people to develop sophisticated, technology-based coastal management tools and complex decision-making models. These models, although comprehensive, are not always user-friendly and are generally of limited use in data-sparse and resource-poor situations. A coastal transects analysis model (CTAM) was developed as a simple tool for individuals and groups to describe and compare various coastal areas 'at-a-glance'. CTAM is a computer-assisted, visualization and interactive tool used to describe key features of coastal areas, such as physical characteristics, habitats, activities, problems and issues. This information is displayed as coastal transects, which can be categorized and compared with other coastal areas worldwide. In this chapter, we present five CTAM models, one for Samutprakan Province, which is at the centre of the Chao Phraya Delta, and the others for four villages in the province. This analysis illustrates the use of CTAM in describing and comparing the complexity and the diversity of natural and human systems, as well as in stimulating general discussion about integrated coastal management.

Introduction

Integrated coastal management (ICM), a recognized approach to address coastal challenges, generally involves a large suite of ecological, social and economic considerations, institutional arrangement in accordance with those considerations and innovative processes (Cicin-Sain and Knecht, 1998; Kay and Alder, 2005). ICM aims to achieve ecosystem integrity, to maintain biodiversity and sustain the resource base, to minimize stakeholder conflicts, and to optimize social and economic benefits for current and future generations. It also acknowledges the historical, cultural and traditional perspectives of coastal communities. Institutional arrangements in ICM generally require integration at vertical and horizontal levels and partnership building and cooperation among actors across sectors. In order for ICM to be legitimized, the process has to be participatory and transparent. Furthermore, it often requires the development of legislative frameworks and policies that consider spatial and temporal dimensions to acknowledge cross-boundary issues and for long-term sustainability. In other words, ICM is a daunting task.

The holistic nature of ICM and the high level of complexity of most coasts, and thus the need to cope with diversity and dynamics at varying scales, have led to the development of highly sophisticated and technology-based coastal management tools. This has been made possible through advances in computerized models. For example, GIS-based tools popular for spatial analysis of coastal areas are often coupled with decision-support systems that incorporate expert judgements and fuzzy logic to address the multiplicity of stakeholders and their several, and often conflicting, interests and demands. In addition to knowledge about GIS software, users of these tools are required to have access to large sets of data and detailed information about their coasts. The accessibility and applicability of such models and tools is therefore limited to data- and resource-rich situations. A different kind of tool is needed for the integrated management of most coasts around the world where data are limited.

Different coastal systems pose different challenges. Biophysical characteristics, habitats, resources and the activities taking place on beaches differ from those of estuaries, deltas, lagoons and fjords. Tropical beaches are also different from those in temperate regions. Management tools that work for one system in an area may not work well in a similar system in other areas or in totally different systems. Tools that are context based and location specific have further limits on their transferability. Selecting tools involves trade-offs, for example between comprehensiveness and sophistication with high data requirements, and ease of application in various settings but lacking analytical power to address all problems. This chapter presents the coastal transects analysis model (CTAM) as a tool in the latter category.

CTAM is a simple, online tool that can be used by individuals or groups of stakeholders to describe and enhance understanding of the complexity of natural and human systems in coastal areas. Users are guided by friendly and interactive interfaces to describe their coastal areas. Icons and images are shown immediately as users provide inputs into the model. CTAM models are saved on a database that can be viewed by all users, who can then make ‘at-a-glance’ comparisons between their coastal areas with others in the database. The simplicity and visual aspect of the tool helps encourage communication, knowledge sharing and participation of stakeholders in the planning and management of coastal areas. An application of CTAM to Samutprakan Province, which is at the centre of the Chao Phraya Delta, is presented to illustrate its functions and potential as a participatory and decision-support tool for ICM.

In this chapter, we first describe the conceptual framework of CTAM and the model. Next, we provide the coastal contexts of the Chao Phraya Delta, along with key management issues. We then apply CTAM to analyse the system complexity of the Chao Phraya Delta in Samutprakan Province. In the final section, we discuss the results of the descriptive analysis and the policy implications of CTAM.

Conceptual Framework and Model Description

Pauly and Lightfoot (1992) visualized a simple way to carry out a comparative analysis of coastal areas around the world. Without the aid of modern computer technology, they divided coasts from upland to offshore into sections using simple drawings in order to examine the key coastal characteristics and management measures taking place in each section. They were interested mainly in comparing various coastal transects to gain an understanding of the interconnectivity of resources and activities in coastal areas, which could lead to improved management of the coasts.

The first implementation of Pauly and Lightfoot’s analytical framework resulted in software called SimCoast™. It combines fuzzy logic, a rule-based expert system and issue analysis to address challenges and concerns in ICM (Hogarth and McGlade, 1998). It is a powerful tool that can be used to identify dominant processes and issues that have significant impacts on coastal environments. Taking into consideration natural, social and economic elements, SimCoast™ offers an interdisciplinary decision-making framework for weighting the impacts of various coastal activities based on a set of goals and targets.

SimCoast™ was developed as a ‘soft intelligence’ system where demands for data and expert knowledge are high. Although it remains useful for ICM, it faces similar challenges as other sophisticated, computer-assisted software with respect to data requirements and accessibility for coastal practitioners in developing countries, as well as the fact that it is expensive at £500 per licence. Although the CTAM structure is similar to SimCoast™, it differs in its aim of software simplification and having modest data requirements. Reviews of existing ICM tools show that simple images are most effective in enhancing communication among various groups of stakeholders (Kay *et al.*, 2006). Interactive and visually attractive images have therefore been developed and incorporated into CTAM.

CTAM is online software that anyone with access to the Internet and a web browser can use. It is a 'descriptive' model intended for general users, with basic required inputs, such as physical descriptions of coastal areas, existing habitats and resources, general information about fishing and other coastal activities, management approaches and tools, and coastal issues and challenges. This information is presented as six consecutive pages on the CTAM website. Each page contains multiple choices which are displayed as descriptive text on the top screen. On the bottom screen of each page, there is a base picture showing an image of a coastal land and sea profile, divided into six equal transects perpendicular to shore, i.e. upland, lowland, intertidal, inshore, offshore and high seas. On the first page, users are asked to describe the landward and seaward slopes of their coasts by clicking on one of the choices at the top of the page (Fig. 29.1a). The selected choice will then show up on the base picture at the bottom panel of the screen (Fig. 29.1b). This first picture establishes the basic transect that users create upon providing information about slopes. Next, they indicate the bottom type by clicking on one of the icons (e.g. sandy, muddy, mixed). Their choice will then appear on this first picture that already contains the slope information. More icons of habitats, fishing activities and other activities are added to the base picture, as users move through the pages in CTAM. The positions of these icons on the base picture are fixed according to certain assumptions. For example, small-scale fishing is considered to take place normally in the 'inshore' transect, since it generally uses boats of 4–6 m in length with 2–4 crew members (Chuenpagdee *et al.*, 2006), and large-scale fishing boats, such as trawlers and purse seiners, tend to operate in the offshore area. It is possible, however, for small-scale fishing boats to operate further offshore and for large-scale fishing boats to operate inshore. Thus, small-scale and large-scale fishing can appear in the inshore and offshore transects, as defined by the user.

In CTAM, users can go back and forth by using the 'back' and 'next' buttons, and make changes as needed without losing information that they want to keep. All the choices are presented as toggled buttons so that they can be selected or deselected at a click of a mouse. Each time an icon is selected (or deselected), an image appears (or disappears) on the corresponding base picture.

Once users reach the end of CTAM, the final picture containing all information provided by the users will appear and they can then choose to download, print and save their models. All CTAM models are stored in an online database, which can be searched by coastal type (e.g. delta, fjord, estuary, beach, etc.) and location (country). These models are available for viewing and downloading by all users, and are also shown on a global map by their approximate location and coastal type. They are, however, password protected to allow only the model developers to retrieve, modify and revise the models. Currently, 165 models are available at www.coastaltransects.org.

CTAM models can be developed by single users or groups of users. Users can also compare the models developed for their areas with others elsewhere for similarities and differences. When used in a group setting, CTAM enables discussion among stakeholders about different features of their coastal areas. CTAM can be used among stakeholders to standardize the information about the coasts. Once stakeholders agree on what their coastal profile looks like, they can then discuss what they would like to see in their coastal areas and consider what management measures are required. CTAM models can be updated regularly to observe and monitor changes in key coastal features over time.

Description of the Chao Phraya Delta

The Chao Phraya Delta, located in central Thailand, comprises three major basins, namely

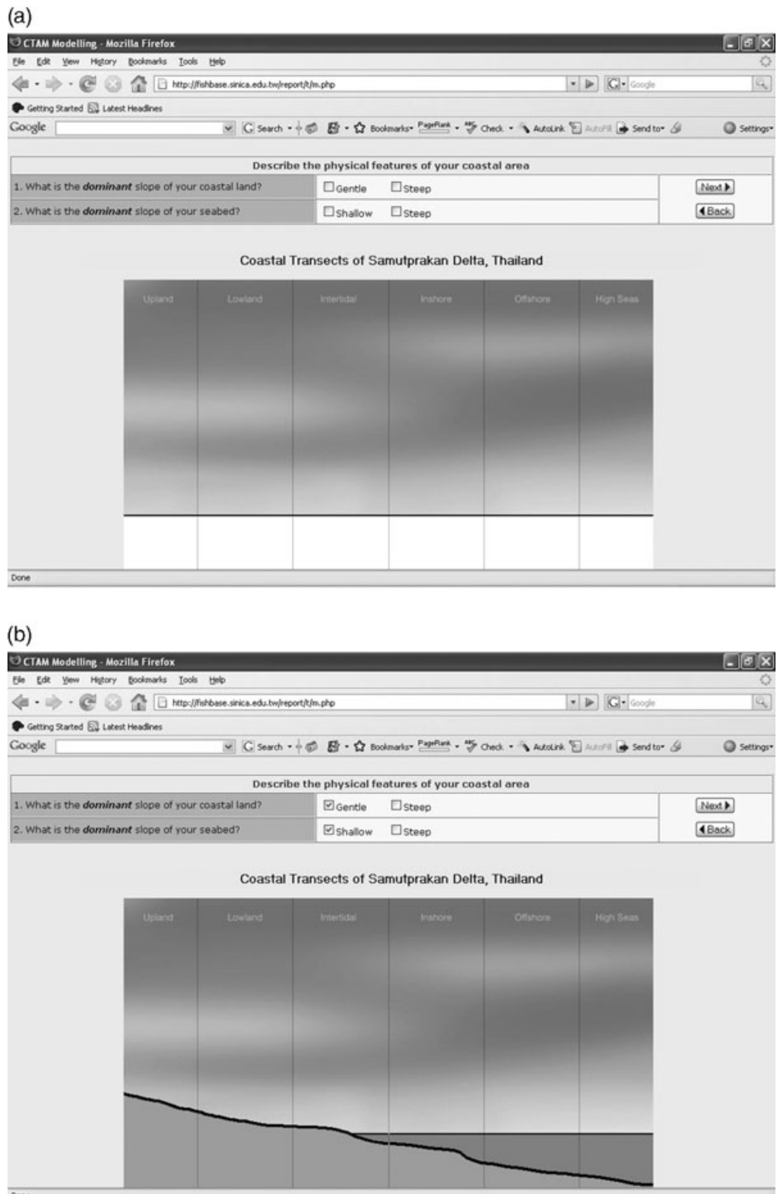

Fig. 29.1. An example of the interface in CTAM showing the data entry form and the resulting picture. (a) The first page of CTAM before information about the coast is entered; (b) the same page of CTAM after user indicates information about slopes.

the Chao Phraya, the Tha Chin and the Mae Klong, extending about 115 km from Samutsongkhram Province in the west to Samutprakan Province in the east (Fig. 29.2). The Chao Phraya River, Thailand's largest and most important river, covers an area of over 10,000 km^2 and flows through 15 provinces before draining to the Gulf of Thailand in Samutprakan Province. The river is the principal source of water for domestic and industrial uses. The lower basin,

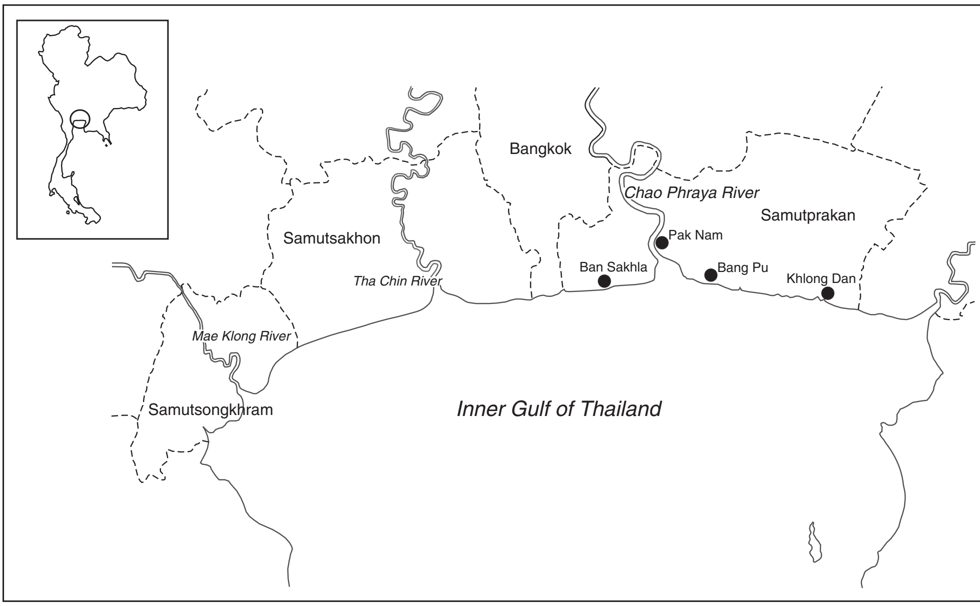

Fig. 29.2. Map of Chao Phraya Delta and four study sites.

the Chao Phraya Delta, is a flood plain area suitable for rice cultivation. The delta is sometimes referred to as the Rice Bowl of Asia, given its extensive rice cultivation covering an area of about 8.4 million ha (Pookpakdi, 2000). The delta supports a population of about 1.2 million in its three main constituent provinces. The area has recorded the highest economic growth in the country, with high levels of investment in infrastructure and extensive development of natural resources over the years. Fishing, aquaculture, animal husbandry, fruit growing and vegetable cropping are prominent activities in the region, generating income and jobs (Cheyroux, 2000; Hungspreug *et al*., 2000). The delta is home to many culturally and ethnically unique communities, for example Damnoen Saduak and Koh Kret, a small island in Nonthaburi Province is a traditional settlement of Mon people (an ethnic group originally from Myanmar), who have maintained their tradition and culture. The island is being promoted as an ecotourism site (Thadaniti, 2000).

As with many populated coastal areas, the Chao Phraya Delta is diverse, complex and dynamic. The management of the delta is challenged by issues such as erosion, flooding, habitat degradation, pollution, urban sprawl and overexploitation of fisheries resources. Flooding is one of the main concerns in the Chao Phraya Delta. Many approaches have been employed to control the water level and mitigate floods in order to provide protection to agricultural land and major municipalities. The most efficient project is the Master Plan 'Kaem Ling' (or 'monkey cheeks') devised by His Majesty the King. The development of transportation canals, the construction of dams and other irrigation projects are part of the efforts to help prevent flooding and to increase the efficiency of water use. Damnoen Saduak, a subdistrict located in the western part of Chao Phraya Delta, is an example of an area with effective water management. A major canal network has been developed to provide drainage and irrigation for orchards and vegetable plantations, as well as transportation. The area has drawn many tourists who are interested in observing traditional lifestyles, with many small non-motorized boats full of produce and other goods that continue to travel and trade along the canals. Water management is necessary, given the high water demand from households, agriculture and industries. Water quality is affected by the heavy use of chemical fertilizers and pesticides in rice farming, soil salinization and effluent from shrimp farms and wastewater from numerous industries and factories, such as textiles and steel production plants. Water quality is monitored regularly and controlled. Change from monoculture rice farming to combined leguminous crops such as mungbean, soybean and groundnut is being promoted to help restore soil fertility and reduce the use of chemical fertilizers and pesticides (Korparditskul and Poss, 2000; Simachaya *et al*., 2000). Technological development to reduce pollution and waste from shrimp aquaculture is also being promoted, by raising a marine species, black tiger prawn (*Penaeus monodon*), in the inland freshwater area (under mesohaline conditions with 3–10 ppt salinity) using a closed system where little or no exchange of water takes place.

In the inner Gulf of Thailand, coastal erosion is caused by several factors, including the building of dams, groundwater withdrawal and loss of mangroves. In the delta, coastal erosion occurs in many areas, especially in small coastal villages on the west side of the Chao Phraya river basin in Samutprakan Province. According to Nutalaya *et al*. (1996), monitoring from 1969 to 1987 showed an average erosion rate of about 28 m per year, resulting in coastal recession of more than 500 m in this area. In Khun Samutchin village, erosion is so severe that more than 1 km of land has been lost over the past 28 years, causing the relocation of schools, offices and houses (Jarupongsakul and Suphawajruksakul, 2005). The delta is a large gentle sloping mudflat that extends to about 5–6 km from the shore, which is partly lined with mangrove fringes. Most mangroves have been clear-cut, mainly during the rapid development of the shrimp farming industry in the 1990s. Fishing takes place in the inshore, offshore and high seas areas using various types of small-scale and large-scale fishing gears. Numerous earthen ponds, previously used for the production of tiger prawn, are now used to raise fish, particularly Siamese gourami (*Trichogaster pectoralis*). Several factories, such as refineries, steel manufacturers, fish processing, textiles and automobile parts, line the coast, along with a couple of urban centres and many small coastal communities. Fisheries and coastal areas are managed by the central government, with little involvement from communities, except through local management authorities known as the Tambon Administrative Organizations (or Au-Bor-Tor, an acronym well known to Thais). These have been established since 1999 as part of the decentralization reform process to allocate some decision-making powers to local government units. Current management issues include erosion, pollution and overfishing.

CTAM Analysis of the Chao Phraya Delta in Samutprakan Province

The descriptive analysis of Chao Phraya Delta using CTAM is a step towards planning and sustainable development of this area. The analysis covers the central part of the delta within Samutprakan Province (Fig. 29.2). The ‘big picture’ of the Chao Phraya Delta (the ‘province’ transect) shows a system with high complexity in terms of fishing and other coastal activities (Fig. 29.3). The study transect is approximately 47 km in width, from Ban Sakhla on the west to Klong Dan on the east. Although the transect width is not relevant to the analysis in CTAM, it is noted for comparative purpose. Field observations suggest that system variation is high in the area, as shown through the analysis of smaller transects along the coast. Four villages in Samutprakan Province, namely Ban Sakhla, Pak Nam, Bang Pu and Klong Dan villages, were selected to demonstrate this. The transect width for each village is about 2 km. The ‘province’ transect and the four ‘village’ transects cover the same distance from the shoreline in both directions (upland and seaward). Upland areas extend to about 2 km from shore, where the coastal road that runs parallel to the shore is located. Although dams are constructed further upstream of the Chao Phraya River, this feature is indicated in the upland transect of the Samutprakan model to account for the downstream effects.

The four village transects are similar in terms of landward and seaward slopes, except for Pak Nam, where the seaward slope is relatively steeper compared to the other

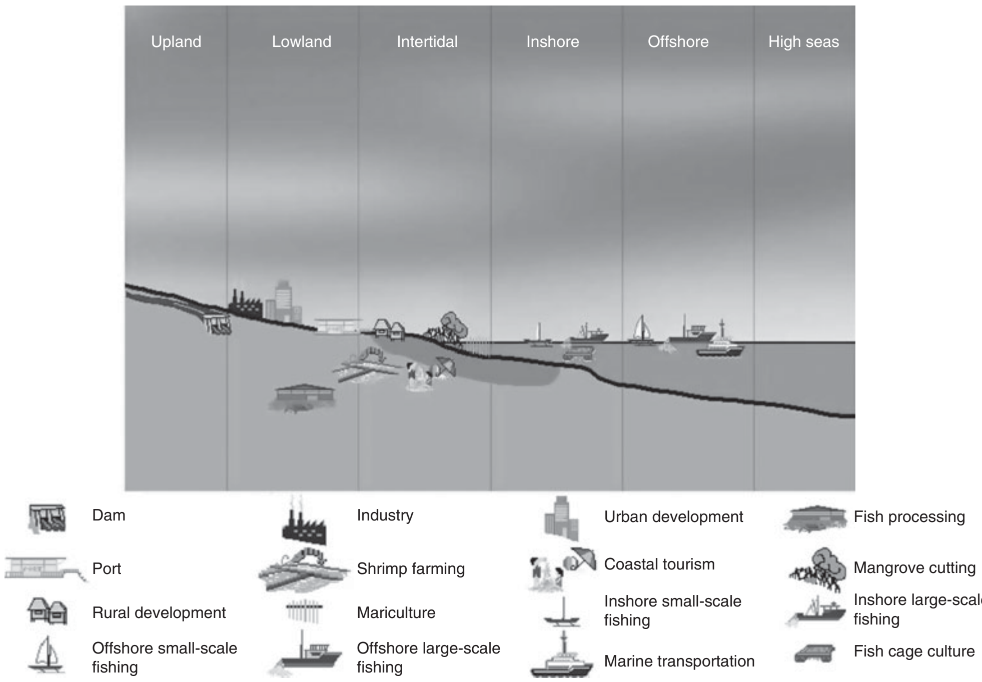

Fig. 29.3. Coastal transects of Chao Phraya Delta, Samutprakan, Thailand.

three areas (Fig. 29.4). The main differences in these four transects are related to fishing activities, industry and tourism, as summarized in Table 29.1. By comparison, Pak Nam and Klong Dan have more ongoing activities than the other two sites. Commercial fishing is most active in Pak Nam, which is the main landing site for the entire province. Large-scale fishing boats operating in inshore areas use various types of gears, including pushnets, pots and traps, bottom gillnets, dredges and mid-water trawls. Gears used in offshore fishing boats are otter trawls, mid-water gillnets, mid-water trawls, pair trawls and purse seines. In addition to fishing, many factories are located in Pak Nam and discharge directly into the delta, causing concerns about water quality.

Table 29.1. Key features of four coastal communities in the Chao Phraya Delta, Samutprakan Province.

	Ban Sakhla	Pak Nam	Bang Pu	Klong Dan
Population	9000	56,900	114,700	19,200
Mangrove forests	Yes	Yes	Yes	Yes
Industries	No	Yes	Yes	No
Fishing	Yes	Yes	Yes	Yes
Shrimp culture	Yes	No	No	Yes
Fish culture	No	No	No	No
Shellfish culture	Yes	No	No	Yes
Tourism	No	No	Yes	No
Urban development	No	Yes	Yes	Yes
Rural development	Yes	Yes	No	Yes
Main problems	Erosion	Water pollution, erosion, overfishing	Water pollution, erosion	Mangrove cutting, erosion

Fishing is also active in Klong Dan, but the majority of the gears are small-scale pushnets targeting krill (Euphosids), which are used as raw materials for shrimp paste. Processing of krill, mainly done by women, is therefore another important economic activity in this village. Small-scale fisheries also take place in Ban Sakhla village. It is here, however, that erosion is the major problem affecting coastal households. Contrary to other sites, there is no fishing in Bang Pu. Its proximity to Bangkok makes it popular for tourists who enjoy seafood and birdwatching.

Discussion and Conclusions

The complex and diverse characteristics of coastal ecosystems are well recognized, but generally are poorly understood. The complexity of resources and activities in coastal areas often discourages the participation of stakeholders in management. CTAM provides a framework for systematic description and communication among resource users and other stakeholders who may have different views about the coasts, and possibly conflicting interests and priorities. Individuals and groups can use CTAM to describe their coasts and arrive at a shared understanding about the relevance of various habitats and activities interacting in their coastal areas. This common understanding of the coastal profiles is useful to initiate an in-depth discussion in order to arrive at a consensus on how to manage the areas. CTAM helps engage stakeholders in the discussion in a meaningful way and encourages stakeholders to provide additional inputs useful for priority setting and the development of management plans.

Stakeholders' concerns and management challenges vary by sites. CTAM can be used to facilitate discussion about the development of a provincial coastal management plan, as well as municipality plans that are consistent and in accord with the former. The simplicity in the development of CTAM and its visualization enable frequent consultation with stakeholders to record changes and adjust plans and priorities. CTAM models can be developed at a regular time interval (e.g. every 6 months or 1 year) to monitor changes in the coastal areas. The Samutprakan model shows the complexity of the Chao Phraya Delta. The four submodels illustrate the range of diversity to be considered in ICM. CTAM enables a simple comparative analysis of the four village transects, as well as comparison with the province transect. The visual 'at-a-glance' comparison of these four sites, as shown in Fig. 29.4, suggests varying opportunities for economic development by location, and related differences between key coastal stakeholders. For example, fisheries are important in Klong Dan and Pak Nam, but less so in the other two sites. Tourism, on the other hand, is important only in one site, Bang Pu. Issues related to fisheries in Klong Dan and Pak Nam may therefore require more urgent attention than tourism in these areas. The reverse is the case for Bang Pu.

As a participatory tool for management and planning, CTAM facilitates further discussion among stakeholders to address differences in opinion and priorities. Informal discussions with key stakeholders at these sites were conducted as part of the ground truthing of the models. The results reveal that fisheries issues in Klong Dan are related mostly to the small-scale fisheries sector, whereas in Pak Nam they are related to the large-scale fisheries sector. Furthermore, fish processing in Klong Dan is performed at household level, mostly by women. This information provides important inputs for discussion about the management of fisheries in Klong Dan, which, based on these characteristics, should differ from those in Pak Nam.

Bang Pu is the only site with prominent coastal tourism. Mangroves in this area and the mudflat are highly productive and are abundant with crabs and other shellfish, as well as seabirds during the breeding season. Tourists enjoy the unique scenery, birdwatching opportunity and consumption of fresh seafood. Conservation and restoration of mangrove forests should be made a priority in this village to maintain its values for tourism.

Among the four locations, Ban Sakhla is the least complex and diverse, but the erosion problem it faces is rather severe. All households in this village are vulnerable to natural and anthropogenic changes impacting on the coast. As in other parts of Thailand, coastal development in this area involves clear-cutting of mangrove forests. The importance of mangrove

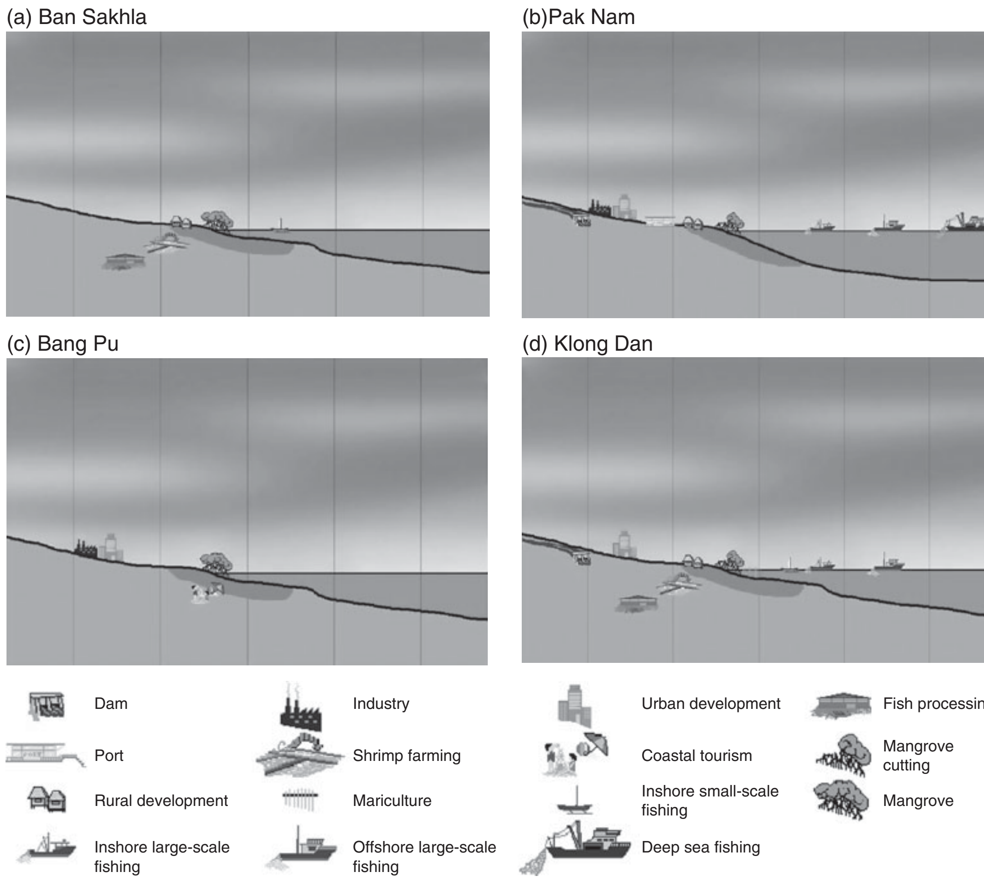

Fig. 29.4. Coastal transects of four study sites in Samutprakan Province.

forests in protecting the shoreline (Chang *et al.*, 2006) suggests that conservation of mangroves forests, including restriction of development that involves mangrove clear-cutting, should be made a priority for management of this area.

As illustrated in this chapter, the strengths of CTAM include its interactive features and visualization, few data requirements and simple interface. However, it lacks the analytical power and the spatial dimension that coastal managers may require. In its current form, CTAM can be used in conjunction with other ICM tools, particularly GIS and spatial dynamic decision-support tools. The logical next step for the development of CTAM involves a detailed analysis of the fisheries systems and the distribution of benefits through incorporation of fisheries-specific data such as landings, values, number of boats, number of crew members, boat ownership and market distribution. These additional data requirements are not very onerous, given that some may already be available through an existing data collection programme.

ICM recognizes the importance of understanding the complexity and diversity of natural and human systems, as well as their interactions. Participation from stakeholders is essential to gain better understanding about the coastal areas, and to generate further discussion about management. Through CTAM, local stakeholders, scientists and policy makers can work collaboratively in describing their coastal ecosystems, discussing potential impacts of different activities and identifying and prioritizing issues. CTAM does not allow powerful analysis, but its descriptive features and visualization enables simple analysis and comparison of systems, which are important first steps. Such analysis leads to further discussion about the ecological, social and economic importance of coastal ecosystems. For coastal management, this means progress towards better planning for ecosystem sustainability and the well-being of coastal communities.

Acknowledgements

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References

Chang, S.E., Adams, B.J., Alder, J., Berke, P.R., Chuenpagdee, R., Ghosh, S. and Wabnitz, C. (2006) Coastal ecosystems and tsunami protection after the December 2004 Indian Ocean Tsunami. *Earthquake Spectra* 22(S3), S863–887.

Cheyroux, B. (2000) Fruits and vegetables in Thailand's rice bowl: the agricultural development of poldered raised bed systems in Damnoen Saduak area. *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok, pp. 1–17.

Chuenpagdee, R., Liguori, L., Palomares, M.L.D. and Pauly, D. (2006) Bottom-up, global estimates of small-scale fisheries catches. *Fisheries Centre Research Report* 14(8), 110p (http://www.fisheries.ubc.ca/publications/reports/report14_8.php, accessed 2 July 2009).

Cicin-Sain, B. and Knecht, R.W. (1998) *Integrated Coastal and Ocean Management: Concepts and Practices*. Island Press, Washington, DC.

Hogarth, A.N. and McGlade, J. (1998) SimCoast™: Integrating Information About the Coastal Zone. *Echos of Expo'98 Bulletin* 11(3–4), 29–31.

Hungspreug, S., Khao-uppatum, W. and Thanopanuwat, S. (2000) Flood Management in Chao Phraya River basin. *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok, pp. 1–20.

Jarupongsakul, T. and Suphawajruksakul, A. (2005) *Post-Symposium Excursion Guidebook of the 7th Kyoto University International Symposium on Coexistence with Nature in a Globalizing World. Field Science Perspectives*. Department of Geology, Chulalongkorn University, Thailand.

Kay, R.C. and Alder, J. (2005) *Coastal Planning and Management*. E & FN Spon, New York.

Kay, R.C., Gardner, S., Bello Pineda, J., Juntarashote, K., Pierce, G.J., Pita, C., Wang, J. and Chuenpagdee, R. (2006) Concepts and tools for ICZM with a special focus on stakeholder engagement and visualization tools in fisheries management. INCOFISH Report Work Package 6, Deliverable 6.1 (http://www.incofish.org, accessed 2 July 2009).

Korparditskul, R. and Poss, R. (2000) Environmental aspects of intensive agricultural practices: the case of the raised bed system. *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok.

Nutalaya, P., Young, R.N., Chumnankit, T. and Buapeng, S. (1996) Land subsidence in Bangkok during 1978–1988. In: Milliman, J.D. and Haq, B.U. (eds) *Sea-Level Rise and Coastal Subsidence*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 105–130.

Pauly, D. and Lightfoot, C. (1992) A new approach for analysing and comparing coastal resource systems. *Naga* 15(2), 7–10.

Pookpakdi, A. (2000) Establishing rice legume cropping system in the central plain for better productivity and sustainability. *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok, pp. 1–15.

Simachaya, W., Watanamahart, P., Kaewkrajang, V. and Yenpiem, A. (2000) Water quality situation in the Chao Phraya Delta. *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok, pp. 1–21.

Thadaniti, S. (2000) Towards sustainable eco-cultural tourism for water-based settlements on the banks of the Chao-Phraya River, a case of Koh Kret, Nonthaburi Province. In: *Proceedings of the International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, 13–15 December 2000. Kasetsart University, Bangkok, pp. 12–15.

30 Mangrove System Sustainability: Public Incentives and Local Strategies in West Africa

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Abstract
The need to reconcile biodiversity conservation and development issues, notably the equitable sharing of benefits, recognized in the Convention on Biological Diversity (Secretariat of CBD, 1992; see http://www.cbd.int) and reaffirmed in the Millennium Ecosystem Assessment (MEA, 2005), has led public policies to pay more and more attention to innovative schemes of goods and services value-adding, such as the promotion of local specialities. This chapter analyses the connection and consistency between value-adding schemes such as labelling and the norms that shape these schemes, and coastal biodiversity management practices and local representations in the context of two West African Marine Protected Areas: the Saloum Delta Biosphere Reserve in Senegal (RBDS) and the Biosphere Reserve of the Bolama Bijagos Archipelago in Guinea Bissau (RBABB). These study sites are characterized by mangrove ecosystems, communities of peasant fishers and the exploitation of molluscs (*Anadara*, *Crassostrea*, *Cymbium*, *Murex* and *Pugilina*). Through an interdisciplinary approach (involving a biologist, an economist, a historian and a geographer), this chapter examines the present and potential contributions of shellfish enhancement initiatives to improving biological and cultural diversity in mangrove systems and assesses contradictions between local strategies and national and international policies.

Introduction: Growing Interest in Local Specialities

In response to the difficult problem of resolving both biodiversity erosion and local poverty, notably in the less developed countries of the south, market-based incentives have been invoked by more and more international agencies (World Bank, International Monetary Fund, FAO, etc.) and national governments as potential policy tools that may be able to improve environmental incomes (Jasanoff, 2004). Among these incentives, local specialities enhancement schemes are being increasingly implemented around the world (Muchnik *et al.*, 2008). The success of these schemes is associated with diverse strategies (Barjolle and Sylvander, 2003): legal – the fight against a product name's usurpation and counterfeiting and the protection of intellectual property rights; commercial – product promotion and livelihood improvement; and patrimonial – conservation of the various levels of biodiversity (genes, animal species and vegetal varieties, ecosystems and landscapes, traditions and know-how). Moreover, these schemes are also extremely diverse, from simple recognition and qualification of local products to ecolabelling and certification (Cormier-Salem and Roussel, 2009).

To assess these innovative schemes in the context of southern countries, an interdisciplinary (anthropology, geography, economics, sociology, ethnobiology, ecology and law) and comparative programme, the BIODIVALLOC[1]

 Tropical Deltas and Coastal Zones: Food Production, Communities and Environment at the Land–Water Interface (eds C.T. Hoanh *et al.*)

programme, conducted in eight study sites of megabiodiverse countries from the Brazilian Amazon to South India, has focused its attention on agrofood products (coffee, spices, rooïbos and honeybush tea, vegetables, fruit and seafood). The aim of this programme is to examine the connection and consistency between the schemes and the norms that shape local specialities enhancement (value-adding) and biodiversity management practices and local representations, in order to determine how labelling can be used to preserve and enhance the value of biodiversity.

This chapter presents the results of research conducted in two mangrove protected areas of the West African coast (in Senegal and Guinea Bissau). It focuses on the economic, institutional and legal incentives for managing mangroves in a sustainable way and discusses the policies designed to obtain greater value from shellfish. These include not only commercial promotion but also labelling actions (with or without certification) to protect intellectual property rights and determine their impact on the environment and local livelihoods.

First, we present public incentives for biodiversity conservation in the context of globalization and sustainable development. Next, we describe mangrove-based products, show the multiplicity of strategies to enhance their value and highlight the way in which quality standards are achieved. Finally, we discuss the changes that accompany these policies and their consequences in terms of mangrove conservation and local development.

New Context, Higher Stakes from Global to Local Levels

New international governance

Since the late 1980s, there has been a new paradigm of international governance of the environment, discussed in the arena of international conventions and supported by governmental or non-governmental agencies that play major roles in the context of state decentralization (Jasanoff, 2004). This change is significant for mangrove policies and management. Moreover, the earlier objectives of rational exploitation and/or strict protection against human impact (see the Ramsar Convention of 1971) have been replaced with a concern for the co-viability of ecological and social systems, based on the connections between biodiversity conservation and livelihood enhancement. The UNESCO Man and Biosphere programme (MAB) launched in 1970 is one of the earliest examples of this change, introducing the new concept of a 'Biosphere Reserve'. These reserves combine core protected areas with zones where sustainable development is fostered by local residents and users.

The concept of sustainable development popularized by the Brundtland Report (see Brundtland, 1987) has a multidimensional outlook, at once economic, social and environmental. The need to link biodiversity conservation and local development is clearly recognized. This report was followed in 1992 by the Convention on Biological Diversity (CBD), which reaffirms the sovereignty of states regarding their renewable resources and, for the first time, affirms the same for genetic resources (Queffelec, 2006). The CBD also recognizes, in its article on *in situ* conservation, the prior role of the 'knowledge, innovations and practices of indigenous and local communities' (CBD, article 8 (j), 1992 (see www.cbd.int)). Traditions and know-how have long been ignored and considered an impediment to progress (Brush and Stabinski, 1996). Today, they are not only taken into account but are also considered to be useful in conserving biodiversity (Berkes, 1989; Agrawal, 2005). Local communities with their traditional and local ecological knowledge are increasingly recognized as constituting a heritage to be preserved (Cormier-Salem and Roussel, 2002).

Reaffirmed during the Earth Summit in Johannesburg in 2002 and the World Congress on Protected Areas in Durban in 2003, the transfer of management to local communities – co-management or 'good governance' – has become the central objective of public policies with respect to biodiversity conservation (Cormier-Salem and Roussel, 2002). This recognition is accompanied by ethical and social considerations: although local communities are legitimately entitled to manage their environments in a sustainable way, they must also be able to draw benefits from biodiversity conservation (Secretariat of the Convention on Biological Diversity, 2008). It is no longer sufficient to preserve nature without providing economic incentives and local amenities. As alternatives to extractive activities, management strategies seek to emphasize ecological services and promote ecotourism and local products.

Context and stakes in countries with high biodiversity

In countries with high biodiversity, the promotion of products through labels is increasingly common. Labels aim to inform consumers about product qualities: environment-friendly production (ecolabel), respect for workers' social rights (fair trade), origin of production or gustatory quality. These labels can be protected by intellectual property rights such as geographical indications or collective trademarks to prevent use of the label by producers outside of the label's framework. To reinforce the reliability of the label's information, the label can be certified by an accredited organization.

Many studies carried out in developed countries show how these instruments contribute to biodiversity conservation at various levels: genes, species and varieties, species and populations, ecosystems and landscapes, know-how and traditions (Barjolle and Sylvander, 2003; Bérard and Marchenay, 2004). Studies on labels in developing nations, however, are still in their infancy. In these countries, the extent of local involvement and public policy in favour of these schemes depends on the political, legal and socio-economic context. In emergent countries such as Brazil, India and South Africa, legal instruments (private, collective or certification trademarks, geographical indication) and institutional bodies (certifying organizations) support the development of many origin-based products. In less advanced countries, as in West Africa, from our surveys (Cormier-Salem, 2007; Sarr and Cormier-Salem, 2007) and studies conducted in Niger, Burkina Faso and Benin (Lacombe, 2008), decision makers express a clear interest in these instruments, actors of networks are becoming informed about them and many products have a well-established reputation and strong specific features. Some institutions and legal texts exist, but few products have identified labels and even fewer have certified labels. Moreover, in coastal ecosystems such as mangroves, there are specific problems in labelling local seafood production.

Coastal biodiversity conservation and seafood promotion in West Africa

Along the West African coast, incentives for seafood labels are just starting up. Most initiatives are exogenous, supported by foreign NGOs. Labelling of seafood is rare, far less developed than for agricultural products. This discrepancy is also obvious on a global scale, although there are exceptions. The NGO Marine Stewardship Council created a fishery label with principles and criteria based on the code of conduct for responsible fisheries adopted by the FAO in 1995. The FAO Committee on Fisheries (COFI) adopted Guidelines for the Ecolabelling of Fish and Fishery Products from Marine Capture Fisheries (Rome, 7–11 March 2005) (Wessells *et al.*, 2001; Gulbrandsen, 2006).

Public policies show a growing interest in this labelling, which has a double purpose: to find sustainable alternatives to overfishing, to improve local livelihoods and to give new impetus to rural territories that suffer from drought and global warming, rural exodus and agricultural crises (retreat of mangrove management, salinization and acidification of soils, rice cultivation retreat, landscape degradation, etc.) (Cormier-Salem, 1999).

To meet these related objectives, many programmes have been implemented at national and transnational scales, such as the *Le Programme Régional de Conservation de la zone Côtière et Marine en Afrique de l'Ouest* (PRCM)/West African Conservation Program of Marine and Coastal Zones, which aims to coordinate the efforts of governmental and non-governmental organizations (International Union for the Conservation of Nature (IUCN), World Wildlife Fund (WWF), Wetlands International, Fondation Internationale du Banc d'Arguin

(FIBA), etc.) in the following countries: Mauritania, Senegal, Gambia, Guinea Bissau, Guinea, Cape Verde and Sierra Leone. The frequent failures of environmental policies and the conflicting claims on coastal resources show the limits of strict protection and the need to share benefits derived from biodiversity conservation beyond park boundaries (IUCN, 2005). Hence, studies conducted in West Africa question the effectiveness of Marine Protected Areas (MPAs) – national parks as well as biosphere reserves. Although they might be ecologically efficient, most often they are not economically viable, or socially acceptable (Boncoeur *et al.*, 2002; Cormier-Salem, 2006). Policies have to be more integrated and on a larger scale. PRCM is in favour of ecological corridors and the MPAs network, and of ways to strengthen the links between fishers and their coastal environment, such as seafood labelling.

This chapter examines the relevance of labelling incentives in two MPAs: the Saloum Delta Biosphere Reserve (RBDS) in Senegal and the Biosphere Reserve of the Bolama Bijagos Archipelago (RBABB) in Guinea Bissau. The environmental, territorial and social characteristics of the study sites are given in Table 30.1.

The chapter does not discuss the problems of MPA governance, as these have been addressed elsewhere (see Cormier-Salem, 1999 and 2006; Dahou and Weigel, 2005). Nevertheless, it is necessary to underscore two points in order to understand the sharp tensions between local strategies and public incentives. On the one hand, the changes in the multiple uses of mangrove systems – the decrease of traditional uses such as rice cultivation, the explosion of small-scale fishing and shellfish gathering for the market, the development of new uses, commercial or non-merchant, such as tree growing, tourism and ecotourism – have led to competition for mangrove resources and spaces. On the other hand, the disengagement of the state, the lack of an effective legal framework, insufficient infrastructure, decentralization and devolution without corresponding transfer of funds and the inadequacy of public funding have led to the arrival of new actors and mediators such as NGOs, and hence to social recomposition (such as the declining power of the Elders or chiefs of the lineages, whose legitimacy is contested by younger people and state officials) and, notably, privatization of commonly held resources and lands. It should be noted that many commentators, especially social anthropologists, have pointed out that external interventions may be counterproductive and end up promoting individuals' privileges and exacerbating social inequalities rather than strengthening communities' self-reliance and self-governance (see Cook and Kothari, 2001). In addition, there is a multitude of local institutional measures: for example, the establishment of beach committees, the more or less temporary closing of *bolon* (tide channels), bans on the use of zones considered as nurseries and/or sacred sites. The two study sites, RBDS and RBABB, have contrasting characteristics (Table 30.1), but they are both territories under severe constraints because of their status as MPAs. Women, with their know-how and techniques to 'work shellfish from mangrove', are central actors, as they effectively control the activities of shellfish gathering, processing and sale.

In the two study sites, similar investigations were conducted: (i) to identify the species and products considered in this analysis; (ii) to describe the operating conditions (technical, practical, knowledge); (iii) to carry out stakeholder analysis in the trade chain from production sites to markets (fishers and gatherers, manufacturers, sellers, consumers, etc.); (iv) to describe the legal framework for qualifying and certifying products (traceability, norms and devices, territorial limits); and (v) to highlight the consequences of the policies for improving quality and adding value to the products.

Specifics of mangrove production and know-how related to mangrove products

In the Bijagos Archipelago and the Saloum Delta, without minimizing the importance of the other mangrove products (honey, salt, etc.), shellfish (bivalves and gastropods) clearly occupy a privileged place, because of several factors (Sarr and Cormier-Salem, 2007).

First, the numerous species are well identified (see Table 30.2).

Table 30.1. Characteristics of the study sites.

MPA	Saloum Delta	Bolama Bijagos Islands
Surface area (ha)	330,000	1,050,000
Category, date of creation	National Park (76,000 ha), 1976 Biosphere Reserve, 1981	Orango National Park, 1997 Cacheu National Park, 1997 João Vieira et Poilào National Park, 2001 Bolama Bijagos Biosphere Reserve, 1996 Community Reserve of Urok Islands, 2005
Population living in the park	120,000	35,000
Population density (individuals/ha)	122	13
Number of villages	114	189
Major groups	Serer-Niominka and Soce	Bijagos
Other minorities	Many migrant groups from other areas of Senegal (Wolof, Guet-Ndar) and other countries (Republic of Guinea, Mali, etc.)	Some groups from Guinea Bissau (Pepel, Manjak) and Senegal
Main activities	Fishery and exploitation of mangrove resources	Agriculture (rice cultivation)
Other cash-earning activities	Tourism, fruit and vegetable gardens	Gathering of various products from mangrove (shellfish, fish, honey) and terrestrial forest (cashew nuts, palm oil, palm wine, cola nuts, etc.)
Labelling	Improvement of processed shellfish with packing and labelling for national and African markets	No project for shellfish. Tentative brand on *Bubacalhao* (dried cod from Buba)
Main operators of these projects	A lot of projects supported by NGOs and international cooperation (Japan, Belgium, etc.): FIBA/IUCN project 'Women and Shellfish'; Waame NGO; Pagerna; Paped, AFVP, etc.	Very few projects: FIBA/IUCN; NGO Tiniguena

Table 30.2. Main species of bivalves and gastropods exploited in Senegal and Guinea Bissau.

Shellfish	Scientific name	Vernacular name (w, wolof; s, soce; c, crioulo; b, bijogo)
Mangrove oyster	*Crassostrea tulipa* *Crassostrea gasar*	*yoxos* (w); *nañeng* (s); *ostra* (c); ecbée (b)
Arks	*Anadara (Arca) senilis*	*pagne* (w); *bosso* (s); *combé, concha* (c); *conho* (b)
Murex	*Murex hoplites* *Murex cornutus*	*tuffa* (w); *niambaxo* (s)
Black melongena	*Pugilina morio*	*gandim* (c); *umcoco* (b)
Volutes	*Cymbium cymbium* *Cymbium marmoratum* *Cymbium glans* *Cymbium pepo*	*yeet* (w); *sefo* (s); *cuntchurbedja* (c); *edenà* (b)
Razor clam	*Tagelus adansoni*	*lingron* (c); *éna* (b)

Second, products are diversified, with several names according to the species, processing techniques and sites. For instance, under the generic term of 'yeet' – fermented and dried *Cymbium* spp. – consumers typically distinguish four products, which vary according to the species, the sex of individuals, the colour (more or less red), the origin and the actors in the processing chain. The distinctive visual and gustatory qualities are well established by housewives from Dakar (Moity-Maïzi, 2006).

Third, the long-standing importance of seafood in local diets and in long-distance trade is attested to by the shell clusters or *kjokkenmödding* found from the Saloum District to Sierra Leone (Cormier-Salem, 1999). The clusters, whose construction is spread out over a period ranging between 200 and 700 AD, contain a lot of shells (*Anadara senilis*), fish bones of marine origin and pottery from other areas. Hence, they attest to the presence of very old 'eaters of shellfish' who depended on coastal resources for their livelihoods, and also on their relations with people from inland and from other coastal areas trading dried shellfish and fish for rice, cola nuts, palm oil, etc. It should be noted also that the Saloum Delta shell clusters used to be the graves of powerful social groups – religious chiefs and royal lineages – and so are now considered as the cultural heritage.

In Bijagos culture, shellfish also have patrimonial and symbolic values. Religious aspects and ceremonies punctuate Bijagos's social life and influence the spatial organization (for instance via sacred sites) and resources exploitation (for instance via shellfish-gathering regulations in terms of site access and seasons). Initiation rites, based on the transition from one age group to another, show the importance of shellfish in the older/younger relationship. The youngest help the oldest, offering them such products as tobacco, rice, palm wine or shellfish. It is called *o pagamento de grandeza*, meaning 'pay [respect to] the greatness [of] wisdom'. Moreover, shellfish have a role in various Bijagos ceremonies, among which the most famous are the Fanado and the Difuntu. Each ceremony is dedicated to a particular shellfish. The most used shellfish in initiation ceremonies are oysters and arks. Through these practices and beliefs, Bijagos communities make the resource (shellfish) and spaces (rios, mangrove trees, etc.) sacred and turn them into a common heritage. For instance, the mangroves made sacred by and for the group of initiated (or *Difuntu*) women are controlled by a system of traditional rules, which limit access to the sites and their exploitation.

Fourth, it is recognized that local communities are knowledgeable about species, harvesting conditions (sites, seasons, tides and 'the tidal period', which is spread out over 7–10 days, according to the local women, etc.) and processing techniques (cooking). Practices that contribute to the preservation of the resource deserve particular attention. One example is the traditional Moundé basket, which ensures that the smallest shellfish are not harvested (see Fig. 30.1).

Last, shellfish play a major – and undoubtedly growing – role in the local economy. In the Saloum Delta, arks, murex and melongenas have long held a prevalent place in local consumption and in trade. Now, the local communities – Niominka and Soce – consume mostly fish. Shellfish, especially oysters, are intended for sale, supplying the weekly markets of Saloum or the urban markets in Senegal (Kaolack, Dakar, etc.). They have become one of the primary sources of income for the Niominka and Soce people (see Table 30.3). For instance, collectors of arks earn on average 84,000 FCFA per month (approximately US$140).

In the Bijagos Archipelago, the diversity of the exploited species is even larger than in Saloum (see Table 30.2). The shellfish, produced in abundance, constitute the principal, if not the sole source of animal protein. As a staple food, they are called 'Bijagos rice' (Schwarz, 2002). Shellfish are widely used as food. They are cooked with diverse oils (palm, *chebem*, groundnut), fried, boiled or dried, and thus offer a wide variety of dishes and local specialities (with different names, cooking methods, etc.). As in the Saloum Delta, shellfish gathering is an activity dedicated exclusively to women. However, whereas 92% of Niominka and Soce women consider shellfish gathering as their prime activity in terms of time, 80% of Bijagos women consider it only as a secondary activity in terms of time

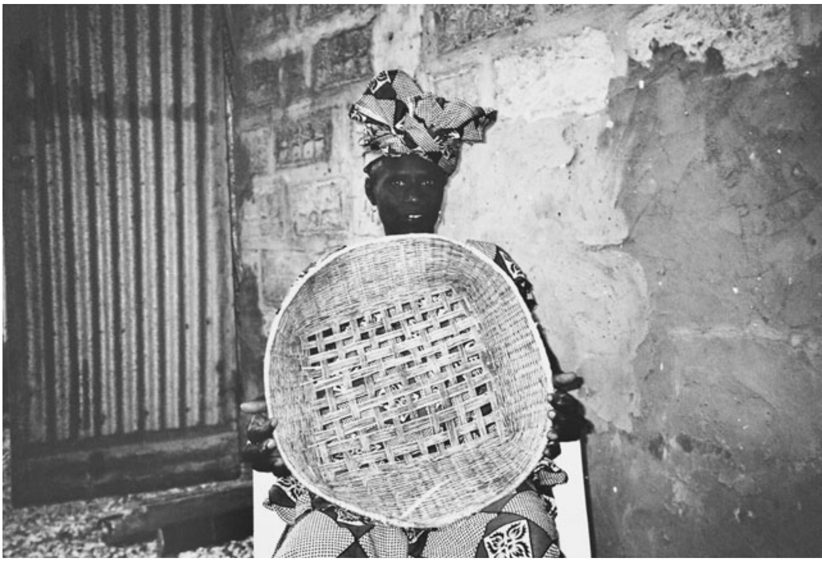

Fig. 30.1. The Moundé basket: a traditional and sustainable technique of gathering shellfish (Saloum Delta).

Table 30.3. Importance of shellfish gathering as source of income for Niominka and Soce women.

Shellfish gathering as source of income	Sample	(%)
Alone	5	6.8
Prime	56	75.7
Important	9	12.2
Minor	1	1.3
No answer	3	4
Total	74	100

(far behind rice culture), but also in terms as a source of income (see Table 30.1 and Table 30.4). In fact, rice culture – overall for domestic consumption – is the core of the Bijagos farming system, their prime occupation in the wet season. During the dry season, Bijagos women are involved in various domestic and marketing productions, among them oil and wine, cashew nuts and wine, mangrove honey, cola nuts, smoked fish, etc. Shellfish collection constitutes one activity among others. Only the surplus is sold. Thus, the average earning per month is less than 10,000 FCFA (approximately US$14), almost nothing in comparison to the US$140 earned by a Niominka woman specialized in ark collection. On average, a gatherer collects 25 kg shellfish/day. Estimating that she can gather 210 days/season (with a break between June and October), her annual production would amount to 5250 kg of shellfish. If 1 kg sells for 100 francs on the islands of Bijagos, she can earn 10,000 FCFA per month (approximately US$20) and 75,000 FCFA (approximately US$150) per month in the markets of Bissau. These earnings are used for everyday expenses, and especially for the purchase of rice.

The shellfish market is potentially wide – the Bissau Guineans of various ethnic origins, specifically from coastal areas, are fond of these products. Tourism, and notably ecotourism, is developing, but it is still limited. In Guinea Bissau, the human development index is 0.35, and 75% of the people depend on international assistance. Thus, national consumers, most of them poor, even very poor, buy shellfish only occasionally, because of their relatively high price (see Table 30.5). Demand from hotels and restaurants is weak because of a precautionary stance invoking the fact that hygiene standards are not respected.

In the Saloum Delta, the women 'who work the shellfish' are largely organized and supported by local and international NGOs (West African Association for Marine Environment (WAAME), IUCN, FAO) who have organized operational groups and cooperatives (Economic Interest Group), the National Federation of Processed and Fresh Fish Operators (FENATRANS) and

Table 30.4. Schematic timetable of the Bijagos women's activities.

	Month											
Women activities	J	F	M	A	M	J	J	A	S	O	N	D
Rice culture						×	×	×	x	×	×	×
Salt collection				×	×	×	×					
Oil palm extraction	×	×	×	×	×	×	×			×	×	×
Groundnut production					×	×	×	×	×	×	×	×
Shellfish gathering	×	×	×	×	×	×	×	×	×	×	×	×
Oyster gathering	×	×	×	×	×			×	×	×	×	×
Bolons fishery	×	×	×	×	×	×	×	×	×	×	×	×
Fish and shellfish processing	×	×	×	×	×	×	×	×	×	×	×	×

Survey of 180 women in 18 Bijagos villages (Bernatets, 2009).

Table 30.5. Price of processed shellfish according to place of sale in Guinea Bissau.

Products (price for 1 kg)	On the islands	At Bissau market
Fresh ark	100 FCFA[a]	750 FCFA
Dried ark	750 FCFA	1500 FCFA

[a]10,000 FCFA = US$20.00.

Fig. 30.2. An example of labelling in the Saloum Delta.

implemented projects, such as the FIBA 'Women and Shellfish' project. The process of labelling consists mainly of guaranteeing the safety of the product (flushing and washing several times with water, addition of chlorine, three successive cookings) and improving its presentation and its traceability (vacuum bagging, labelling) (see Fig. 30.2). Innovations also include exploitation techniques. For example, a Japanese cooperation project has introduced oyster seedings in shallow waters, improved the collection of young oysters ('detroquage') and improved the protection of drying trays with nets against pests.

In the Bijagos Archipelago, despite the scarcity of some species (including razor clams) and the importance and reputation of mangrove-based products like honey and shellfish (Cormier-Salem, 2007), few initiatives have been undertaken, except on the three islands of Formosa, Nago and Chediã, which form the 'Urok complex' and where the NGO Tiniguena has focused its interventions (Biai *et al.*, 2003). On these islands, sales of shellfish are banned to limit mangrove resource exploitation. Tiniguena aimed initially to preserve biological diversity. More recently, it has also sought to conserve cultural diversity and to enhance food security and local capacity building. A *Cocina da Terra* ('home of local products') was opened in January 2008 to recognize Bijagos traditions and know-how, to promote local specialities and to generate added value and improved market access. Tiniguena rounds off with a number of social and cultural events and activities (theatre, dance, local cooking, etc.).

Another initiative, conducted by the IUCN, involved the promotion of dried cod from Buba

Island, sold under the name of 'bubacalhao'. Attempts were made to transfer this initiative to the whole Bijagos Archipelago. The trade name did not have the expected success because of the weak capacity building of Bijagos's producers, the lack of infrastructure and the gap between local and exogenous models of development. After several years of studies (Weigel, 2002), the so-called 'participative' approach has obviously shown its limitations: in fact, it is often excluded from interventions. These animist communities are characterized by their late and very long initiation courses, which limit the younger generation's entrepreneurial freedom. Many projects, especially in the fishing sphere, have failed because the loan beneficiaries (the youngest, who constitute the active population and who are more educated) have no autonomy. The 'seniors' control the whole sphere of life. Moreover, the islands' isolation (with respect to each other and the continent) is a powerful constraint on the development of the fishing industry. Lastly, the inhabitants' mistrust of the state is an inhibiting factor.

Discussion: Seafood Quality Signs and Mangrove Sustainability

The links between product quality and the sustainability of the mangrove (ecological as well as social) system are not obvious and the promotion of technical ecological knowledge via seafood quality labels can have unexpected effects. We focus our attention on the elaboration of quality standards and their application to illustrate these contradictions. In fact, the perception of quality varies from one actor in the commercial chain to another. The criteria are extremely diverse: hygienic, nutritional, organoleptic and technico-legal (Mariojouls, 2000). Some economists (Charles and Boude, 2004) distinguish 'intrinsic' quality, which depends on the products themselves, namely gustatory, nutritional or medicinal value, and 'extrinsic' quality conferred by the conditions of exploitation, processing and marketing, namely respect for the environment, responsible and sustainable uses, poverty reduction, equitable sharing of benefits generated by protected areas, etc. Some of these criteria are compatible, but very often they are contradictory; for example, hygiene criteria often conflict with organoleptic criteria. We consider dried, smoked and fermented fish as examples in the following section.

Development of parallel commercial networks for seafood in Senegal

With shellfish labelling, two parallel commercial networks have emerged in the RBDS. One is recent, initiated by foreign operators; it guarantees that products are fit for human consumption, but sacrifices specific qualities. This network has a very limited impact. Whereas the Saloum Delta Biosphere Reserve counts 114 villages (see Table 30.1), the project 'Women and Shellfish' involves only four rural communities: Fadiouth, in the north of Saloum, and Niodior, Dionewar and Falia, which are located on Gandoul, one of the principal islands of the Saloum Delta. Moreover, in these communities, few women participate in this scheme. Those who do, contribute only 1 day's worth of shellfish per week. Hence, one may stress the unequal involvement of women and the *de facto* exclusion of the majority of collectors, who are not, up to now, the target of NGO interventions. Although the improved shellfish are sold at a higher price, production costs are higher and there are fewer customers. Finally, these products are promoted only at the time of the International Fair in Dakar and are not well known or sought after. Generally, they are sold on an irregular basis to well-off urban middle- and upper-class customers at the end of the working day when offices are closing. The other 'traditional' network involves the majority of the 'shellfish' women and a high volume of production and sales. In fact, demand exceeds supply and is rising for certain renowned mangrove-based products, such as *tuffa* from Betenty, *pañe* from Dionewar, *yeet* from Niominka and oysters from Diola (which are smoked, unlike those of Niominka, which are dried). The processed shellfish are sold at local and weekly markets (*lumo*) in the Saloum District, but mostly in urban markets in Dakar-Pikine, the Senegalese capital. Our surveys of the various actors in the commercial chain (gatherers, manufacturers, wholesalers and retailers, and consumers) show that four criteria are retained regarding product quality (Sarr and Cormier-Salem, 2007): (i) the size of the individual shellfish; (ii) the colour of the processed product; (iii) their consistency, which depends on the transformation process and storage techniques; and (iv) taste, which validates the three preceding criteria. According to women producers, the quality of the product is judged first by appearance, then by touch and finally by taste. The product must be sufficiently dry and well preserved. Signs of 'poor quality' are worms and other pests, broken and flaking fish, rotted and mouldy shellfish and strong odour of decomposition. Poor quality results from insufficient cooking, a too short drying time, bad storage and during the wet season, products may spoil quickly. When quality is not good, sales are prohibited. Agents of the Fisheries Department must issue a certificate attesting to the product's provenance and compliance with sanitary and health requirements. The quality standards applied by public services are not limited to health criteria. The differences in the elaboration of quality standards between these two networks highlight their contrasting approaches: on the one hand requirements focusing on hygiene and stability, leading to homogenization and standardization for the international market, and on the other hand, concern for preserving the authenticity, diversity and specificity of the product for a local and national market. Furthermore, labelling schemes could have harmful effects in economic, social and nutritional terms. Up until now, only a small number of products have been 'improved'. In the long term, taking into account the higher production costs and prices obtained for these products, producers as well as consumers may no longer have access to these resources and products. Similarly, most Senegalese no longer prepare the traditional *cee bu jen* (rice with fish) with cod or other high-value species that are now exported, but with sardinellae, that have long been considered as by-catch.

Another issue arises regarding the effects of these schemes in terms of ecological sustainability. Clearly, if their products had a higher value, the women exploiting the shellfish have declared that they would try to increase their production, or at least increase their cash income (see Table 30.6).

Table 30.6. Gathering strategies of women in the Saloum Delta.

Increasing involvement in shellfish gathering	Sample	(%)
No	17	23
Yes	52	70.3
No answer	5	6.7
Total	74	100

These schemes would thus work counter to the desired effect by increasing pressure on mangrove resources and aggravating the risk of losing traditional practices. Nevertheless, one may argue that increasing value may allow these women to increase their cash income without necessarily increasing pressure on the resource. In fact, there are other modes of regulation: the availability of the labour force (which depends on the mobilization of the lineage members and the women, who are already very busy) and the material conditions of resource access and use (dugout canoes, markets and commercial networks, and tidal periods) constitute strong constraints. Thus, shellfish gathering is currently under local control.

Commercial networks in the Bijagos Archipelago remain traditional

Shellfish consumption in the archipelago remains local and domestic. The sale of island products, issued from farming or fishing systems, is a real problem in Guinea Bissau. The difficulty comes from various factors: physical (geographic distance because of insularity, isolation and dispersion of resources), economic (poverty is worse in the Bijagos Archipelago because of accessibility problems and the limitation of sea transportation, transport costs, lack of facilities for product packaging and conservation, and irregularities in the export of Bijagos products to the continent), political (long instability because of civil war) and social (weak commitment or empowerment of organized producers).

Conclusions: Ambivalent Effects and Internal Contradictions of the Value-adding Schemes

These case studies show: (i) the existence of origin-based products, with strong and recognized links between the mangrove ecosystem and the heritage, tradition and know-how of local communities; (ii) the undeniable reputation of mangrove products, although those identified by the local populations do not always correspond to those identified by NGOs or potential customers; and (iii) the heavy impact of culture in the definition of quality standards: when public policies, relayed by NGOs, stress hygiene criteria and encourage the local actors to use chlorine liberally, one wonders whether the dried and fermented shellfish are genuinely ‘typical’.

Everywhere, origin-based products are growing in importance. Certification schemes are becoming more and more diversified and complex. To be effective, these schemes are based on two main principles: delimitation of a production zone and the setting up and enforcement of a schedule of conditions. Labels of origin represent an unquestionable economic advance for the operators and give new impetus to communities, but cannot ensure overall development. They sometimes lead to the preference for one option (a race or a variety, a practice, a manufacturing process, an ingredient, etc.) to the detriment of others. These constraints, which guarantee product quality or at least compliance with standards for targeted customers, thus have effects that may be contrary to the stated objectives.

These schemes are binding and thus exclusive. The unexpected effects are as follows:

- Loss of biological and cultural diversity – increased pressure on mangrove resources and loss of traditions.
- The unequal involvement of local communities – potential marginalization of certain actors who are excluded from the commercial networks (women not involved in the NGOs’ projects, men collectors and rural communities located outside of the targeted area), multiplication of producers’ organizations and private operators, growing power of NGOs.
- Reorganization of territories – modification of use and access rules, competition for the control of mangrove resources and spaces.
- Competition between traditional and improved products – unequal access to markets and to resources (bioecological, economic, institutional, etc.). With regards to poverty and food shortages that concern more and more people in developing countries, the value-adding of local products is questionable.
- Contradiction between local dynamics and national and international mechanisms.

These points count among the major drawbacks, clearly identified by the local actors.

In the developing countries, these innovative dynamics, generally initiated and implemented by foreign operators, targeting specific categories of customers, are unequally reappropriated by the local communities and very often still occupy a minor place in local economies. Nevertheless, they also constitute alternative ways to draw value from natural renewable resources while maintaining them for the future. They are spaces for negotiation, revealing the power plays on all scales. Vis-à-vis globalization, these schemes lead communities to reappropriate their territory as a model of sustainable local development. As an element in the constructive thinking behind win–win ecology, they push authorities to set up incentives based on a combination of instruments, applied in keeping with local ecological, social, political and economic conditions.

Notes

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References

Agrawal, A. (2005) *Environmentality: Technologies of Government and the Making of Subjects (New Ecologies for the Twenty-First Century)*. Duke University Press, London.

Barjolle, D. and Sylvander, B. (2003) Facteurs de succès des produits d'origine certifiée dans les filières agro-alimentaires en Europe: marché, ressources et institutions. *INRA Productions Animales* 16(4), 289–293.

Bérard, L. and Marchenay, P. (2004) *Les produits de terroir entre cultures et règlements*. CNRS Edition, Paris.

Berkes, F. (ed.) (1989) *Common Property Resources. Ecology and Community-based Sustainable Development*. Belhaven Press, London.

Bernatets, C. (2009) Les Bijagos: des communautés oubliées, des îles magnifiées. Thèse du MNHN (ED227), Paris, 406 p.

Biai, J., Campredon, P., Ducroq, M., Henriques, A. and Silva, A. (2003) Plan de gestion de la zone côtière des îles Urok (Formosa, Nago & Chediã). 2004/2008. Réserve de Biosphère de l'archipel de Bolama/Bijagós/Tiniguena, Guinée-Bissau.

Boncoeur, J., Alban, F., Guyader, O. and Thébaud, O. (2002) Fish, fishers, seals and tourists: economic consequences of creating a marine reserve in a multi-species, multi-activity context. *Natural Resource Modeling* 15(4), 387–411.

Brundtland, G.H. (1987) What is sustainable development? Towards sustainable development. In: *The Panos Institute. Nordic Conference on Environment and Development*. 8–10 May 1987, Saltsjöbaden, Stockholm, Sweden.

Brush, S.B. and Stabinsky, D. (eds) (1996) *Valuing Local Knowledge: Indigenous People and Intellectual Property Rights*. Island Press, Washington, DC.

Charles, E. and Boude, J.P. (2004) Exploitation d'une ressource naturelle et politique de valorisation par des signes de qualité. La pêcherie du bar de ligne de Bretagne. *Economies et Sociétés, série Socio-économie du travail (AB),* 23. Presse ISMEA, France

Cook, B. and Kothari, U. (eds) (2001) *Participation: The New Tyranny?* Zed Books, London.

Cormier-Salem, M.C. (ed.) (1999) *Rivières du Sud. Sociétés et mangroves ouest-africaines*. IRD Edition, Paris.

Cormier-Salem, M.C. (2006) Mangrove: changes and conflicts in claimed ownership, uses and purposes. In: Hoanh, C.T., Tuong, T.P., Gowing, J.M. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflict*. CAB International, Wallingford, UK, pp. 163–176.

Cormier-Salem, M.C. (2007) Rapport de mi-parcours du programme BIODIVALLOC. ANR Biodiversité, IRD/MNHN, Paris, France.

Cormier-Salem, M.C. and Roussel, B. (2002) Patrimoines et savoirs naturalistes locaux. In: Martin, J.Y. (ed.) *Développement durable? Doctrines, Pratiques, Evaluations*. IRD Editions, Paris, pp. 126–142.

Cormier-Salem, M.C. and Roussel, B. (2009) Localiser les produits et valoriser les spécialités locales. Une dynamique générale et foisonnante. *Autrepart* 50, 3–16.

Dahou, T. and Weigel, J.Y. (2005) La gouvernance environnementale au miroir des politiques publiques: le cas des aires marines protégées ouest-africaines. *Afrique contemporaine* 213, 217–231.

Gulbrandsen, L.H. (2006) Creating markets for ecolabelling: are consumers insignificant? *International Journal of Consumer Studies* 30(5), 477–489.

IUCN (2005) Benefits beyond boundaries. *Proceedings of the Vth IUCN World Parks Congress*. IUCN, Gland, Switzerland.

Jasanoff, S. (ed.) (2004) *Earthly Politics: Local and Global in Environmental Governance*. MIT Press, Cambridge, Massachusetts.

Lacombe, P. (2008) Territoires et alimentation. *Cahiers Agricultures* 17(6), 509–510.

Mariojouls, C. (2000) Introduction to quality: quality concepts, quality perception by producers, clients and consumers; quality signs (geographic origin, ecolabelling, etc.); translation of quality concepts into products, procedures and services. *Cahiers Options Méditerranéennes* 51, 15–22.

MEA (Millennium Ecosystem Assessment) (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Moity-Maïzi, P. (2006) Artisanes et artisans dans la transformation de poissons au Sénégal. In: Granié, A.M. and Guétat-Bernard, H. (eds) *Empreintes et inventivité des femmes dans le développement rural*. Presses Universitaires du Mirail/IRD, Toulouse, France.

Muchnik, J., Cañada, J.S. and Salcido, G.T. (2008) Les systèmes alimentaires localisées: état des recherches et des perspectives. *Cahiers Agricultures* 17(6), 513–519.

Queffelec, B. (2006) La diversité biologique: outil d'une recomposition du droit international de la nature – l'exemple marin. PhD thesis. Brest University, France.

Sarr, O. and Cormier-Salem, M.C. (2007) Shell's valorisation policy in Saloum (Senegal). In: Promoting local specialities from southern countries. Origin-based products and biodiversity: heritage, territories, governance. Contribution for the International Symposium, 23–28 April 2007, CFEE/EPA/IRD/IDDRI, Addis Ababa.

Schwarz, C. (2002) A Importância das conchas e da sua exploração no grupo de ilhas da Formosa, Nagô e Chediã – Reserva de Biosfera do Arquipélago dos Bijagós. Tiniguena, Bissau, Guinée-Bissau.

Secretariat of the Convention on Biological Diversity (2008) *Access and Benefit-Sharing in Practice: Trends in Partnerships Across Sectors*. CBD Technical Series No 38, Montreal, Canada.

Weigel, J.Y. (2002) *Assessment of The Role of Marine and Coastal Protected Areas as a Vector for Conservation and Economic and Social Development*. IRD (CONSDEV Synthesis/WP1/01), Dakar.

Wessells, C., Cochrane, K., Deere, C., Wallis, P. and Willmann, R. (2001) Product certification and ecolabelling for fisheries sustainability. FAO, Fisheries Technical Paper 422, Rome, Italy.

31 Assessing the Impact of Small-scale Coastal Embankments: a Case Study of an LGED Polder in Bangladesh

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Abstract

Shrimp farming has proved to be a highly profitable agricultural activity compared to rice farming in coastal areas with brackish water. It is, however, widely perceived that shrimp farming has negative effects on socio-economic equity, food security and the environment. In response to the negative perception, the Local Government Engineering Department (LGED) began constructing small-scale polders in the 1990s in the hitherto unprotected coastal region to induce change from a shrimp-based to a rice-based farming system. This chapter assesses the impact of one such polder on agricultural production and the rate of return on investment. It was found that the polder has had little impact on the dry-season rice crop (*boro* rice), which has been spreading in the unprotected areas. The polder has, however, reduced the risk of losses from salt-water intrusion for the monsoon-season rice crop (*aman* rice), which has induced farmers to adopt modern varieties and use chemical fertilizers. The yield of *aman* rice is more than double inside the polder compared to outside the polder. Under the restrictive assumption that the increase in *aman* rice yield is the only benefit of the polder, the rate of return on investment in constructing the polder is estimated at 37%.

Introduction

During the 1960s, the East Pakistan Water and Power Development Authority (EPWAPDA) initiated construction of a number of large-scale polders and embankments in the coastal areas, with the objective of protecting against tidal flooding and saltwater intrusion (World Bank, 2000). Following independence in 1971, a similar policy was taken up by the Bangladesh Water Development Board (BWDB) to protect the environment and promote agricultural development by taking advantage of improved technologies in rice cultivation. These polders provided rice farmers with the necessary infrastructure to improve the productivity of their land through the irrigation and drainage required by modern rice cultivation.

However, not all sections of the coastal regions were covered by the BWDB programme. Because of incomplete construction or exclusion from the planning process, some areas that remained outside the large-scale polders were exposed to saltwater and tidal surges. It was in these areas that export-oriented brackishwater shrimp farming became prominent during the 1980s (Barraclough and Finger-Stich, 1996). In comparison with rice, shrimp farming has proved to be a highly profitable business in Bangladesh, providing substantially higher incomes for shrimp farmers. As the number of shrimp farms (*ghers)* has grown, a perception has arisen that shrimp farming has an overall negative social and environmental impact in Bangladesh (Ito, 2002). The major concerns are: (i) the inflow of urban-based capital to exploit the industry's profitability has led to socio-economic inequity; and (ii) the introduction of saltwater into fields has contributed to soil degradation and threatened forestry and livestock farming, as well as future agricultural production and therefore food security. In addition, agricultural land surrounding a *gher* is often vulnerable to saltwater seepage, rendering the soil unsuitable for crop cultivation and forcing farmers either to sell or to rent their land to the *gher* owner, resulting in social conflict (World Bank, 1999; Rahman, 2000; SRDI, 2001).

The perception of the above negative social and environmental developments has led to intervention by the Local Government Engineering Department (LGED) in the form of the construction of small-scale polders (MoWR, 1999) under the Small-Scale Water Resource Development Project (SSWRDP), particularly in the Khulna Division where about 80% of Bangladeshi shrimp farms are found (Ito, 2002; SRDI, 2003). These small-scale embankments are designed to shift the cropping pattern from a shrimp-based system back to a rice-based system by protecting against saltwater intrusion.

There is a dearth of objective studies on how this type of government intervention affects the livelihoods of households and thus this study addresses this gap by conducting an assessment of the socio-economic impact of such a polder through household-level surveys.

The structure of this chapter is as follows: the next section presents the methodology used for assessing the impact, followed by an examination of the environmental characteristics of the samples in the polder and of those of a control group outside the polder, to test the validity of the methodology using 'with and without' comparisons to assess the impact. The subsequent section compares socio-economic profiles of the survey households. Then follows discussion of the major findings of the impact assessment on the basis of a quantitative analysis of land use, cost and returns of rice-based and shrimp-based systems, income distribution and the livelihoods system. The final section assesses the economic welfare of the sample households based on the respondents' perception of current and previous conditions.

Methodology and Data Collection

The Jethua-Kanaidia FCDI subproject in the Khulna Division of south-western Bangladesh was purposively selected as a representative case of small polders constructed by the LGED. The polder was constructed during 2000–2001, encompassing an area of 1005 ha with a benefited area of 689 ha. The project involved constructing an embankment of 14.13 km, irrigation and drainage canals of 2.89 km and four regulators. The total cost of the polder was Taka19.8 million (US$0.29 million), of which 45% was accounted for by the construction of embankments and canals, which involved mostly earthworks. It was projected that 595 out of 1055 households in the polder command area would benefit from the polder.

The ideal methodology for this study would be comparisons between the 'before and after' situations for both the polder and the control areas ('with–without'), in order to: (i) dissociate autonomous changes that occur over time; and (ii) identify possible differences between the polder and control area before the intervention. However, no pre-project benchmark data were available for either the polder or control areas in this study. Consequently, there was no alternative but to assess the effects of the polder by comparing the two areas during the period of evaluation, that is through 'with–without' comparisons.

An area similar to the polder but not yet protected was selected as the 'control' area for comparisons, in order to assess the changes resulting from the polder. Four villages were purposively selected from each of the 'polder' (inside the polder) and the 'control' areas. The villages were selected to represent different land elevations – one with predominantly high elevation lands, one with predominantly medium elevation lands and two with predominantly low elevation lands. It is in the low-level lands that the polder is supposed to have maximum impact as these are highly exposed to soil salinity when unprotected. The location of the polder and the study area can be seen in Fig. 31.1.

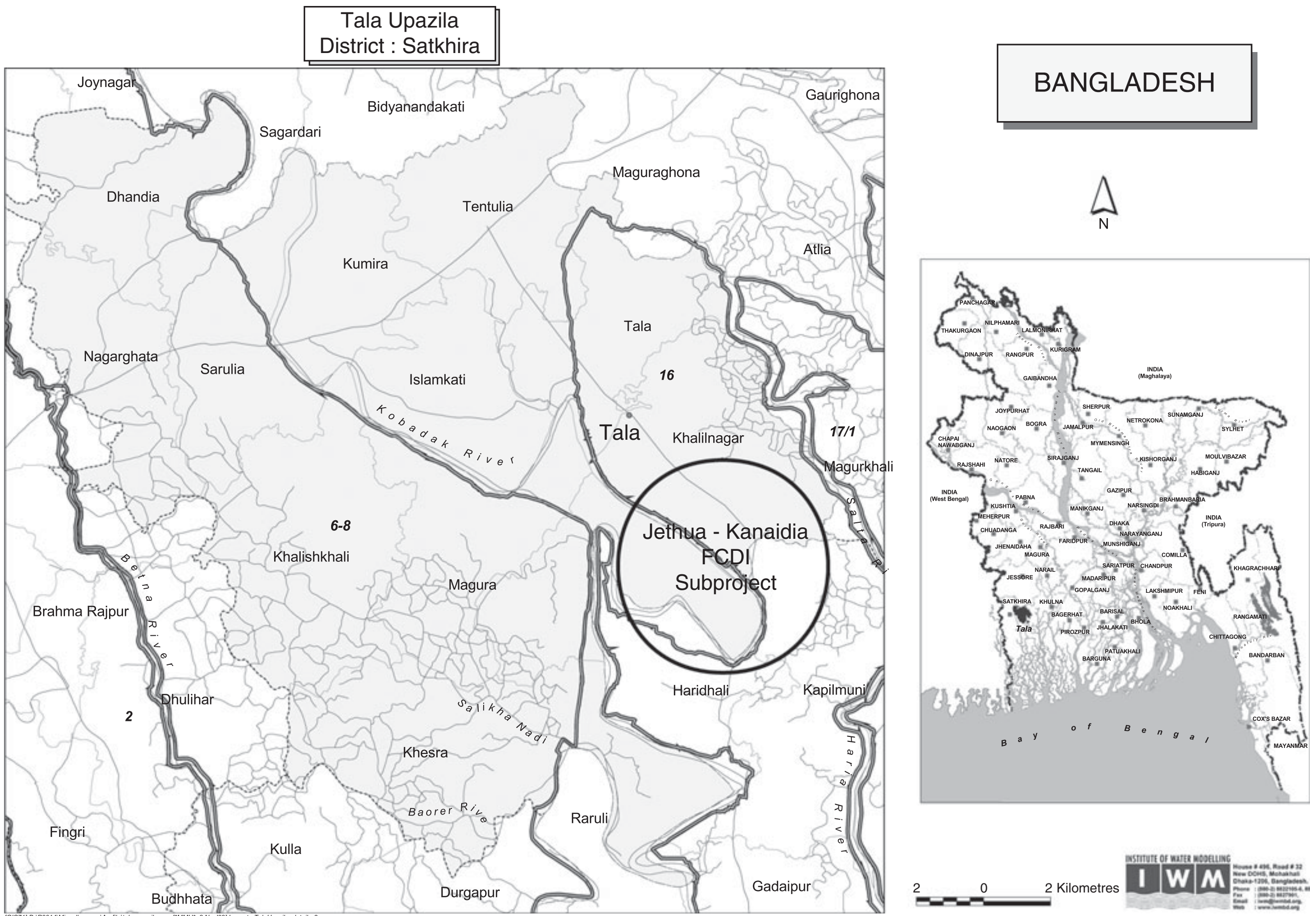

Fig. 31.1. Location of the polder and the study area.

The data in this study are drawn from a sample survey conducted in 2005–2006 using a combination of purposively selected villages and a random selection of households in these villages by stratifying all households by the wealth ranking method.

A census of all households was conducted in the selected villages using participatory rural appraisal (PRA) methods, allowing households to be allocated into 'poor' and 'non-poor' groupings. Based on these wealth classifications, 50 households from each of the eight villages were selected using the proportionate random sampling method. Thus, the sample size should consist of 400 households. However, one household from each area failed to present sufficient information and was excluded from the study. The sample size is therefore 398 households. Details of the selected villages are presented in Table 31.1.

Using a pre-tested structured questionnaire, the selected households were interviewed to generate data on the demographic characteristics of all household members, operations on all owned and rented land used by the households, all non-land assets owned, costs and returns of major crop cultivation, costs of marketing and inputs, employment in non-agricultural activities and incomes of working members derived from these, and the economic standing of the household within the village and changes in its economic conditions as perceived by the respondent. Additional qualitative data were gathered using a PRA methodology through 16 focused group discussions (FGDs) with both 'poor' and 'non-poor' groups in all eight villages in order to ensure an overall understanding of the socio-economic circumstances in the survey area.

As BIDS–IFPRI (1985) point out, the validity of this methodology is critically dependent on the assumption that the polder and control areas are highly similar in the pre-project conditions. Although in practice it was virtually impossible to select a control area similar in all aspects to the polder area before the polder was constructed, a number of factors were compared in order to judge the validity of the selected control area. The findings of the sample survey revealed that the control area had an average farm size of 1.32 acres compared to 0.91 acre in the polder area. Only 35% of the households in the control area were functionally landless, compared to 55% in the polder area. The control villages had a significantly larger proportion of land under clay soil compared to the polder villages. Thus, the control areas have better land endowment and superior quality land and should have higher agricultural incomes on this account. These findings on land endowment indicate that households in the command area of the polder are economically worse-off compared to the households in the control area. So, not all impacts can be assessed accurately through the 'with–without' comparison used in this study.

Results

Land ownership

In both polder and control areas, land was distributed unevenly, with the vast majority of

Table 31.1. Village locations, land elevation and sample size.

Village name	Union	Upazilla	Zilla	Land level	Sample size
Polder					
Char Kanaidia	Jalal Pur	Tala	Satkhira	High	50
Jethua	Jalal Pur	Tala	Satkhira	Medium	49
Krisnakati	Jalal Pur	Tala	Satkhira	Low	50
Kanaidia	Jalal Pur	Tala	Satkhira	Low	50
Control					
Char Gram	Magura	Tala	Satkhira	High	50
Dhaulunda	Magura	Tala	Satkhira	Medium	50
Dohar	Jalal Pur	Tala	Satkhira	Low	50
Gacha	Kalish Khali	Tala	Satkhira	Low	49

Authors' field survey, 2005–2006.

Table 31.2. The distribution pattern of land ownership.

Land ownership group (acres and hectares)	Polder area		Control area	
	Households (%)	Share of land (%)	Households (%)	Share of land (%)
Up to 0.50 acres; up to 0.20 ha	55.8	9.4	35.2	4.7
0.51–1.00 acres; 0.21–0.40 ha	20.1	15.3	18.6	10.7
1.01–2.50 acres; 0.41–1.01 ha	14.1	24.1	31.7	39.9
2.51 acres and above; 1.02 ha and above	10.0	51.2	14.5	44.7
Total	100.0	100.0	100.0	100.0
Average size (acres and hectares)		0.91 acres; 0.37 ha		1.32 acres; 0.53 ha

Field survey, 2005–2006. Pearson's chi-square within polder is 24.52 ($p < = 0.001$).

households possessing little more than a homestead (Table 31.2). The polder area was particularly polarized, with more than 50% of households owning less than half an acre, with a share of less than 10% of the land, whereas the top 10% of households in the land ownership scale owned more than 2.5 acres, controlling 50% of the land. About 20% of households owned between 0.5 and 1 acre, accounting for roughly 15% of the total land, whereas about 14% possessed between 1 and 2.5 acres, about 24% of the landshare. The average land size was 0.91 acres.

Land ownership was less polarized in the control area in comparison to the polder. About 35% of households owned up to 0.50 acres (called 'functionally landless' in Bangladesh) in the control villages compared to 56% in the polder villages. At the other end of the scale, households owning more than 2.5 acres (medium and large landowners) accounted for 15% of all households in the control villages compared to 10% in the polder villages. The average size of land owned was 1.32 acres in the control area, about 50% higher than in the polder villages. The control villages thus have better land endowment and should have higher agricultural incomes on this account.

Demographic characteristics

There were few differences between responding households in both polder and control areas regarding basic age and gender characteristics (Table 31.3). In both areas there were few earning female members, a little over 2% in each. Conversely, the vast majority of male adult members in both polder and control villages were earning. Only 30% of the household members reported earning, indicating a very high dependency ratio. The proportion of school-attending children was higher in the control villages than in the polder, indicating higher economic prosperity in the former compared to the latter.

Agriculture is the main source of livelihood for households both in the polder and control villages (Table 31.4). Crop cultivation accounted for the overwhelming majority of primary occupations in both areas, whereas fisheries accounted for relatively low proportions. In terms of secondary occupations, agricultural labour, business and cottage industries were the most prominent. About 10% of the workforce in the control villages was engaged in aquaculture/fisheries, compared to 2% in the polder villages. Agricultural labour accounted for similar proportions of primary workers in both areas, about 10% in each. Agricultural labour was a secondary occupation for about 20 and 15% of the polder and control workers, respectively. Non-agricultural activities were more predominant as a primary occupation in the polder area, accounting for approximately 40% of the labour force, compared to 31% in the control area. Business was a predominant means of livelihood in the polder area, with

Table 31.3. Basic demographic characteristics by gender.

	Polder		Control	
Characteristic	Male (%)	Female (%)	Male (%)	Female (%)
Overall	50.3	49.7	52.0	48.0
16 years and older	35.7	33.0	36.0	32.7
Earning	31.2	2.3	31.0	2.1
Agriculture	19.0	0.4	24.5	0.5
Non-agriculture	12.2	1.9	7.3	1.6
Not earning	4.5	30.7	5.0	30.6
Up to 15 years	14.6	16.7	16.0	15.4
Student	7.8	11.3	10.6	9.5
Not studying	0.6	0.2	0.2	0.7
Infant (below 5 years)	6.2	5.1	5.2	5.2

Field survey, 2005–2006.

Table 31.4. Distribution of working members by occupation.

	Main occupation		Main + secondary occupation	
Occupation	Polder (%)	Control (%)	Polder (%)	Control (%)
Agriculture	58.0	73.7	94.6	106.9
Crop cultivation	46.9	63.1	62.1	72.5
Fisheries/ aquaculture	0.6	0.6	1.9	9.7
Agricultural labour	10.5	10.0	30.6	24.7
Non-agriculture	42.0	26.3	66.3	47.2
Business	17.5	6.3	26.4	14.7
Service	10.8	9.4	12.4	10.9
Cottage industry	8.3	6.3	21.3	15.0
Non-agricultural labour	5.4	4.3	8.9	6.6
Total	100.0	100.0	160.9	153.4

Authors' field survey, 2005–2006.

17% of the workers reporting it as a primary occupation, whereas the figures for service and cottage industries were approximately 10 and 8%, respectively.

The physical environment

Irrigation infrastructure

Shallow tube wells (STWs) were the main sources of irrigation water, whereas deep tube wells (DTWs) and traditional sources were rarely used in both the polder and control areas. Low lift pumps (LLPs) were used to a small extent. STWs were more prevalent in the polder than in the control area, a difference of almost 10 percentage points, because of a lower level of salinity in the polder area resulting in a high level of non-saltwater available at shallow depths. This is considered to be a major impact of the embankment. The point to note, however, is that even in the absence of the polder, farmers in the locality are going for the installation of STWs for the cultivation of *boro* rice in the dry season. During the *aman* rice season, rainfall was a more widespread source of water in the control area, a difference of 9 percentage points from the polder land. This shows that with the larger availability of STWs, some farmers go for supplementary irrigation for the *aman* rice crop.

Soil salinity

Overall salinity levels were perceived by farmers to be higher in the control area than in the polder. This was expected because of salinity protection from the polder embankment. The land distribution in both areas was skewed negatively towards the lower salinity levels, the concentrations being mild and non-saline; however, the proportions were greater in the polder area in terms of the least saline classifications (Table 31.5). About 43% of the polder area was classified as non-saline compared to 34% of the control villages. Lands suffering from high salinity levels were rare in both the polder and control area.

Depth of flooding

Table 31.6 shows the distribution of land by flooding depth during the last monsoon season. Although there existed low-lying land in both polder and control areas and there was flooding to varying degrees, the polder did give households in the polder area more protection against flooding than those in the control area outside the polder. The distribution of polder land was skewed towards lower levels of flooding, whereas the situation in the control area was less skewed. About 42% of the land in the polder area was not flooded at all, whereas the corresponding figure in the control area was 10 percentage points lower. A further 43% of the polder area was flooded up to 0.5 m, whereas approximately 38% of the control land was flooded to this level. The proportion of land flooded between 50 and 100 cm in the polder area was half that in the control area.

Table 31.5. Distribution of land by level of salinity: farmers' perceptions.

Salinity level	Polder area (%)	Control area (%)
Non-saline (< 2.0 dS/m)[a]	42.8	33.6
Mild saline (2.1–4.0 dS/m)	49.8	55.1
Moderate saline (4.1–8.0 dS/m)	7.0	9.6
High saline (8.1–12.0 dS/m)	0.4	1.7
Total	100.0	100.0

Field survey, 2005–2006; [a]SRDI (2000) soil salinity classification.

Table 31.6. Distribution of land by depth of flooding: farmers' perception.

Flooding level	Polder area (%)	Control area (%)
Not flooded	41.9	32.1
Up to 50 cm	43.4	37.7
50–100 cm	14.3	29.6
Over 100 cm	0.4	0.7
Total	100.0	100.0

Field survey, 2005–2006.

Cultivation practices

The polder was constructed to shift cultivation away from shrimp and back towards rice by creating a rice-friendly environment inside with the aim of producing higher yields from rice farming. This appears to have been achieved to a certain extent. The vast majority of shrimp farms were located outside the polder rather than inside the polder area. However, it was found that land was used more intensively for crop cultivation in the unprotected area, whereas the reverse was expected. It should be noted that when referring to *ghers,* these are used to cultivate brackishwater shrimp in the control area, whereas in the polder area they are used for the farming of freshwater prawns.

Farm households accounted for 77% of the total in both polder and control areas, despite the expectation of a higher proportion of rice farmers in the polder. The average farm size was found to be larger in the control area, a difference of about 0.1 ha compared to that of the polder area (Table 31.7). This is the outcome of the larger endowment of land in the control villages, as noted earlier.

The average size of a rice-cultivating area was notably higher in the control area (0.56 ha) compared to the polder area (0.35 ha). The difference is statistically highly significant. The area allocated to rice cultivation is also substantially higher in the control area and the difference is statistically significant. Non-rice crop cultivation was conducted on similar sizes of land in both areas, about 0.15 ha in each. In terms of proportion, a larger percentage of land area was devoted to high-value non-rice crops in the polder area compared to the control area; a positive effect of the polder. The area used for a shrimp/prawn–rice cropping

Table 31.7. Farm size, land use and cropping intensity.

	Polder		Control	
Area/percentage	Mean	SE	Mean	SE
Farm households (%)	77		77	
Rented holdings (%)	30		27	
Average farm size (ha)	0.36	0.03	0.47	0.03
Average rice area (ha)	0.36	0.03	0.56	0.05
Average non-rice area (ha)	0.16	0.02	0.15	0.02
Average shrimp/prawn–rice area (ha)	0.02	0.00	0.13	0.01
Total cropped land (ha)	0.52	0.04	0.84	0.05
Cropping intensity (%)	144	3.80	179	6.31

Field survey, 2005–2006.

system was insignificant in the polder area but substantial in the control area.

It was expected that the incidence of crop cultivation and the cropping intensity would be higher in the polder area. The survey data, however, show both were considerably higher in the control area (Table 31.7). Total cropped land per farm was more than 0.5 ha in the polder area, whereas the equivalent in the control area was 0.85 ha. The difference in cropped land per farm household is highly statistically significant. Cropping intensity in the control area was about 180%, whereas the corresponding polder figure was 144%. Despite higher salinity, more land was used seasonally for crop cultivation in the control area than in the polder area.

As expected, shrimp/prawn cultivation was more prevalent in the unprotected area in all aspects. The proportion of households engaged in shrimp farming in the control area, about 21%, was more than five times higher than the corresponding polder value of about 4% (Table 31.8). The average *gher* size was also comparatively higher in the control area, a statistically significant difference of more than 0.2 ha, indicating shrimp farming on a considerably larger scale outside the polder. As expected, a far greater proportion of *ghers* were on rented land in the control area, as large-scale shrimp production was perceived as being more productive and therefore required a higher quantity of land, which was usually rented.

Close to 30% of control households were engaged in rice–shrimp/prawn cropping systems, whereas the polder involvement was marginal, with a corresponding proportion of less than 3%. Consequently, the proportion of farmland used for this system was about 3% in the polder area, compared to roughly 24% in the control area. It appears then that the polder has induced agricultural practices more towards rice-based systems than shrimp-based systems.

Table 31.8. Engagement in shrimp/prawn farming.

Area/percentage	Polder	Control
Households engaged (%)	3.5	21.1
Average size of *gher* (ha)	0.67	0.91
Shrimp/prawn farms rented (%)	57	88
Farm households practising rice–shrimp system (%)	2.6	29.2
Rice–shrimp/prawn area as per cent of farmland	3.1	23.7

Field survey, 2005–2006.

Costs and returns

Aman rice produced considerably greater returns in the polder area than in the control area. This was more so in the lowland areas where the embankment was expected to have the greatest impact, indicating more favourable conditions overall for rice in the polder area, particularly during the wet season.

The yield of *aman* (wet season) rice was higher in the polder area in lowland areas than in areas that were supposed to be affected by the polder. There was a difference of 1.76 t/ha between the polder and the control areas, and the difference was statistically highly significant (Table 31.9). It appears that with the polder controlling high flooding, the farmers in the polder could grow high-yielding *aman* rice varieties, whereas farmers in the control villages had no option but to cultivate traditional low-yielding varieties on such land. Costs overall were higher in the polder area. Labour, the majority of which was hired, was the highest expense all round. Family income and operating surplus were higher in the polder area compared to the control area, by about Tk10,300/ha, despite the higher overall costs. This was a result of the higher yields and resulting higher gross values. The higher income in the polder is statistically significant.

Boro rice cultivation has spread widely in the polder area because of the installation of shallow tube wells after the construction of the polder, which help control salinity. But, the study noted that groundwater irrigation with shallow tube wells had also taken place outside the polder. So, even without the polder, *boro* rice cultivation could have spread in the area. In the lowland areas that were most suitable for *boro* rice cultivation, the yield in the control area was nearly 0.5 t higher per hectare than in the polder area (Table 31.9). The higher yield in the control area may be a result of better soil fertility from the regular deposit of silt from flooding, which the polder area is deprived of because of the polder.

Boro rice is a high-input intensive crop compared to *aman* rice, requiring a large investment in irrigation as well as in chemical fertilizers. The cost of production per hectare in *boro* rice cultivation was almost double that of *aman* rice cultivation (Table 31.9). So, despite the substantially higher yield for *boro* rice, the net return per hectare for *boro* rice was almost the same as for *aman* rice. The net return was higher in the control area than in the polder area for the low land. It appears then that the polder did not have any positive impact on dry-season rice cultivation or on farmers' income from this source.

Because of higher salinity levels, it was expected that shrimp cultivation would be practised extensively, with higher productivity and profits, in the unprotected area. Given high prices and low mortality, the fisheries business can be immensely profitable, especially in unprotected areas. However, the net returns for shrimp/prawn/fish in both polder and control areas were almost the same as for *boro* rice, the main alternative for dry-season cultivation (Table 31.10). It appears that given the current production conditions (higher virus infestation and mortality) for shrimp/fish cultivation in both areas, the farmer should show no preference between *boro* rice cultivation and shrimp farming.

Table 31.9. Costs and returns in rice cultivation in low land (in Taka).

	Aman rice (wet season)				*Boro* rice (dry season)			
	Polder		Control		Polder		Control	
Costs/returns	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Returns								
Yield (t/ha)	3.15	0.25	1.39	0.26	4.47	0.24	4.92	0.15
Gross value (Tk/ha)	32,419	2,438	19,738	3,968	42,684	2,965	47,453	1,494
Costs	13,496	854	11,315	804	26,172	1,670	22,890	870
Inputs	4,443	289	3,584	412	15,715	828	14,673	746
Machine and animal power	1,784	177	1,779	124	2,333	271	1,616	91
Irrigation	Nil		Nil		8,122	688	7,393	674
Labour	7,269	620	5,952	513	8,124	968	6,601	320
(Hired)	(5,194)	441	(4,012)	597	(5,434)	723	(4,477)	395
Paid out cost	11,421	640	9,375	871	23,482	1,131	20,766	923
Operating surplus	18,923	2,592	8,422	3,715	16,512	2,843	24,563	1,524
Family income	20,998	2,553	10,363	3,788	19,202	2,796	26,687	1,527

Field survey, 2005–2006.

Table 31.10. Costs and returns in shrimp cultivation: polder versus control area (Taka/ha).

	Polder		Control	
Costs/returns	Mean	SE	Mean	SE
Returns				
Shrimp/prawn yield (kg/ha)	92	15	131	11
Fish yield (kg/ha)	217	47	236	25
Gross value	43,501	5,503	55,371	4,323
Costs				
Fingerlings	12,203	4,149	23,652	2,169
Fertilizers	1,219	314	1,632	403
Feed	3,613	4,149	2,376	2,169
Harvesting	354	127	635	155
Total cost	29,815	9,014	37,407	3,559
Net returns	13,686	4,120	17,964	2,595

Field survey, 2005–2006

Both the shrimp/prawn and fish yields per hectare were higher in the control area, which would be expected. The shrimp/prawns account for most of the gross value from aquaculture because they fetch a much higher price in the market than other fish harvested from fishponds. The gross value of production in the control area was just over Tk55,000, approximately Tk12,000 higher than the equivalent figure for the polder area, and the difference was statistically significant (Table 31.10). Fingerlings were the major expense in terms of production costs in both areas. They amounted to about Tk23,000 in the control area, more than double the corresponding amount for the polder area. As a result, overall costs were higher in the control area. The net income in the polder area was about Tk4200 lower than that in the control area of Tk18,000, but the difference was not statistically significant.

Wage rates and wage earnings

Wage rates and wage earnings are important indicators of the polder's impact on landless households who derive their livelihoods from participation in the labour market. It appears that in terms of highland areas, the polder has had little positive impact on either wage rate or wage payment. The reverse is true of the lowland areas. As the latter are impacted most by the embankment, this trend is to be expected.

In the dry season, the daily wage rate in the highland polder area was Tk56, lower than the rate of Tk60 found in the control area (Table 31.11). A similar disparity was observed during the wet season, the wage rate per day's work was found to be higher by Tk5 in the control area compared to the polder area.

The total wage bill paid by farmers per hectare of land was also considerably lower (Tk1000) in the polder area than in the control area in the upland areas, which were not supposed to be affected by the polder. The patterns in wage rate and payments in lowland areas were found to be opposite to those observed in the high land. The daily wage rate in the polder area during the dry season was Tk55, over Tk10 higher than in the control area. A similar situation occurred during the wet season, although the disparity was slightly lower. Wage payment per hectare was considerably higher in the polder area during both dry and wet seasons, around Tk1000 higher than the corresponding values in the control areas.

Income disparity

Expectations were that per capita income would be distributed more evenly in the polder area than in the control villages. It was predicted that wealthier households, as well as entrepreneurial outsiders, would exploit the perceived profitability of shrimp farming without any benefit passing to the poor. However, contrary to these

Table 31.11. Impact of polder on wage rate, wage payments.

	Wage rate (Taka/day)		Wage payment (Taka/ha)	
	Polder	Control	Polder	Control
Dry season				
High land	56	60	3871	4727
Low land	55	44	5194	4012
Wet season				
High land	46	61	4530	5631
Low land	56	48	5434	4478

Field survey, 2005–2006.

expectations, it was found that, overall, household income was distributed similarly in both areas. The concentration of income as measured by the Gini coefficient was the same for both polder and control villages (Table 31.12).

The largest difference in income distribution was in terms of rice income. In the polder area, there was double the concentration of wealth among the top 10% of households than in the control area. Conversely, the proportion of income held by the bottom 40% in the polder area was about half that of the corresponding control value. As a result, the Gini coefficient was considerably higher in the polder area.

The distribution of income from shrimp/aquaculture activities was similar overall in both polder and control areas. There was a higher concentration of income among the top 10% of households in the control area; the reverse was true in terms of the middle 40%.

Self-assessment of poverty

In general, a higher proportion of households perceived themselves to be poor in the polder area than in the control area. This is expected in view of the lower land endowments and larger proportion of landless households in the polder villages compared to those for the control area.

The proportion of households who considered themselves poor was virtually the same in both areas; however, a substantially higher percentage of households considered themselves very poor in the polder area. Thus, the main difference in poverty levels between the two areas was that for the poorest, who were more numerous in the polder area (Table 31.13). This would be expected, given the higher proportion of landless households in the polder area.

Changes in economic conditions

Both polder and control areas have experienced a positive net change in economic conditions over the past 10 years. The net change in the economic position of households was higher in the former, a difference of 11.3 percentage points (Table 31.14). However, the result of the Pearson chi-square test indicates that these changes are statistically non-significant. The proportion of households who judged their welfare to have deteriorated was similar, about

Table 31.12. Distribution of household income: polder versus control (percentage share of income).

Household rank in per capita income scale	Rice income		Fish income		Agricultural income		Household income	
	Polder	Control	Polder	Control	Polder	Control	Polder	Control
Bottom 40%	12.9	23.2	18.2	13.5	13.2	11.6	15.2	16.3
Middle 40%	47.2	45.8	39.8	47.6	40.5	34.3	39.6	39.3
Ninth decile	18.0	18.2	6.4	14.6	21.0	17.8	17.6	16.4
Top 10%	22.9	12.7	35.6	24.2	25.3	36.2	27.6	28.0
Gini coefficient	0.35	0.25	0.38	0.37	0.41	0.49	0.39	0.39

Field survey, 2005–2006.

Table 31.13. Economic status of households: self-perception.

Economic status	Polder area households (%)	Control area households (%)
Solvent	11.1	9.0
Self-sufficient	42.7	54.8
Poor	29.6	30.2
Very Poor	16.6	6.0
Total	100.0	100.0

Field survey, 2005–2006.

30% in both areas, suggesting the polder has had little effect on preventing worsening economic conditions. About half of the polder households and approximately 37% of the control households experienced an improvement in economic conditions, which might suggest the polder had a positive effect, although there was no certainty that the polder was responsible. The percentage of households whose economic position has not changed over the past 10 years is 19.6 and 34.7 in the polder and control areas, respectively (Table 31.14).

Discussions of the Polder's Impact

Impact on rice production

Achieving and sustaining food security is a key challenge for Bangladesh. The country has done well in increasing rice production since the late 1980s as a result of the expansion of groundwater irrigation, which facilitated the adoption of modern high-yielding varieties. These varieties now cover over 70% of the rice area, and there is limited scope for further expansion. However, the population is still growing at two million every year, almost the same level of increase as at the time of independence in 1971. The small-scale water management polders aim to address this challenge by expanding the area under irrigation, drainage and salinity control, thereby encouraging farmers to extend the area under improved high-yielding rice varieties further. One of the key objectives of the polder under review is to increase rice production by inducing a shift from a shrimp-based to a rice-based farming system.

The polder document reports an estimated cereal production at 2456 t at the time of the construction of the polder. From the data obtained from the survey, we estimate rice production for the command area (689 ha) at 2170 t and *boro* rice production (about 44% of the area was under *boro* rice) at 1354 t. Thus, as a result of the implementation of the polder, total rice production has increased to 3524 t/year, which is 44% higher than the benchmark level. Besides contributing to food security at the household level in the locality, this additional production has saved the country valuable foreign exchange by reducing the need to import. The value of the additional production at the import-parity price is about US$195,000.

Rate of return on investment in the polder

What has been the rate of return on investment made in the polder? As noted earlier, the main benefit of the polder appears to be reducing the risk of rice cultivation in the wet season, which has encouraged farmers to adopt modern varieties. Although there has been a substantial expansion of the area under *boro* rice cultivation during the dry season, it would be improper to attribute this change to the polder. As noted from the findings reported earlier, *boro* rice production has also expanded in the control villages at almost the same rate,

Table 31.14. Changes in economic conditions: self-perception.

Economic change	Polder area (%)	Control area (%)	Total (%)
Improved	49.7	36.5	48.1
Same	19.6	34.7	22.2
Deteriorated	30.7	28.8	29.7
Net Change	19.0	7.7	18.4

Pearson's chi-square within the polder area is 2.259 ($p = 0.47$).
Field survey, 2005–2006.

even in the absence of the polder. The main impact of the polder has been on *aman* rice cultivation in the wet season in terms of the adoption of modern varieties because of reduced flooding, which has contributed to substantial yield increases.

The difference in net family income from *aman* rice cultivation between the polder and the control areas is estimated from the survey to be Tk10,635/ha, which we assume represents the financial return of the polder. For estimation of the economic benefit, we need to take into account the market distortions resulting from taxes and subsidies. We assume, on the basis of the available information, a subsidy on fertilizer at 25% of the market price, a shadow wage rate of 90% of the market wage and the border price of rice (import-parity price) 5% higher than the market price. On the basis of these assumptions, the economic return is estimated to be Tk11,654/ha. We also assume (personal communication with LGED officials) a yearly operating and maintenance and depreciation charge of 7.5% of the investment on embankments and canals and 2.5% of the investment on regulators, which is deducted from the benefits estimated above. We also assume a 2-year investment phase, a 20-year life of the polder and a discount rate of 10%/year.

On the basis of these assumptions, the benefit–cost ratio of the polder is estimated at 3.75. The internal rate of return (the discount rate at which the net benefit is equal to the cost) is estimated at 38% at prevailing market prices and 41% at economic prices. Thus, the polder has yielded a high return on investment, even under a conservative assumption of the polder having no effect on *boro* rice cultivation.

The polder has also induced a shift from a shrimp-based system to a rice-based system in the low-lying areas. This has not only contributed to an increase in rice production, but has also halted the long-term negative effect of shrimp farming on the build-up of soil salinity and on livestock and forestry cultivation. We also note that with reduced flooding and overflowing of the water across privately owned parcels of land during the wet season, the farmers in the polder have started practising rice–fish and rice–prawn mixed farming in the polder. With the diffusion of the system in the future, the polder will bring additional benefit.

Conclusions

The primary aim of the LGED polder was to protect agricultural land from salinity intrusion and tidal flooding in order to protect the environment and facilitate a change from shrimp to rice cultivation during the dry season. This study found that this shift in farming practices occurred in the protected area, but was also taking place in the control area, without protection from the embankment. Earlier, brackishwater shrimp proved immensely profitable in salinity-exposed areas, especially in comparison with returns on the alternative rice–fallow system for the low-lying land. However, recent falls in shrimp prices, in addition to higher mortality rates, and the experience of *boro* rice cultivation with groundwater irrigation have led to a change in the system from shrimp farming to *boro* rice cultivation for such land. The use of non-saline groundwater for irrigation in an otherwise relatively high saline area, which allowed the cultivation of high-yielding varieties (HYVs) in the dry season in large parts of Tala, was reported as a major factor for economic improvement by an equal proportion of households in both the polder and the control areas.

The main impact of the polder has been on rice cultivation during the wet season, providing improved control over irrigation and the opportunity to cultivate *aman* rice HYVs through salinity protection. Indeed, during the wet season, the difference between polder and control rice yields was substantial, particularly in the lowland areas where the yield per hectare in the protected area was more than double that in the unprotected villages. As a result, both operating surplus and family income were over 100% higher in the polder villages compared to the control area. The polder also provided the opportunity for fish and prawn farming in extreme lowlands through flood control and salinity protection, cultivation practices not found in the control area. In *boro* rice cultivation, the polder also reduces the risk from the intrusion of saltwater during high tides late in the dry season. The total rice production has increased by 44% compared to the benchmark level. On the basis of net gains estimated for the wet season, the benefit–cost ratio of the polder is estimated at 3.75 and the internal rate of return at 38%. The benefit has, however, accrued more to the land-owning households than the land-poor, leading to an increase in inequality in the distribution of rice income.

It is felt that polders such as those assessed in this study would have the greatest impact in areas where high salinity levels are found, even in the groundwater, preventing any possibility of *boro* rice cultivation. Households in such areas have no choice but to leave their land fallow or to farm brackish-water fish and shrimp during the dry season – a practice that appears to produce diminishing returns and is perceived to be environmentally unsustainable.

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References

Barraclough, S. and Finger-Stich, A. (1996) *Some Ecological and Social Implications of Commercial Shrimp Farming in Asia*. Discussion Paper 74. United Nations Research Institute for Social Development (UNRISD), Geneva.

BIDS–IFPRI (Bangladesh Institute of Development Studies and the International Food Policy Research Institute) (1985) *Technical Papers: Development Impact of the Food-for-Work Program in Bangladesh*. Dhaka and Washington, DC.

Ito, S. (2002) From rice to prawns: economic transformation and agrarian structure in rural Bangladesh. *Journal of Peasant Studies* 29(2), 47–70.

MoWR (Ministry of Water Resources) (1999) *National Water Policy*. Ministry of Water Resources, Dhaka.

Rahman, M.S. (2000) *Consultancy Report on Coastal Agriculture*. Bangladesh Agricultural Research Institute, Gaizpur, Bangladesh.

SRDI (Soil Resource Development Institute) (2000) *Soil Salinity Map of Bangladesh*. Ministry of Agriculture, Dhaka.

SRDI (Soil Resource Development Institute) (2001) *Soil and Water Salinity in the Coastal Area of Bangladesh*. Ministry of Agriculture, Dhaka.

SRDI (Soil Resource Development Institute) (2003) *Soil Salinity in Bangladesh*. Ministry of Agriculture, Dhaka.

World Bank (1999) *Project Appraisal Document on a Proposed Credit in the Amount of SDR20.6 Million (US$28.0 Million Equivalent) and a GEF Grant in the Amount of SDR3.7 Million (US$5.0 Million Equivalent) to the People's Republic of Bangladesh for a Fourth Fisheries Project*. World Bank, Washington, DC.

World Bank (2000) *Bangladesh – Climate Change and Sustainable Development*. World Bank, Washington, DC.

32 Dynamics of Livelihoods and Resource Use Strategies in Different Ecosystems of the Coastal Zones of Bac Lieu Province, Vietnam

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Abstract

The coastal areas in Bac Lieu Province of the Mekong Delta have undergone rapid changes in environmental and socio-economic conditions since the early 1990s when a saltwater control project was established to promote food crop production in the traditional rice–saltwater-based farming areas. A series of coastal embankments and tidal sluices was constructed gradually to control saltwater intrusion, which was used subsequently to regulate fresh and salt water in order to facilitate saltwater aquaculture. Household land and water use have evolved with the levels and intensity of these water management interventions. This study uses the Sustainable Livelihoods Framework to assess the resource base at the household level and the livelihoods strategies and outcomes for six villages representative of the four different ecosystems in Bac Lieu Province. The ecosystems were distinguished by the scale and timeframe of the water management intervention. The 'early intervention zone' is characterized by alluvial soil types, with the water and environment having been changed from a brackish to a freshwater ecology prior to 1998, providing stability after the transition had been completed. The 'recent intervention zone' has large areas of acid sulfate soils, with the water and environment having been changed to a freshwater ecology after 1998. However, since 2002 most areas of this zone have been converted back to a brackishwater system. The 'marginal intervention zone' is not affected much by the closure of sluices. The 'no intervention zone' located to the south of the embankment has not been affected by the sluice system and was under salt water throughout the survey period. A panel data set generated from household surveys conducted on the selected hamlets in all the intervention zones was used for this study. A baseline survey was first conducted in 2000 and repeat surveys of the sample households were conducted in 2003 and 2007, including the households of the baseline survey plus an additional sample to assess changes in land use and livelihood systems. A data set from household surveys conducted in the control zone – no water management intervention – in 2003 and 2007 was used for comparative analysis. The study noted that the dynamics of livelihoods resulted from changes in resource use and productivity. Land use intensity by double and triple cropping and productivity of rice had increased in the early intervention zone, where freshwater and soil conditions prevailed. Variation among paddy yields was reduced gradually. Shifting from rice–shrimp to shrimp and back to rice–shrimp systems was observed in the marginal intervention zone, where less variability of shrimp farming was also noted. Extensive shrimp culture under rice–shrimp systems had much higher benefit–cost ratios compared with mono shrimp culture in the recent and no intervention zones. The most drastic changes in land use and also in the livelihood outcomes were observed in the recent intervention zones in the period of analysis. As a result of the saltwater control regimes, farming systems in this zone shifted from saltwater based on rice–aquaculture systems to intensive rice, and then shifted to saltwater shrimp farming. High variability in the profitability of shrimp and, as a result, in livelihoods was also noted in this zone.

Introduction

The study covers an area of 245,000 ha in Bac Lieu Province of the Ca Mau Peninsula of Vietnam. The region has experienced rapid environmental and socio-economic change, particularly since the 1990s, when the policy to expand rice production was introduced. To increase agricultural production, a series of sluices was constructed progressively from 1994 to 2000 from the east to the west to control salinity intrusion (Tuong *et al.*, 2003). As a result, the canal water became fresh, as indicated by the retreat of the isohalines from the east to the west. In the protected area, the duration of freshwater conditions was extended in line with the policy to promote double or triple cropping of rice. However, as the freshwater zone spread gradually westward, the local economy underwent rapid change. The profitability of the rice-based cropping systems declined at the same time that aquaculture was experiencing a dramatic boom fuelled by technical innovations and the high local and export price of tiger shrimp (*Penaeus monodon*). Traditional extensive systems of shrimp production based on the natural recruitment of shrimp larvae were being replaced by semi-intensive monoculture production systems (Hoanh *et al.*, 2003). By 1998, tiger shrimp culture was widespread in the western part of the project area.

When the supply of brackishwater required for shrimp production was cut off, many farmers were forced to abandon aquaculture and to convert to less profitable rice farming. Some shrimp farmers resisted and attempted to maintain favourable conditions by blocking secondary canals and pumping brackishwater into their fields, but this created conflicts with rice farmers, who depended on fresh water to irrigate their fields. The conflict reached a peak in February 2001 when shrimp farmers destroyed a major dam to let salt water flow into the region. This event prompted the government to re-examine the original policy emphasizing rice production and to explore alternative land use plans that would accommodate shrimp cultivation in the western part and at the same time maintain the areas of intensive rice production in the eastern part.

Salinity control has thus been the key intervention in changing production systems. The dynamic nature of these changes and interventions has meant that households have had to respond rapidly and devise livelihood strategies to minimize their vulnerability to these changes and maximize their livelihood outcomes. An assessment of the social and environmental impact of the change in water management in the project area was presented by Gowing *et al.* (2006). The effects of the water management policy intervention on the livelihoods of the people in the area were analysed by Hossain *et al.* (2006) using the extensive survey of the households selected in 2000. The assessment of the impact of these changes on farmers' livelihoods and farmers' resource-use strategies has involved surveys conducted at representative sites with representative households. This chapter provides an extension of the analysis by Hossain *et al.* by focusing on the dynamic aspects of the change in the period 2000–2006 at the project areas.

This chapter assesses the change in livelihoods and resource use at the household level and the livelihood strategies and outcomes for six villages representative of the different ecosystems in Bac Lieu Province. The analysis extends and supplements the study by Hossain *et al.* (2006) by using the panel data set generated from household surveys conducted in selected hamlets. A baseline survey was conducted in 2000 and repeat surveys were conducted in 2003 and 2007 on the same set of sample households to assess changes in land use and livelihood systems. The survey households in 2003 and 2007 included the households of the baseline and additional sample households from the same set of villages.

Methodology

The Sustainable Livelihoods Framework (Chambers and Conway, 1992; Carney, 1998; Dearden *et al.*, 2002) was used as the framework for the study. A livelihood constitutes the capacities, assets (including both material and social resources) and activities needed for a means of living. Livelihoods are sustainable when they are resilient in the face of external shocks and stresses, are not dependent on external support, maintain the long-term productivity of natural resources and do not compromise the livelihood options of others (Hossain *et al.*, 2006). The framework was used to study the change in the livelihood systems and dynamics of poverty in the same area of the study by Hossain *et al.* (2006). This study extends the scope of time by using the panel data generated from repeated surveys of the same set of households in selected villages three times: in 2000, 2003 and 2006. A structured questionnaire was used to elicit household information on livelihoods.

Household physical capacity was represented by land ownership and size of landholding, value and access to assets such as TV, radio, rowing boat, motorboat and tiller/pump/thresher. Human capital was represented by the number of workers available per household, age of the household head (HH) and main occupation of the HH.

Resource use and change were measured by cropping patterns, crop production, aquaculture production (shrimp and other), capture fisheries' catch and seasonality, including destination of catch (home consumption or sale).

Livelihood system dynamics and strategies were represented as changes in total household income; contribution to total household income from rice, shrimp, other aquaculture, livestock, employment, capture fisheries; and remittances from relatives and other funds.

Sampling and samples

Definition of ecosystems in study region

The study region covers an area of 245,000 ha in Bac Lieu Province of Ca Mau Peninsula of Vietnam (Fig. 32.1).

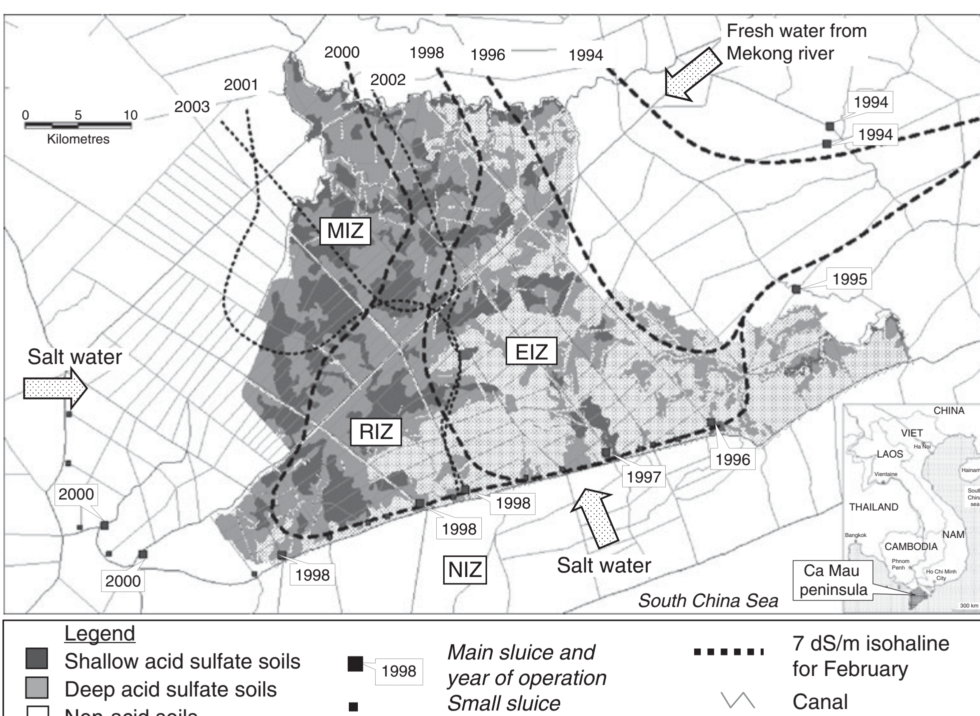

Fig. 32.1. Study area showing extent of saline intrusion at different stages of the project development. Gowing *et al.* (2006).

Based on the soil types and the time since the canal water became fresh water, the project area can be classified into four zones (Hossain *et al.*, 2006):

ZONE 1: in the east of the project site (east of the 1998 isohaline), is characterized by alluvial soil types, with the water and environment changed from a brackishwater to a freshwater ecology prior to 1998. This zone was referred to as the 'early intervention zone' (EIZ), representing a situation of stability once the transition from brackishwater system to freshwater system was complete.

ZONE 2: lies in the middle section of the study area, between the 1998 and the 2000 isohalines. Large areas of the zone have acid sulfate soils. The water and environment changed to a freshwater ecology after 1998 but before 2000. However, by 2002, most of the areas of this zone had converted back to brackishwater shrimp culture. This zone is referred to as the 'recent intervention zone' (RIZ).

ZONE 3: lies to the west and north of the 2000 isohaline. This area is not affected much by the closure of sluices because salt water can flow throughout the area from the West Sea when the sluice system is closed. This zone is referred to as the 'marginal intervention zone' (MIZ).

ZONE 4: lies to the south of the embankment and is not affected by the sluice system. All areas of this zone had salt water throughout the survey period. This zone is referred to as the 'no intervention zone' (NIZ).

Using this typology, repeated surveys in 2000, 2003 and 2006 on the same set of households in the four ecology zones gathered information on the socio-economic conditions of households before and after the reversal of the salinity management strategy. The first household survey, conducted in 2000, covered 250 households in six designated villages in the EIZ, RIZ and MIZ. Households were stratified into one of four different wealth or stakeholder groups based on the results of a participatory wealth-ranking exercise (Gallop *et al.*, 2004). These stakeholder groups were very poor, poor, average and rich. The very poor and poor groups in the 2000 sample were merged and designated as the poor group. This social stratification was not repeated in the follow-up surveys as the definitions could well have changed during the project period, thus making it difficult to compare livelihood outcomes for the stakeholder groups in 2000 and 2003 in terms of participatory wealth ranking.

The second household survey of 2003 involved 335 households, including the original 250 households in the selected villages of the first survey and 100 households in the NIZ. The third round survey in 2007 included all 250 households covered in the 2000 and the 2003 surveys and 100 households covered in the 2003 survey in the NIZ. Table 32.1 shows the breakdown of the households surveyed in each year.

Table 32.1. Household surveys in 2000, 2003 and 2006.

Name of village	Type of village	Abbreviated zone names	Number of households			Wealth categories of sample households in 2000 survey		
			2000	2003	2006	Poor	Average	Rich
Minh Dieu	Early intervention	EIZ	50	60	50	17	21	12
Ninh Quoi	Early intervention	EIZ	50	57	50	21	20	9
Phong Thanh Tay	Recent intervention	RIZ	25	61	25	9	10	6
Phong Thanh	Recent intervention	RIZ	75	104	75	29	28	18
Ninh Thanh Loi	Marginal intervention	MIZ	25	53	25	11	10	4
Vinh Loc	Marginal intervention	MIZ	25		25	8	10	7
Vinh My A	No intervention	NIZ		51	51			
An Trach	No intervention	NIZ		49	49			
Total			250	435	350	95	99	56

Results

Livelihood capacity and assets

Human capital was the predominant asset in the area. The average household size was 5.1 persons. The household size varied very little across the different zones and time periods from 2000 to 2006 (Table 32.2). The quality of human capital in terms of educational attainment of the workers was low. The average of schooling years for the HH was 4.9. The education level of the HH did not differ noticeably between the intervention zones.

The average size of land owned by the household was much higher in the MIZ than in other zones. Since the villages in the MIZ were settled more recently and were less populated than villages found in other zones, households in this zone had much larger land holdings. The average size of land of the sample households in the EIZ was 1.03 ha compared with 2.11 ha in the MIZ, 1.51 ha in the RIZ and 1.46 ha in the NIZ (Table 32.2). About one in every ten households bought or sold land during the survey period 2000–2006. The frequency of land transactions was lower in the EIZ than in the other zones.

Physical capital measured by the total value of agricultural and non-agricultural assets of the households showed an increasing trend of asset accumulation. Although starting from a relatively lower base, the households in the EIZ had the highest asset accumulation rate. The average asset value of households increased from US$297 in 2000 to US$457 in 2006 (a 50% increase). Compared to the base year of 2000, the average asset value of households in the MIZ increased by only 5% in the period 2000–2003 but increased by 40% in the period 2003–2006. Households in the RIZ had the lowest rate of physical capital accumulation, with the rate of 14% during the period 2000–2003 and 13% in the period 2003–2006. Households in the NIZ had a 27% increase in physical assets in the period 2003–2006.

Livelihood activities

Land is the most important resource of households in the study area. Land endowment in the region is well above the national average. However, the average size of land owned by the household differs largely across the zones, ranging from 2.26 ha in the MIZ to 1.23 ha in the EIZ. The households in the RIZ and the NIZ have an average land area of 1.75 ha and 1.35 ha, respectively. Land is allocated to rice production, aquaculture and a smaller proportion to homesteads, orchards and homestead gardens. Changes in land use patterns in each zone are reflected in Table 32.3.

Early intervention zone (EIZ)

Intensive rice production is currently practised in the EIZ. All sample households in this zone

Table 32.2. Profile of farm households.

	EIZ			RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2000	2003	2006	2003	2006
Number of households	100	117	81	100	165	94	50	53	45	100	92
Land owned (ha)	1.03	1.46	1.16	1.51	2.05	1.49	2.11	1.92	2.83	1.46	1.23
	0.09	*0.10*	*0.13*	*0.13*	*0.11*	*0.15*	*0.28*	*0.23*	*0.40*	*0.12*	*0.11*
Household capital (US$)	297	422	457	393	447	490	423	446	612	494	627
	27	*40*	*34*	*32*	*37*	*36*	*46*	*70*	*52*	*52*	*73*
Household size (persons)	5.0	5.0	4.9	5.2	5.4	5.1	5.2	5.3	4.8	4.9	4.9
	0.20	*0.16*	*0.22*	*0.20*	*0.14*	*0.18*	*0.32*	*0.25*	*0.22*	*0.19*	*0.18*
Education of head (years of schooling)	4.9	4.9	5.0	4.6	4.8	4.8	4.9	4.6	4.9	4.9	4.9
	0.35	*0.17*	*0.18*	*0.30*	*0.13*	*0.17*	*0.46*	*0.26*	*0.22*	*0.22*	*0.20*

Figures in italic are standard errors of the means.

Table 32.3. Land and land use by zone, 2000–2006 (ha/household).

	EIZ			RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2000	2003	2006	2003	2006
Land owned	1.03	1.46	1.16	1.51	2.05	1.49	2.11	1.92	2.83	1.46	1.23
Garden and cash crop area	0.26	0.20	0.21	0.19	–	0.19	0.28	0.15	0.18		0.15
	0.04	*0.03*	*0.03*	*0.02*		*0.03*	*0.05*	*0.03*	*0.03*		*0.03*
Rice cropped area	2.43	1.99	2.20	2.12	0.38	0.12	1.35	0.64	1.15	0.16	0.05
	0.25	*0.17*	*0.26*	*0.26*	*0.09*	*0.08*	*0.21*	*0.16*	*0.18*	*0.06*	*0.02*
Aquaculture area	0.02			0.27	1.89	1.24	1.57	1.82	1.54	1.30	1.03
	0.01			*0.07*	*0.11*	*0.14*	*0.38*	*0.18*	*0.40*	*0.15*	*0.11*

Figures in italic are the standard errors of the means.

cultivated three rice crops in 2000. Rice cropping had shifted from one crop of traditional varieties in the 1980s to double cropping by the adoption of short duration varieties when freshwater was available. In 1999 and 2000 farmers tried to intensify their production system further by growing three rice crops. But, as the yield of the third crop declined, farmers reverted back to a double cropping system. The third rice crop in parts of this zone was affected by the latest change in canal water management. Farmers reported that the third rice crop was affected by salt water and waterlogging.

The rice-cropping index computed from sample households changed from 2.36 in 2000 to 1.37 in 2003, then to 1.89 in 2006. Rice yield in this area increased substantially during the survey period, from an average of 4.06 t/ha in 2000 to 4.10 t/ha in 2003 and to 4.94 t/ha in 2007 (Table 32.4). Yield increase helped to boost the efficiency of rice production measured in terms of per unit area net returns in the EIZ. Net income from rice production has increased steadily in the EIZ – increasing from US$272 in 2000 to US$415 in 2003 and to US$474/ha in 2006. Yield increase and a higher market price contributed to net income increase.

Recent intervention zone (RIZ)

Before 1996, farmers used to cultivate one crop of salt-tolerant rice in the rainy season and shrimp in the dry season. After 1996, as canal water became progressively fresher, farmers started to grow two crops of high-yielding rice varieties. In 2000, all the area in this zone was planted to rice. Although the canal water was fresh, acid sulfate soils caused very low rice yields, in spite of the use of high-yielding rice varieties, resulting in low returns

Table 32.4. Productivity and profitability from rice.

	EIZ			RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2000	2003	2006	2003	2006
Yield (t/ha)	4.06	4.10	4.94	3.24	2.42	5.65	2.78	–	3.06	5.50	4.87
	0.40 [a]	*0.18*	*0.22*	*0.32*	*0.36*	*0.72*	*0.16*		*0.25*	*0.80*	*0.78*
Gross value	449	576	809	377	379		339	–	534		
(US$/ha)	*135*	*79*	*150*	*129*	*125*	b	*102*		*120*	b	b
Paid-out cost	177	162	336	181	183	240	127	–	197	305	384
(US$/ha)	*50*	*28*	*46*	*53*	*52*	*65*	*35*		*42*	*72*	*85*
Family income	272	415	474	177	241		212	–	337		
(US$/ha)	*93*	*56*	*60*	*67*	*107*	b	*83*		*91*	b	b
BCR	1.54	2.56	1.41	0.98	1.31		1.67		1.71		

[a]This and other figures in italics are the standard errors of the means; [b]gross value and net family income are not reported, since the average was derived from a small number of farmers.

to farmers. The intervention affected the livelihoods of all categories of households in this area, but large farmers were particularly affected (Hossain *et al.*, 2006). In 2001, the original policy promoting rice production was revised to accommodate shrimp cultivation in the west, at the same time maintaining rice production in the east. With salt water back in the canals, farmers converted to shrimp culture. The average area per household allocated to rice declined from 2.12 ha in 2000 to 0.38 ha in 2003 and to 0.12 ha in 2006. However, a few farmers continued to grow rice on suitable (elevated) fields in the rainy season and achieved good yields. Rice yield averaged from these fields resulted in the high yield figures reported for 2006 in Table 32.4. Net income from rice production in the RIZ averaged US$177 in 2000 and US$241 in 2003, much lower than the figures obtained in the EIZ.

Marginal intervention zone (MIZ)

The low price of rice and the high price of shrimp from 2000 to 2003 encouraged farmers to prolong the shrimp cultivation period by applying several stockings of seed and maintaining salt water on the field into the following rice crop. Many farmers abandoned the wet-season rice crop. Average rice area per household decreased from 1.35 ha in 2000 to 0.64 ha in 2003, then increased back to 1.15 ha in 2006 when the rice–shrimp system gained greater acceptance.

This zone lies to the west and north of the 2000 isohaline and is not affected significantly by the closure of sluices. The dry-season rice crop was affected by saline soil and water. After one or two shrimp crops in the dry season, farmers planted one crop of traditional rice in the rainy season. Cultivation of traditional varieties of rice using transplanting costs less than cultivation of direct-seeded modern varieties because they require less chemical fertilizer and less seed. The residual effect of lime used to neutralize the acid generated from pyrite during shrimp cultivation was also beneficial to rice. This aggregation of factors led households in this area to have the lowest rice production costs. With higher rice yields and lower costs, rice production in the MIZ was more effective at generating income than in other regions.

No intervention zone (NIZ)

This area lies to the south of the embankment and is not affected by the sluice system. Land use was mainly for aquaculture, which contributed to more than 80% of the household income. Pockets of rice production were found in this area. A few farmers in the NIZ planted rice on small, elevated fields in the rainy season and were able to get quite high yields. The exceptionally high average yields that appeared in Table 32.4 were computed from a small number of sampled households. However, as the average area planted to rice accounted for only a small portion of land, the contribution of rice production to household income was insignificant. The intensive rice farming commonly practised in the NIZ is reflected in the higher investment per land unit and higher shrimp yields. Higher net income per land unit could be obtained from intensive shrimp farming, but the financial efficiency of investment is much lower than with the rice–shrimp system practised in the MIZ. This issue will be discussed in the subsequent section.

Changes in productivity and profitability of rice and shrimp production

This section discusses the trends in productivity and profitability at the household level in rice and aquaculture farming in the project area. Mass of marketable produce per hectare was used to measure physical production. The benefit–cost ratio (BCR), defined as the ratio between net return and total paid-out cost/hectare, was used to measure the efficiency of farmer investment in farm production. BCR depends not only on the productivity of farming but also on the market price farmers pay for production inputs and receive for produce sold. BCRs were computed for each household, then averaged for each time period and location.

Rice productivity

Average rice yield in the EIZ increased steadily in the period 2000–2006. Estimates of average yield from all rice crops planted in a cropping calendar year increased from 4.0 t/ha in 2000 to 4.1 t/ha in 2003 and 4.9 t/ha in 2006 (Table 32.4). Aside from yield increase, rapid increases of the gross value of rice output per hectare contributed by the higher market price of paddy in the period 2003–2006 were observed. Net income per hectare per household from rice farming increased from US$272 in 2000 to US$415 in 2003 and to US$474 in 2006. Average BCR of investment in rice production in the EIZ increased from 1.54 in 2000 to 2.56 in 2003, but then dropped to 1.41 in 2006. The higher cost of paddy production in 2006 was partly a result of the rise in the cost of material inputs bought by farmers. The lowest value of BCR was found in the RIZ, where all the rice areas were replaced by aquaculture in 2006. The BCR of rice farming in the MIZ was more stable at a level of 1.6–1.7.

Shrimp productivity

A very high variation of shrimp yield was observed across locations in all survey periods. The lowest average shrimp yields were observed in the RIZ, varying from 133 kg/ha to 153 kg/ha. A higher proportion of households practised intensive shrimp culture in the NIZ, and this region had the highest yield averages, varying from 391 kg/ha in 2003 to 452 kg/ha in 2006. Average net return to shrimp culture in the RIZ showed a downward trend in the survey period 2000–2006, declining from US$839/ha in 2000 to US$549/ha in 2006.

The highest value of BCR for shrimp farming was observed in 2000 in all locations. The BCR ratio then declined very rapidly in the RIZ, from a high value of 5.2 in 2000 to 2.4 in 2003, then to 1.6 in 2006 (Table 32.5). Rising costs and lower yields over the periods contributed to the declining trend of BCR in shrimp farming in the study area.

Although average shrimp yields in the NIZ were highest, the investment cost was also high. On average, the net returns per hectare from shrimp culture in the NIZ were higher than in the MIZ. However, high production cost resulted in much lower BCRs in this zone. The range of average BCRs in the MIZ varied from 2.8 to 4.9, whereas those in the NIZ were in the range of only 1.1–1.3. The higher cost of pumping, field maintenance, fertilizer application and hired labour combined with a much higher risk in terms of variation in productivity rendered the shrimp farming in the NIZ less attractive in the long term. The risk in rice and shrimp farming will be discussed in a later section of the chapter.

Livelihood outcomes

The level of income is low and highly unequally distributed; the incidence of poverty is high in the study areas (Hossain *et al.*, 2006). However, the average income earned by the household has increased steadily in all survey locations. Yearly income per household in the

Table 32.5. Economic efficiency of shrimp culture.

	RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2003	2006
Shrimp yield (kg/ha)	140	153	133	210	229	193	391	452
		17.0	*50.8*		*21.3*	*24.0*	*82.1*	*94.5*
Gross return (US$/ha)	1000	913	895	1411	1415	1206	2343	2948
	164	*136*	*77*	*164*	*340*	*155*	*585*	*670*
Total cost (US$/ha)	161	266	346	239	368	248	1,097	1287
	65	*40*	*56*	*65*	*53*	*38*	*250*	*270*
Net return (US$/ha)	839	637	549	1172	1028	959	1247	1661
	210	*120*	*80*	*390*	*318*	*156*	*470*	*510*
BCR	5.21	2.40	1.59	4.90	2.79	3.87	1.14	1.29

Figures in italics are the standard errors of the means.

EIZ increased from US$1052 in 2000 to US$1960 in 2006 (Table 32.6). With the household consisting of five members, per capita income increased from US$210 to US$392 in this zone. Most of the income increase in the EIZ was a result of the intensification of rice production and a much smaller part from raising animals and non-farm activities. Households in the MIZ and NIZ had a higher average income and equivalent rate of increase as the households in the EIZ. Annual income per household in the MIZ increased from US$2623 in 2000 to US$3362 in 2006, whereas households in the NIZ rose from US$2854 in 2003 to US$3375 in 2006. The average per capita income in these two zones in 2006 was about US$675, which was double the average of the EIZ and RIZ and higher than the national average, owing to the large income contributed by shrimp farming and fisheries. The households in the RIZ had the same level of income as in the EIZ, but a lower rate of increase. As noted earlier, the rate of asset accumulation of the household in this zone was also lowest in comparison with the household in the other three zones.

Income from rice farming was the major component of household income in the EIZ. However, the contribution of rice farming declined from 62% in 2000 to 46% in 2003 and 55% in 2006 as a result of a rapid increase in income from livestock production (Table 32.7). In the MIZ, income from shrimp farming contributed to more than 70% of the household income. The income proportion had increased from 70% in 2000 to 77% in 2003 and 78% in 2006. On average, income from shrimp was three to four times higher than from rice for households in the EIZ.

Rice production contributed 33% of household income in the RIZ in 2000, but then declined to about 5% in 2003 and 2006 when

Table 32.6. Sources of income (US$/year/household).

	EIZ			RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2000	2003	2006	2003	2006
Rice	659	825	1072	376	92	85	286		377	76	22
Aquaculture	9	0	0	226	1168	830	1839	1816	2639	2392	2599
Livestock	72	208	356	47	43	144	28	57	112	16	41
Home garden	28	270	76	6	31	28	156	56	47	25	65
Off-farm	86	147	47	66	174	29	92	187	46	51	22
Non-farm	165	274	338	309	226	384	126	209	113	275	374
Natural fishery	24	62	24	75	11	78	79	34	2	19	31
Remittance	8		45	31		30	15	0	22		219
Total	1052	1788	1960	1137	1748	1610	2623	2360	3362	2854	3375

Income figures included costs of family labour and were expressed in 2000 constant price.

Table 32.7. Change in structure of income (%).

	EIZ			RIZ			MIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2000	2003	2006	2003	2006
Land owned (ha)	1.03	1.46	1.16	1.51	2.05	1.48	2.11	1.92	2.78	1.46	1.23
Rice	62.7	46.2	54.7	33.1	5.3	5.3	10.9		11.2	2.7	0.7
Aquaculture	0.8			19.9	66.8	51.6	70.1	76.9	78.5	83.8	77.0
Livestock	6.8	11.6	18.2	4.1	2.5	8.9	1.1	2.4	3.3	0.6	1.2
Home garden	2.7	15.1	3.9	0.5	1.8	1.8	5.9	2.4	1.4	0.9	1.9
Off-farm	8.2	8.2	2.4	5.8	10.0	1.8	3.5	7.9	1.4	1.8	0.6
Non-farm	15.7	15.3	17.3	27.2	13.0	23.9	4.8	8.8	3.4	9.6	11.1
Natural fishery	2.3	3.4	1.2	6.6	0.6	4.8	3.0	1.4	0.1	0.7	0.9
Remittance	0.8	0.0	2.3	2.8	0.0	1.9	0.6	0.0	0.7	0.0	6.5
Total income (US$/HH/year)	1052	1788	1960	1137	1748	1610	2623	2360	3362	2854	3375

farmers in this zone shifted to shrimp culture. Income contribution by shrimp farming increased from 20% in 2000 to 66% in 2003 and 52% in 2006. Nevertheless, the income from shrimp farming of the households in this zone was not much higher than the income from rice farming of households in the EIZ. It was noted that, over time, there was a very large variation in the income from shrimp farming in the RIZ. Livestock and production from home garden plots increasingly became a source of income of the households in the EIZ (Table 32.7). The proportion of income from these two sources increased from 10% in 2000 to about 20% in 2006. Non-farm income accounted for nearly 20% of the household income in the RIZ. The households in the NIZ had the highest income contribution from shrimp farming both in terms of absolute and relative value.

Risk in rice and shrimp farming

Risk is defined as uncertain consequences, particularly exposure to unfavourable consequences. Production risk comes from the unpredictable nature of weather and uncertainty about the performance of crops or livestock, e.g. through the incidence of pests and diseases, or from many other unpredictable factors (Hardaker *et al*., 1998). Given the available information from the panel data collected from repeated surveys on the same groups of farms over time in this study, only one dimension of production risk which was yield and financial return variation was discussed. Variation of rice and shrimp yield, the two principal farming activities in the area, was analysed using household data from the four ecological zones.

Coefficients of variation (CVs) of yield and net returns from rice production for three periods – 2000, 2003 and 2006 – for dry- and wet-season rice crops are reported in Table 32.8. Yield variances in the RIZ were not estimated for 2006 because there were too few data points. CVs of rice yield in the EIZ both in the rainy and dry seasons were in the normal range, i.e. between 20 and 30%. Extremely high variations in rice yield and profit were noted in the RIZ where conditions of acid sulfate soils affected the rice crop negatively. High variation in rice production practices among farmers that reflected differences in costs per land unit within the same location were noted in all locations.

CVs of shrimp yield and net return are presented in Table 32.9. Yield variation of shrimp was much larger in the NIZ and the RIZ than in the MIZ. Both intensive and semi-

Table 32.8. Variation of rice yield and net income of rice cultivation in the dry and wet seasons.

	Dry season			Wet season				
	EIZ			EIZ			RIZ	
	2000	2003	2006	2000	2003	2006	2000	2003
Average yield (t/ha)	3.95	3.96	5.37	3.99	4.54	5.17	3.82	3.47
CV (%)	25	20	29	23	22	30	125	112
Net return (US$/ha)	301	340	600	306	168	482	269	215
CV (%)	45	33	63	43	37	63	136	4934

Table 32.9. Variation of shrimp yield and net income of shrimp culture.

	MIZ			RIZ			NIZ	
	2000	2003	2006	2000	2003	2006	2003	2006
Average yield (kg/ha)	140	153	133	210	229	193	391	452
CV (%)	187	177	190	84	85	90	343	184
Net return (US$/ha)	839	637	549	1172	1028	958	1247	1661
CV (%)	281	252	307	126	332	484	650	728

intensive shrimp practices were included in the yield data in the NIZ and enlarged the values of CVs of this area. Very large variation in shrimp yield and financial return implied higher production risk for farmers. The potential to generate wealth undoubtedly exists, yet shrimp aquaculture has been responsible for the deterioration of livelihoods and promotion of poverty in many countries. Drawing on a series of case studies undertaken in Vietnam, Adger and Kelly (2001) concluded that poorer households were most vulnerable because they were likely to depend on a narrower range of resources and income sources and the loss of common property management rights represented a serious erosion of their ability to cope. They found evidence of benefits from an increase in overall wealth, but increased inequality.

Discussion and Conclusions

The natural resource conditions of the study areas are highly dynamic and livelihood strategies have adapted to economic, technological and policy changes. The government intervention in water management succeeded in controlling saltwater intrusion. The base level of income is low and highly unequally distributed and the incidence of poverty is high in the study areas (Hossain *et al*., 2006). However, the average income earned by the household increased steadily in all survey locations. Per capita income increased at a faster growth rate than the whole delta and the national averages. Higher value and higher profitability of shrimp production indicate that the brackish water in the coastal area is an important resource. This has helped reverse the downward economic mobility of the transition zone (Hoanh *et al*., 2003).

Availability of fresh water has encouraged farmers to intensify rice production in the eastern part of the protected area where there is good alluvial soil and fresh water. Rice productivity and income from rice production in the region has increased since the transition to the freshwater system. Production risk in terms of variation of paddy yield has also reduced gradually. Intensification of the rice production system involves relatively low risk for farmers, but results in relatively low income.

The most drastic changes in land use and also in livelihood outcome were observed in the RIZ. As a result of saltwater control regimes, farming systems in this zone shifted from a saltwater-based rice–aquaculture system to intensive rice, then shifted to saltwater shrimp farming. The transition to rice production was seriously constrained by soil conditions. Income from shrimp has increased the average household income. High variability in the profitability of shrimp and, as a result, in livelihoods was also noted in this zone.

In the marginal intervention zone, shifting from rice–shrimp to shrimp and back to rice–shrimp systems was observed. The variability in shrimp yield under the rice–shrimp system in the MIZ was much lower compared to the RIZ and NIZ.

For the whole project area, the freshwater zone on non-acid soils, the current strategy of double-cropped rice appears to be favoured by local stakeholders and no major sustainability concerns have been identified. Elsewhere, an integrated rice–shrimp system offers the best prospects for balanced and sustainable development (Gowing *et al*., 2006). The net effect of the government's intervention in the construction of embankments was a substantial reduction in the transitional stage. The situation has increased over time as farmers gain experience with the new land use and cropping patterns.

The low yields and large variation of shrimp yield suggest that the productivity of the brackishwater resource could be increased further by developing and diffusing improved technologies and cultural practices.

Limited accumulation of physical capital was observed in the study areas as a result of income growth. However, improvement of the quality of human capital is limited, implying the need for more investment in education, extension and infrastructure in these coastal areas.

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References

Adger, W.N. and Kelly, P.M. (2001) Social vulnerability and resilience. In: Adger, W.N., Kelly, P.M. and Nguyen Huu Ninh (eds) *Living with Environmental Change*. Routledge, London and New York.

Carney, D. (ed.) (1998) *Sustainable Rural Livelihoods: What Contribution Can We Make?* Department for International Development, London.

Chambers, R. and Conway, G. (1992) Sustainable rural livelihood: practical concept for the 21st Century. IDS Discussion Paper 296, Institute of Development Studies, Brighton, UK.

Dearden, P., Roland, R., Allison, G. and Allen, C. (2002) Sustainable livelihood approaches: from the framework to the field. Sustainable Livelihood Guidance Sheets. University of Bradford, Department for International Development, UK.

Gallop, K.M., Khiem, N.T., Dung, L.C. and Gowing, J.W. (2004) Changes in farmer livelihoods and land-use strategies during the project period 2000–2003. Working Paper WP1-2. DFID-CRF Project – R7467C. Accelerating poverty elimination through sustainable resource management in coastal lands protected from salinity intrusion: a case study in Viet Nam.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. and Khiem, N.T. (2006) Social and environmental impact of rapid change in the coastal zone of Vietnam: an assessment of sustainability issues. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 48–60.

Hardaker, J.B., Huirne, R.B.M. and Anderson, J.R. (1998) *Coping with Risk in Agriculture*. CAB International, Wallingford, UK.

Hoanh, C.T., Tuong, T.P., Gallop, K.M., Gowing, J.W., Kam, S.P., Khiem, N.T. and Phong, N.D. (2003) Livelihood impact of water policy change: evidence from a coastal area of the Mekong River delta. *Water Policy* 5, 475–488.

Hossain, M., Ut, T.T. and Bose, M.L. (2006) Livelihood systems and dynamics of poverty in a coastal province of Vietnam. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. CAB International, Wallingford, UK, pp. 48–60.

Tuong, T.P., Kam, S.P., Hoanh, C.T., Dung, L.C., Khiem, N.T., Barr, J.J.F. and Ben, D.C. (2003) Impact of seawater intrusion control on environment, land use strategies and household incomes in a coastal area. *Paddy and Water Environment* 1, 65–73.

33 Utilization of Aquatic Resources Along the North Brazilian Coast with Special Reference to Mangroves as Fish Nurseries

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Abstract

The coastline of Brazil stretches approximately 8400 km, with a continental shelf area of 822,800 km^2 and a declared exclusive economic zone of approximately 4.5 million km^2. Mangroves are the dominant coastal vegetation, particularly in the north of the country, covering an area of 13,400 km^2, accounting for 8% of the global mangrove cover. Common marine fish include sardines, corvinas, snappers, croakers, tunas, lobsters and shrimp. In 2005, 750,000 t were landed, including 60,000 t of molluscs and crustaceans (predominantly shrimp). Fishing is practised on both a small scale and an industrial scale. Fish production has decreased from about 1 million t to the low current numbers in the past two decades, an indication of the overexploitation of these resources. Long-term management plans are urgently required, taking into consideration the life cycles of the fish, to guarantee sustainable utilization of the resources by the local population. Juveniles of many marine fish species use estuarine nursery habitats before moving as adult populations to the coastal waters. However, data on numbers of individuals from the exploited populations, which spend their early life in the different estuaries, are lacking. Thus, it is not known whether all estuaries contribute equally to maintaining local stocks or if adult stocks in the coastal waters rely on recruitment from only one estuary or a number of estuaries. This question has significant implications for coastal management and land–ocean exchange processes. Connectivity studies, using biogeochemical signals on fish otoliths, will contribute to our understanding of the relationships between populations of marine and estuarine fish species and their population dynamics, and will help to distinguish between open and closed populations, information which is essential for stock assessment purposes and the design of marine and coastal protected areas. The findings will help clarify if the different estuaries are habitat patches inhabited by metapopulations. As human activity continues to impact and eliminate natural habitats, the mangrove forest being a prime example, understanding the spatial connectivity between juvenile and adult populations becomes increasingly important. Connectivity is likely to depend not only on the distance between the habitats of two life-history stages, but also on the presence of movement corridors or stepping stones of natural habitats.

Introduction

Marine fishery in Brazil

Brazil is characterized by a coast extending 8400 km along the Atlantic Ocean, with a large continental shelf of 822,800 km^2. Fishing is practised both on a small scale and an industrial scale and represents an important source of food and income. Brazilian fishing policy has placed priority on: (i) the development of long-distance fisheries with facilities for renting foreign fishing vessels through governmental measures; and (ii) the development of fish farming in marine and continental waters that takes advantage of the favourable conditions offered by the topography. The socio-economic characteristics of the Brazilian marine fisheries are very diversified as a result of the length of the coast and the variety of cultures, which influence fisheries in the different geographical regions (Isaac *et al.*, 2006a).

The types and abundances of marine resources are determined mainly by the physical, oceanographic and climatic characteristics of the different regions of the Brazilian coast (Isaac *et al.*, 2006b). Although the actual mean catches for 2000–2003 were about 500,000 t (Isaac *et al.*, 2006b), a potential yield of 1.4–1.7 Mt has been estimated for the zone up to 200 m deep (FAO, 2001).

The marine fisheries fleet is divided into three categories: coastal, long distance and artisanal. The coastal industrial fleet has 1630 vessels, which are able to operate in distant zones to exploit the fisheries resources. The oceanic modality of industrial fishing is not yet very significant in Brazil and involves only 100 vessels able to operate across the entire exclusive economic zone (EEZ). The artisanal fleet comprises about 23,000 vessels of small and medium capacity, typically using motor propulsion, and the fishing gear is not well diversified. The common boat operating near the coast is made of wood and its state of technology allows only small catches.

The principal marine target species are: sardines, *Sardinella braziliensis* (30,000 t); corvinas, *Macropogonias furnieri* (28,800 t); snappers, Lutjanidae (15,000 t); croakers, Scianidae (27,500 t); lobsters, *Panulirus argus* and *P. paevicauda* (6200 t); shrimps, Penaeidae (22,000 t) and *Xiphopenaeus* spp. (14,200 t); tunas, Scombridae and *Thunnus* spp. (8000 t); and skipjack tuna, *Katsuwonus pelamis* (23,200 t) (FAO, 2001).

The fisheries situation in northern Brazil

The two northern, mostly mangrove-dominated coastal regions (Fig. 33.1), differ significantly in their productivity:

- North region 05°N–02°N: the abundance of fishes and crustaceans in this region benefits from the nutrient-rich Amazon River, as well as from the large size of the continental shelf. A potential catch of 385,000–485,000 t/year is estimated for this region, comprising 235,000 t of pelagic species and between 150,000 and 240,000 t of demersal species. This corresponds to about 25% of the total catch.
- North-east region 02°N–23°S: despite the vast coastal extension, this region is less favoured in terms of production, because of the hot and salty waters of the Brazilian and South Equator currents that are associated with the small width of the continental shelf. A potential catch of 200,000–275,000 t/year is estimated for this region, comprising 100,000 t of pelagic species and about 100,000–175,000 t of demersal species, corresponding to approximately 17% of the potential yield.

The State of Pará is located in the northern region. The region encompasses 560 km of marine littoral and is dominated by macro tides (4–5 m). The climate is tropical (mean air temperature 25.7°C), with hot dry periods from May to December and conventional rains from January to April. Annual precipitation exceeds 2545 mm. The Caeté Bay, which connects Bragança with the open sea, belongs to the northern part of the South Atlantic Basin. During the rainy season, increased freshwater run-off by the river Caeté reduces salinity (≈ 17), whereas during the dry season, marine waters with higher salinity (> 35) prevail.

Although the Amazonian river fishery has been described by many authors (e.g. Bayley and Petrere, 1989; Ruffino, 2004), information on its estuary and coastal fishery is very scarce. Mangrove forests dominate the entire northern coast of Brazil. There are varying degrees of association between mangrove-dwelling fish and their habitat. Mangroves serve as breeding grounds for marine animals of commercial value and many fish species are found here during at least some period of their life (e.g. Saenger *et al.*, 1977).

Ecological and population studies of fish from the Caeté Estuary have been carried out by the German/Brazilian MADAM

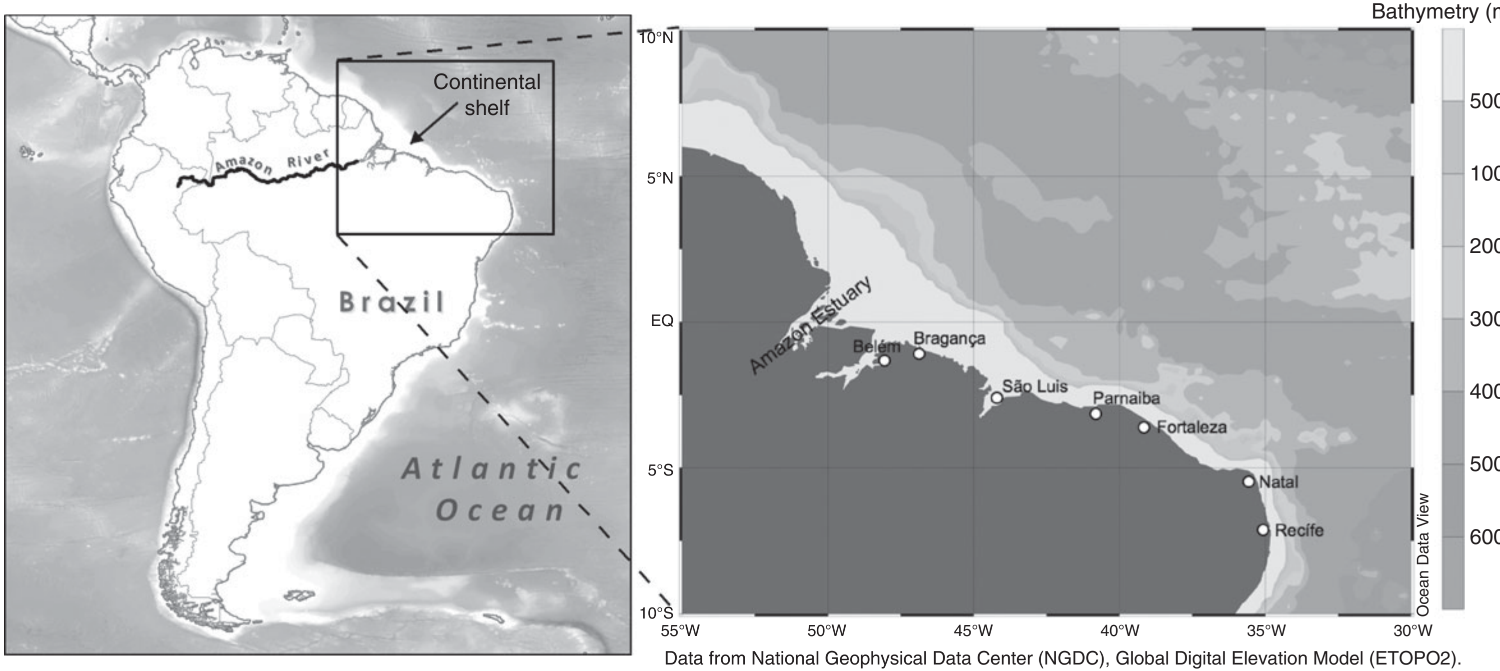

Fig. 33.1. Map of Brazil's north-east coast. *Source*: Schlitzer, R., Ocean Data View, http://odv.awi.de, 2009.

project (Barletta *et al*., 1998) and another study has been conducted by the Brazilian RECOS project (Isaac *et al*., 2006a). The fishery structure is characterized by a long-ranging fishing area, reaching over 400 km and extending from Salinas to the Baixada Maranhense, and a predominant artisanal fishing fleet. Half of the fish production of the state depends on artisanal fishery, whereas industrial fishery supplies fish for export. A high proportion of the fish landed is exported to other states and only a small share of the fish (of mainly secondary quality) is sold in the local markets.

Fish are brought by truck equipped with cold storage to the different regional markets according to the local preferences, demonstrating that regional fishery is of nationwide importance. For instance, Peixe pedra (*Geniatremus luteus*) is sold to São Luis/MA and *Serra* (*Scomberomorus* spp.), Pescada amarela (*Cynoscion acoupa*), Corvina (*C. microlepidotus*) and Bandeirado (*Bagre bagre*) to Belém/PA and Fortaleza/CE. The local fish market in Bragança receives Gó (*Macrodon ancylodon*), Uricica amarela (*Cathorops spixii*), Uricica branca (*Cathorops* sp.), Sardinha (*Cetengraulis edentulus* and *Anchovia clupeoides*), Bagre (*Arius hertzbergii*), Bandeirado (*B. bagre*), Uritinga (*A. proops*) and Gurijuba (*A. parkeri*) (Barletta *et al*., 1998).

As the Caeté Estuary is influenced principally by marine and fresh waters without any notable impact from the Amazon River, Bragança fishing stocks are dominated by marine or brackishwater species throughout the year: Pescada amarela (*C. acoupa*), Uritinga (*A. proops*), Camorim (*Centropomus* spp.), Xaréu (*Caranx hippo*, *C. crysus*), Gurijuba (*A. parkeri*), Serra (*Scomberomorus* spp.), Pargo (*Lutjanus purpureus*) and Cação (Carcharinidae) (Barletta *et al*., 1998).

Both studies mentioned above show that tropical estuarine fish are linked inextricably to mangroves. Yet evidence for this remains circumstantial. More experimental and quantitative studies are urgently needed to prove that retaining healthy mangrove systems and halting their destruction is vital. This chapter summarizes the current knowledge on mangrove fisheries connectivity in Brazil.

Mangrove Fisheries Connectivity

A review of the northern Brazilian mangrove as fish habitat and nursery

Mangroves are a dominant feature of undisturbed tropical and subtropical shorelines around the globe. However, these habitats are in a state of decline. Approximately one-third of the world's mangrove forests have been lost to coastal development over the past 50 years (Alongi, 2002). Although there is general agreement that mangroves provide a buffer against storm surges, reduce shoreline erosion and turbidity, absorb and transform nutrients and are inhabited by a variety of organisms, opinions vary as to the importance of mangrove habitats to fish and, by extension, to offshore fisheries (Blaber *et al*., 1989). Manson *et al*. (2005a, b) analysed the empirical link between the extent of mangrove habitat and fishery production for some key species that use mangroves as nursery habitats. However, causal relationships remain unclear. They suggest a rigorous data collection programme for better understanding of the relationship between mangroves and fisheries.

Today, the protection of mangroves worldwide is based almost entirely on their purported importance to fisheries and/or a number of rare and endangered species (Baran and Hambrey, 1998). Because the same mangrove species often occur under marine, estuarine and freshwater conditions, a wide variety of fish assemblages can be found among the inundated prop roots of red mangroves or in tidal creeks. As such, mangrove habitats serve a variety of functions in the lives of associated fishes: providing lifelong feeding areas for some species or feeding areas during at least some of the life stages of other species, daytime refuge for others, nursery and/or nesting areas for yet more. Hence, the specific contribution of a given mangrove habitat to the diversity, productivity and stability of broader fish communities (and their exploited components) is not understood completely. Skilleter and Loneragan (2003) broadened the discussion when pointing out that it is not just a specific habitat that is of importance, but that the spatial arrangement of different habitats within an area – or the 'mosaic' of habitats within an area – needs consideration, at least for those species which do not complete their whole life cycle in one single habitat.

This nursery role of mangroves is also reflected in the composition of the larval fish assemblage of a study in northern Brazil, with 54 species being recorded (Barletta-Bergan *et al*., 2002a). However, the annual means of species diversity are low in this study since a few species dominate the community, a situation found in many other estuarine fish populations (Bell *et al*., 1984). Low species diversity may be associated with increased fluctuations of abiotic conditions, as demonstrated by various authors in different estuarine ecosystems in earlier years (e.g. Dahlberg and Odum, 1970; Moore, 1978). Another feature documented by Barletta-Bergan *et al*. (2002a) is the higher diversity among larvae of demersal than of pelagic fish in the ichthyoplankton assemblage in northern Brazil. Janekarn and Kiørboe (1991) related such a difference to a more complex benthic environment as compared to a relatively more homogeneous pelagic environment in mangrove areas of Thailand.

According to Barletta-Bergan *et al*. (2002b), the most abundant larval species of northern Brazilian mangroves are species that spawn in mangroves or which have the ability to complete their entire life cycle in the estuary; and the relative contribution of species that spawn exclusively in the sea is low in mangrove areas. Many larvae of marine spawners may not prefer such habitats with high turbidity and seasonally varying salinity. McHugh (1967) described stenohaline species as adventitious invaders of the estuary. Other estuarine fish surveys conducted in Taiwan do not confirm this, since a large portion of the catch consists of marine species because of the marine conditions in these estuaries (Tzeng and Wang, 1992). Barletta-Bergan *et al*. (2002b) reported that larval freshwater species did not occur at all in northern Brazilian mangrove creeks, as no perennial freshwater streams fed the mangroves. The most important euryhaline freshwater component in the mangroves of the Caeté Estuary (northern Brazil) was the small fishes of the Poecilidae (Barletta-Bergan *et al*., 2002a). Barletta *et al*. (2000) found adults of the Ophichtid *Myrophis punctatus* in large numbers in the same system, whereas Barletta-Bergan *et al*. (2002b) collected only a few larval individuals. The authors supposed that it might be that the year was a poor one for spawning of this species. Few larvae of *M. punctatus* in the system studied by Barletta-Bergan *et al*. (2002b) could also indicate recruitment into the estuary at a larger size.

In the tidal mangrove creeks of the Caeté Estuary, fish larvae peaked in abundance in August and, to a lesser degree, in April (Barletta-Bergan *et al*., 2002b). According to Tricklebank *et al*. (1992), overall seasonality patterns are often reflected in the abundance of dominant taxa. Moreover, peaks in abundance often depend on how 'estuarine' a system is, i.e. the environmental conditions of that system. In the study by Barletta-Bergan *et al*. (2002b), the dominant peaks are mainly from estuarine spawners, which can be related to the Eletroid *Guavina guavina* and the Engraulid *A. clupeoides*. The dominance of Gobioidei and Clupeiformes is typical of other estuaries throughout the world (Janekarn and Kiørboe, 1991; Neira *et al*., 1992; Morais and Morais, 1994). The Sciaenid *C. acoupa* was the only marine species of commercial interest that used the estuary extensively as a nursery ground (Barletta *et al*., 1998).

According to Mongkolprasit (1983), Eleotrids spend their complete life cycle in the mangrove area. The constantly small size classes of *G. guavina* over the sampling period in the study by Barletta-Bergan *et al*. (2002a) confirm continuous spawning in the mangroves and subsequent tidal removal. *Guavina guavina* apparently returns to the mangrove system as a juvenile on flood tides and settles to a benthic lifestyle, burrowing into the mud (Barletta *et al*., 2000, 2003). This type of re-recruitment of *G. guavina* parallels that exhibited by the postflexion larvae of Gobiids in an estuary in southern Africa (Whitfield, 1989). Barletta-Bergan *et al*. (2002a) conclude that high densities of *G. guavina* in the mangroves in August indicate that spawning occurs predominantly during the dry season, when salinities are high. Loneragan and Potter (1990), by contrast, found a negative correlation between abundance of estuarine species and salinity. Tzeng and Wang (1992) stress, however, that the response of larval densities to environmental variables is species specific. According to Barletta-Bergan *et al*. (2002a), the temporal pattern of *G. guavina* may ensure that this species reproduces during a time when species competition is lowest. Tzeng and Wang (1992) observed ecological separation of the dominant species by recruitment timing.

Barletta-Bergan *et al*. (2002a) found that the marine Sciaenid *C. acoupa*, by contrast, occurred in relatively high densities in northern Brazilian mangrove creeks in the rainy season, with a peak in April. Likewise, Cervigón (1985) cited maximal spawning intensities for *C. acoupa* in the period from January to April in the Laguna de Maracaibo in Venezuela. Morais and Morais (1994) found that the marine Sciaenid *Micropogonias furnieri* seemed to be dependent on low salinity, as peaks were registered when precipitation and freshwater inputs were high during the rainy season. According to Janekarn and Boonruang (1986), nutrients from land are transported to the sea, causing high primary productivity after heavy rain in the mangrove areas of Thailand. Increased nutrient concentrations, and thus elevated phytoplankton biomass and abundance of *Ucides cordatus* larvae, a most abundant landcrab, could also have stimulated spawning activity of *C. acoupa* in nearshore areas (Barletta-Bergan *et al*., 2002a). Studies by Camargo and Isaac (1998) proved that different Sciaenid species used estuarine habitats as nursery grounds during the early phase of their life cycle.

Connectivity studies between inshore and offshore habitats

The recruitment of predominantly old larvae (postflexion) and early juveniles of marine fish into estuarine nursery areas from offshore is a common feature for both subtropical and temperate estuaries worldwide (Claridge *et al*., 1986; Whitfield, 1989; Blaber, 2007). Barletta-Bergan *et al*. (2002a) emphasized the importance of mangroves as nursery sites for certain marine species at the postflexion larval stage, since a large proportion of the larvae of *C. acoupa* collected were old larvae. However, further sampling outside the estuarine area is required to confirm the nursery function of mangroves for marine species. New techniques in element chemistry of fish otoliths allow the connectivity between nursery site and offshore populations to be proved.

Since the end of the 19th century, the most frequently used method to determine the age of fish is the interpretation and counting of year marks that appear on the hard parts of fish (otoliths, scales). Degens *et al*. (1969) analysed microstructures and growth of otoliths and found patterns that Panella (1971) identified as daily growth increments. These findings allowed a much higher resolution in age determination and constituted a major step forward in assessing age and growth with greater accuracy and precision, especially in younger stages and in tropical, fast-growing species.

Research from the past 10–20 years has shown that otoliths can provide much more information than just daily or yearly age; they are an efficient and conservative storage-house of environmental information. Fish inhabiting different water bodies incorporate chemical microelements into their calcified structure that form a unique chemical signature, reflecting the individual environmental history over the period of time the fish has occupied particular water bodies. The metabolically inert nature of otoliths ensures that, in contrast to other hard structures, deposition of trace elements in otoliths remains unaltered through time (Campana and Neilson, 1985). Deposition occurs in layers over time and differences in microchemistry among the layers can be estimated by reference to the growth zones in the otolith. Radtke (1987) was one of the first to show that otoliths of tropical fish may provide important life history information incorporated in their structural and chemical constituents, e.g. temperature records laid down in the Sr/Ca ratio. More than a decade later, Campana (1999) showed that the daily growth increments of otoliths incorporated elements that were influenced also by other environmental variables, such as of Sr, S, Pb and O.

Just as daily growth increments allow for exact age determination, an exact dating by element incorporation leads to a complete record of the entire life history of the fish (Campana and Neilson, 1985). This has been applied to distinguish between populations of marine species (e.g. Campana *et al*., 1994) or to detect connectivity between populations (e.g. Gillanders and Kingsford, 1996; Gillanders, 2002a). Gillanders (2005) provided an overview of the use of elemental chemistry of fish to determine connectivity between estuarine and coastal habitats. She identified a total number of only 11 publications dealing with this topic. The results of the Third International Symposium on Fish Otolith Research and Application held in Townsville (Australia) in 2004 are synthesized by Begg *et al*. (2005), showing clearly the advantages in the use of the chemical composition of otoliths as a natural data logger.

According to Gillanders *et al*. (2001) and Gillanders (2002a, b), one promising method to determine connectivity among populations is to use chemical fingerprints (metals and/or their isotopes) in calcified tissues (e.g. otoliths) as a natural tag (Campana, 1999). The chemical composition of the otolith layers is thought to reflect the physical and chemical characteristics of the water mass in which the fish is found. This is possible because otoliths continue to grow through time, recording the entire lifetime of the fish. Analyses of either the whole otolith or small areas of an otolith have been used to distinguish stocks or subpopulations in marine species.

In tropical coastal areas, mangrove forests help sustain coastal fisheries as they are the nursery for many commercial species (Blaber and Blaber, 1980; Blaber *et al*., 1985). A habitat can be identified as a nursery for a particular species if juveniles occur at higher densities, suffer lower rates of predation, or have higher rates of growth in this particular habitat than in others (Robertson and Duke, 1987). Also, a habitat can be considered as a nursery if its contribution per unit area to the production of individuals that recruit to the adult population is greater, on average, than production from other habitats where juveniles also occur (Gillander and Kingsford, 2003). This nursery concept for mangroves is widely accepted and has been discussed recently by Manson *et al*. (2005b) and Dahlgren *et al*. (2006).

However, the proportion of individuals in exploited populations that have spent their early life in different estuaries is unknown (Gillanders, 2002a). Thus, it is not known whether all estuaries contribute equally to maintaining local stocks, or if the adult stocks in coastal waters rely on recruitment from only one or a few estuaries (Gillanders, 2002a, b). This question has a number of implications for coastal management and land–ocean exchange processes. Connectivity studies will contribute to our understanding of the relationships between populations of marine and estuarine fish species and their population dynamics (Cowen *et al*., 2000) and our ability to distinguish between open and closed populations. The findings will also ascertain if estuaries constitute habitat patches used by different metapopulations. Such information is essential for stock assessment purposes and the design of marine and coastal protected areas.

More evaluation of the importance of estuaries extending into the ocean and along the coastline is required to establish the basis for maintaining a healthy coastal system vital for all fish communities. For example, one aspect that remains poorly understood is larval dispersal among subpopulations. Information is also lacking on the behavioural movement of juveniles and adults between different habitats. Yet, without this we cannot understand the spatial connectivity of their different life-history stages (Gillanders, 2002a, 2005).

As human activity continues to impact and eliminate natural habitats, the mangrove forest being a prime example, an understanding of spatial connectivity between juvenile and adult populations becomes increasingly important. Connectivity is likely to depend not only on the distance between the habitats of two life-history stages, but also on the presence of movement corridors or stepping stones of natural habitats. Failure to protect coastal habitats and the disruption of the ability of fish to move freely among them may have detrimental effects on adult populations (Gillanders *et al*., 2003). Detailed knowledge on connectivity will support a more sustainable management of fish stocks by preserving those estuaries as habitats that early life stages and recruits use as nurseries.

Ekau *et al*. (1999) were the first to study the ichthyoplankton community along the continental shelf waters off north-eastern Brazil. Fish from the coastal mangrove region along the northern Brazilian coast form a principal component of the local fishery and account for

58% of all fish landed. The most commonly landed fish are those of the family Sciaenidae. In Brazil, 61,400 t of this family are landed each year. This makes the Sciaenidae an economically important group of fish. The weakfish *C. acoupa* is one of the most exploited Sciaenid species in Brazil. Abundant in tropical estuaries, they are carnivorous and inhabit open sand and mud bottoms; some juveniles of this species live only in brackish water. Adults follow an annual migration pattern along the Brazilian coast. *Cynoscion acoupa* spawns between January and April during the rainy season in coastal waters near estuaries and the larvae are transported into the estuaries. The larvae migrate into the mangrove creeks (Camargo and Isaac, 1998; Barletta-Bergan, 1999). The otolith morphometry of juvenile Scaenids has been described by Corrêa and Vianna (1992/93). The natal origin of *C. regalis*, a species from North America, has been determined by Thorrold *et al*. (2001) using geochemical signatures. This evidence of the role of estuary–open sea connectivity in the life cycle of *C. acoupa* can be the basis for delineating its critical habitats as a model for sound fisheries management.

Discussion

Tropical, undisturbed shorelines are fringed by mangroves; however, their utilization by fish is poorly understood. An extensive review of 111 mangrove–fish surveys between the years 1955 and 2005 has been published by Faunce and Serafy (2006). This review clearly shows that certain regions, for example South-east Asia, West Africa and South America, are under-represented and that surveys focus mainly on the spatio-temporal patterns of mangrove use by fish.

Biological connectivity allows for understanding trophic relationships, life-history strategies, predation and mortality, and patterns of distribution and abundance in a spatially and temporally variable context. Fish species that occupy multiple habitats in the course of their life histories are especially vulnerable to the adverse effects of habitat modification, because degradation of any one component of their habitat mosaic can disrupt their life cycles (Matheson and Gilmore, 1995). Fisheries management strategies need to take cognizance of the existence and importance of such habitat mosaics (Sheaves, 2005).

Further studies should incorporate landscape-scale approaches, including habitat connectivity, suitability and the contribution of mangrove habitats in support of adult fish populations, as those initiated by Gillanders *et al*. (2003) and Sheaves (2005). It is important to understand that mangroves do not exist in isolation as tidal forests, but that they are complex ecosystems interconnected with coastal and inland habitats. Skilleter and Loneragan (2003) term this a 'mosaic' of habitats and suggest approaches for its study. Sheaves (2005) further developed this idea, which he termed 'interconnected habitat mosaic' (IHM). Although vital as a fish habitat, the mangrove environment is available to fish only part of the time because of alternate inundation and exposure by the tide, hence influencing the semidiurnal migration of fish. There are other elements, such as salinity changes because of rainfall or lunar phase, which are linked to the life cycle of fish, so patterns of distribution and abundance must be understood in the context of spatial and temporal variability. This poses a whole new set of challenges for the population management of fish species living in such an IHM, as degradation of any one unit of a habitat mosaic can affect a species across the entire mosaic. The objective of a future study is to improve understanding of fish ecology along the north-east coast of Brazil, in the context of a habitat mosaic, to help inform strategies for more sustainable management of these valuable fishery resources.

To date, there are only a few studies that provide good evidence of movement from juvenile to adult habitats (Gillanders *et al*., 2003). Future investigation on fish migratory patterns along the Brazilian coast based on studies of otolith chemistry to determine environmental influences will have significant implications for coastline management. Gillanders *et al*. (2003) point out that not finding fish in their juvenile habitats does not suggest that they have moved successfully to adult habitats, hence implying connectivity between juvenile and adult habitats. The use of artificial or natural tags will help ascertain which juvenile habitats contribute most individuals to the adult population. The most promising tagging method is based on the elemental chemistry of otoliths (Gillanders and Kingsford, 1996). For a comprehensive assessment, there is a clear need to determine the abundance and size distribution of organisms from a range of juvenile and adult habitats, and to sample multiple locations in each type of habitat.

As mangroves are further destroyed along the Brazilian coast, the understanding of connectivity between juvenile and adult populations and their movement corridors becomes increasingly urgent. Disturbance of mangrove nurseries will have detrimental effects on adult populations. The fact that different nurseries supply different numbers of recruits to adult populations will have considerable implications for fisheries management and for delineating marine protected areas.

Although it is widely recognized that mangroves are essential for fish populations, the available evidence remains circumstantial. Therefore, there is an urgent need for more experimental and quantitative studies to provide sound scientific evidence, and to lend weight to the arguments that the economic value for retaining mangroves far exceeds uses that result in their destruction, for whatever purpose. The intended studies by the authors on the connectivity of commercial fish species (e.g. *C. acoupa*) along the Brazilian coast will be such a contribution.

References

Alongi, D.M. (2002) Present state and future of the world's mangrove forests. *Environmental Conservation* 29, 331–349.

Baran, E. and Hambrey, J. (1998) Mangrove conservation and coastal management in Southeast Asia: what impact on fishery resources? *Marine Pollution Bulletin* 37, 431–440.

Barletta, M., Barletta-Bergan, A. and Saint-Paul, U. (1998) Description of the fishery structure in the mangrove dominated region of Bragança (State of Pará, North Brazil). *Ecotropica* 4, 41–53.

Barletta, M., Saint-Paul, U., Barletta-Bergan, A., Ekau, W. and Schories, D. (2000) Spatial and temporal distribution of *Myrophis punctatus* (Ophichthidae) and associated fish fauna in a northern Brazilian intertidal mangrove forest. *Hydrobiologia* 426, 65–74.

Barletta, M., Barletta-Bergan, A., Saint-Paul, U. and Hubold, G. (2003) Seasonal changes in density, biomass, and diversity of estuarine fishes in tidal mangrove creeks of the lower Caeté Estuary (northern Brazilian coast, east Amazon). *Marine Ecology Progress Series* 256, 217–228.

Barletta-Bergan, A. (1999) Structure and seasonal dynamics of larval and juvenile fish in the mangrove-fringed estuary of the Rio Caeté in North Brazil. PhD thesis, University of Bremen, ZMT Contribution 8, Germany.

Barletta-Bergan, A., Barletta, M. and Saint-Paul, U. (2002a) Community structure and temporal variability of ichthyoplankton in north Brazilian mangrove creeks. *Journal of Fish Biology* 61 (Supplement A), 33–51.

Barletta-Bergan, A., Barletta, M. and Saint-Paul, U. (2002b) Structure and seasonal dynamics of larval fish in the Caeté River estuary in north Brazil. *Estuarine, Coastal and Shelf Science* 54, 193–206.

Bayley, P.B. and Petrere, M. Jr (1989) Amazon fisheries: assessment methods, current status and management conditions. *Canadian Special Publication of Fisheries and Aquatic Sciences* 106, 385–398.

Begg, G.A., Campana, S.E., Fowler, A.J. and Suthers, I.M. (2005) Otolith research and application: current directions in innovation and implementation. *Marine and Freshwater Research* 56, 477–483.

Bell, J.D., Pollard, D.A., Burchmore, J.J., Pease, B.C. and Middleton, M.J. (1984) Structure of a fish community in a temperate tidal mangrove creek in botany Bay, New South Wales. *Australian Journal of Marine and Freshwater Research* 35, 33–46.

Blaber, S.J.M. (2007) Mangroves and fishes: issues of diversity, dependence, and dogma. *Bulletin of Marine Science* 80, 457–472.

Blaber, S.J.M. and Blaber, T.G. (1980) Factors effecting the distribution of juvenile estuarine and inshore fish. *Journal of Fish Biology* 17, 143–162.

Blaber, S.J.M., Young, J.W. and Dunning, M.C. (1985) Community structure and zoogeographic affinities of the coastal fishes of the Damper region of northwest Australia. *Australian Journal of Marine and Freshwater Research* 36, 247–266.

Blaber, S.J.M., Brewer, D.T. and Salini, J.P. (1989) Species composition and biomasses of fishes in different habitats of a tropical northern Australian estuary: their occurrence in the adjoining sea and estuarine dependence. *Estuarine, Coastal and Shelf Science* 29, 509–531.

Camargo, M. and Isaac, V.J. (1998) Population structure of the fish fauna in the estuarine area of Caeté River, Bragança Municipality, State of Pará, Brasil. *Acta Scientiarum* 20, 171–177.

Campana, S.E. (1999) Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Marine Ecology Progress Series* 188, 263–297.

Campana, S.E. and Neilson, J.D. (1985) Microstructure of fish otoliths. *Canadian Journal of Fisheries and Aquatic Sciences* 42, 1014–1032.

Campana, S.E., Fowler, A.J. and Jones, C.M. (1994) Otolith elemental fingerprinting for stock identification of Atlantic cod (*Gadus morhua*) using laser ablation ICPMS. *Canadian Journal of Fisheries and Aquatic Sciences* 51, 1942–1950.

Cervigón, F. (1985) La ictiofauna de las aguas costeras estuarinas del delta Río Orinoco en la costa Atlantica occidental, Caribe. In: Yánez-Arancibia, A. (ed.) *Fish Community Ecology in Estuaries and Coastal Lagoons: Towards an Ecosystem Integration*. UNAM Press, Mexico City, pp. 57–78.

Claridge, P.N., Potter, I.C. and Hardisty, M.W. (1986) Seasonal changes in movements, abundance, size composition and diversity of the fish fauna of the Severn estuary. *Journal of the Marine Biological Association of the United Kingdom* 55, 229–258.

Corrêa, M.F.M. and Vianna, M.S. (1992/93) Catálogo de otólitos de Sciaenidae (Osteichthyes-Perciformes) do litoral do Estado do Paraná, Brasil. *Nerítica* 7, 13–41.

Cowen, R.K., Lwiza, K.M.M., Sponaugle, S., Paris, C.B. and Olson, D.B. (2000) Connectivity of marine populations: open or closed? *Science* 287, 857–859.

Dahlberg, M.D. and Odum, E.P. (1970) Annual cycles of species occurrence abundance and diversity in Georgia estuarine fish populations. *The American Naturalist* 83, 382–392.

Dahlgren, C.P., Kellison, G.T., Adams, A.J., Gillanders, B.M., Kendall, M.S., Layman, C.A., Ley, J.A., Nagelkerken, I. and Serafy, J.E. (2006) Marine nurseries and effective juvenile habitats: concepts and applications. *Marine Ecology Progress Series* 312, 291–295.

Degens, E.T., Deuser, W.G. and Haedrich, R.L. (1969) Molecular structure and composition of fish otoliths. *Marine Biology* 2, 105–113.

Ekau, W., Westhaus-Ekau, P. and Medeiros, C. (1999) Large-scale distribution of fish larvae in the continental shelf waters off north-east Brazil. *Archive of Fishery and Marine Research* 47, 183–200.

FAO (2001) *FAO Fishery Country Profile – Brazil*. FID/CP/BRA, Brazil, 5 pp.

Faunce, C.H. and Serafy, J.E. (2006) Mangroves as fish habitat: 50 years of field studies. *Marine Ecology Progress Series* 318, 1–18.

Gillanders, B.M. (2002a) Connectivity between juvenile and adult fish populations: do adults remain near their recruitment estuaries? *Marine Ecology Progress Series* 240, 215–223.

Gillanders, B.M. (2002b) Temporal and spatial variability in elemental composition of otoliths: implications for determining stock identity and connectivity of populations. *Canadian Journal of Fisheries and Aquatic Sciences* 59, 669–679.

Gillanders, B.M. (2005) Using elemental chemistry of fish otoliths to determine connectivity between estuarine and coastal habitats. *Estuarine, Coastal and Shelf Science* 64, 47–57.

Gillanders, B.M. and Kingsford, M.J. (1996) Elements in otoliths may elucidate the contribution of estuarine recruitment to sustaining coastal reef populations of a temperate reef fish. *Marine Ecology Progress Series* 141, 13–20.

Gillanders, B.M. and Kingsford, M.J. (2003) Spatial variation in elemental composition of otoliths of three species of fish (Family Sparidae). *Estuarine, Coastal and Shelf Science* 57, 1049–1064.

Gillanders, B.M., Sanchez-Jerez, P., Bayle-Sempere, J. and Ramos-Espla, A. (2001) Trace elements in otoliths of the two-banded bream from a coastal region in the southwest Mediterranean: are there differences among locations? *Journal of Fish Biology* 59, 350–363.

Gillanders, B.M., Able, K.W., Brown, J.A., Eggleston, D.B. and Sheridan, P.F. (2003) Evidence of connectivity between juvenile and adult habitats for mobile marine fauna: an important component of nurseries. *Marine Ecology Progress Series* 247, 281–295.

Isaac, V.J., Martins, A.S., Haimovici, M. and Andriguetto, J.M. (2006a) *A pesca marinha e estuarine do Brasil no início do século XXI: recursos, tecnologias, aspectos, socioeconômicis e institucionais*. UFPA, Belém, Brazil.

Isaac, V.J., Martins, A.S., Haimovici, M., Castello, J.P. and Andriguetto, J.M. (2006b) Síntese do estado de conhecimento sobre a pesca marina e stearina do Brasil. In: Isaac, V.J., Martins, A.S., Haimovici, M. and

Andriguetto, J.M. (eds) *A pesca marinha e estuarine do Brasil no início do século XXI: recursos, tecnologias, aspectos, socioeconômicis e institucionais*. UFPA, Belém, Brazil, pp. 181–186.
Janekarn, V. and Boonruang, P. (1986) Composition and occurrence of fish larvae in mangrove areas along the east coast of Phuket Island, western peninsular Thailand. *Phuket Marine Biological Research Bulletin* 44, 1–22.
Janekarn, V. and Kiørboe, T. (1991) The distribution of fish larvae along the Andaman coast of Thailand. *Phuket Marine Biological Research Bulletin* 56, 41–61.
Loneragan, N.R. and Potter, I.C. (1990) Factors influencing community structure and distribution of different life-cycles categories of fishes in shallow waters of a large Australian estuary. *Marine Biology* 106, 25–37.
McHugh, J.L. (1967) Estuarine nekton. In: Lauff, G.H. (ed.) *Estuaries. American Association for the Advancement of Science (AAAS), Publication No 83*. AAAS, Washington, DC, pp. 581–620.
Manson, F.J., Loneragan, N.R., Harch, B.D., Skilleter, G.A. and Williams, L. (2005a) A broad-scale analysis of links between fisheries production, mangrove extent, and other environmental factors. *Fisheries Research* 74, 69–85.
Manson, F.J., Loneragan, N.R., Skilleter, G.A. and Phinn, S.R. (2005b) An evaluation of the evidence for linkages between mangroves and fisheries: a synthesis of the literature and identification of research directions. *Oceanography and Marine Biology. An Annual Review* 43, 483–513.
Matheson, R.E. Jr and Gilmore, R.G. Jr (1995) Mojarras (Pisces: Gerreidae) of the Indian River Lagoon. *Bulletin of Marine Science* 57, 281–285.
Mongkolprasit, S. (1983) Fish in mangroves and adjacent areas. In: 1st Training course introduction to mangrove ecosystem, Thailand, 2–30 March 1983. UNDP/UNESCO regional project-training and research pilot program on the mangrove ecosystems of Asia and Oceania Ras/79/002/E/10/13, I-B.
Moore, R.H. (1978) Variation in the diversity of summer estuarine fish populations in Aransas Bay, Texas 1966–1973. *Estuarine and Coastal Marine Science* 6, 495–501.
Morais, T.A. de and Morais, T.L. de (1994) The abundance and diversity of larval and juvenile fish in a tropical estuary. *Estuaries* 17, 216–225.
Neira, F.J., Potter, I.C. and Bradley, J.S. (1992) Seasonal and spatial changes in the larval fish fauna within a large temperate Australian estuary. *Marine Biology* 112, 1–6.
Panella, G. (1971) Fish otoliths: daily growth layers and periodical patterns. *Science* 173, 1124–1127.
Radtke, R.L. (1987) Age and growth information available from the otoliths of the Hawaiian snapper, *Pristipomoides filamentosus*. *Coral Reefs* 6, 19–25.
Robertson, A.I. and Duke, N.C. (1987) Mangroves as nursery sites: comparisons of the abundance and species composition of fish and crustaceans in mangroves and other near shore habitats in tropical Australia. *Marine Biology* 96, 193–205.
Ruffino, M.L. (2004) *A pesca e os recursos pesqueiros na Amazônia brasileira*. IBAMA/ProVárzea, Manaus, Brazil.
Saenger, P., Specht, M.M., Specht, R.L. and Chapman, V.J. (1977) Mangal and coastal salt-marsh communities in Australasia. In: Chapman, V.J. (ed.) *Ecosystems of the World 1. Wet Coastal Ecosystems*. Elsevier, Amsterdam, pp. 293–345.
Sheaves, M. (2005) Nature and consequences of biological connectivity in mangrove systems. *Marine Ecology Progress Series* 302, 293–305.
Skilleter, G.A. and Loneragan, N.R. (2003) Assessing the importance of coastal habitats for fisheries, biodiversity and marine reserves: a new approach taking into account habitat mosaics'. In: Beumer, J.P., Grant, A. and Smith, D.C. (eds) *Aquatic Protected Areas – What Works Best and How Do We Know?* Proceedings of the World Congress on Aquatic Protected Areas – Cairns, August 2002, Australia. Australian Society for Fish Biology, Cairns, Australia, pp. 240–249.
Thorrold, S.R., Latkoczy, C., Swart, P.K. and Jones, C.M. (2001) Natal homing in a marine fish metapopulation. *Science* 291, 297–299.
Tricklebank, K.A., Jacoby, C.A. and Montgomery, J.C. (1992) Composition, distribution and abundance of neustonic ichthyoplankton of northeastern New Zealand. *Estuarine, Coastal and Shelf Science* 34, 263–275.
Tzeng, W. and Wang, Y. (1992) Structure, composition and seasonal dynamics of the larval and juvenile fish community in the mangrove estuary of Tanshui River, Taiwan. *Marine Biology* 113, 481–490.
Whitfield, A.K. (1989) Ichthyoplankton interchange in the mouth region of a southern African estuary. *Marine Ecology Progress Series* 54, 25–33.

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