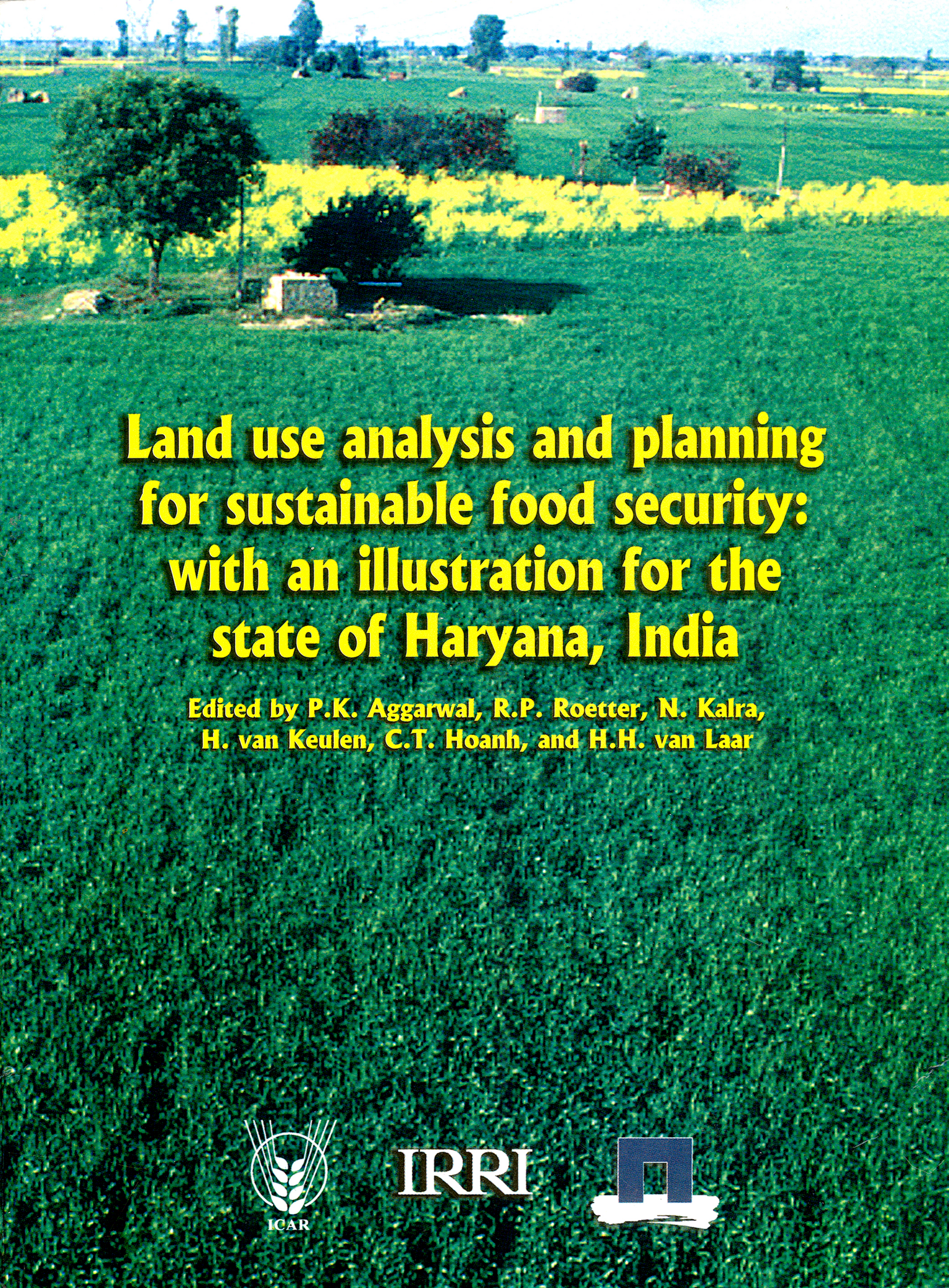

Land use analysis and planning for sustainable food security: with an illustration for the state of Haryana, India

Edited by P.K. Aggarwal, R.P. Roetter, N. Kalra,
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COVER PHOTO: Typical land use in Haryana showing wheat (foreground) and mustard (yellow). Photo by Rice-Wheat Consortium of the International Maize and Wheat Improvement Center.

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Contents

Acronyms

AEU	agro-ecological unit
AEZ	agro-ecological zone
BRI	biocide residue index
DSS	decision support system
FAO	Food and Agriculture Organization of the United Nations
FCDS	food characteristic demand system
FHM	farm household model
FYM	farmyard manure
GDP	gross domestic product
GIS	geographic information system
ICAR	Indian Council for Agricultural Research
IARI	Indian Agricultural Research Institute
IMGLP	interactive multiple goal linear programming
IPM	integrated pest management
IRRI	International Rice Research Institute
lut	land use type
LUST	land use system at a defined technology
MGLP	multiple goal linear programming
NBSSLUP	National Bureau of Soil Survey and Land Use Planning
PCGDP	per capita gross domestic product
RYP	realizable yield potential
TCG	technical coefficient generator
WUR	Wageningen University and Research Centre

Foreword

Food security involves access at all times to the food required by every individual and household for a healthy and productive life. A food-secure region would have biophysical capability of the land to produce food of the quality and quantity required by the people, its farmers would have access to capital, credit, and technology, and consumers would have enough purchasing power to acquire food. Estimates of food demand and supply of different regions have long been made. These estimates differ depending upon the objectives of the studies. Predictive studies intend to give a clear picture of the plausible expectations of food supply and demand based on complicated and ingenious extrapolations. Explorative studies are based on a consistent and scientifically sound study on the technical possibilities to fulfil socioeconomic and ecological goals and overcome constraints. Many of the explorative studies, done in the Western world, point out that the world as a whole can produce enough for everyone, yet several regions, particularly South Asia, may face problems in achieving food security. Thus, food availability at any one scale or place does not guarantee food security at another scale or place.

Our ability to correctly estimate such balances and imbalances at different scales has been limited by the tools at our disposal and our largely disciplinary mode of research. It is therefore necessary to develop improved tools using the fundamentals of production ecology that integrate both biophysical and socioeconomic considerations of the agroecosystems and address the information needs of the entire chain of stakeholders. Development of such systems research tools requires that partnerships across different disciplines, research organizations and nations be closely linked to bring together experience, knowledge and expertise and to increase research efficiency. For more than 40 years, the International Rice Research Institute (IRRI) has been both a major player and a platform for leveraging such partnerships. For instance, one partnership was established in 1985 among the Indian Agricultural Research Institute, IRRI and the Wageningen University and Research Centre (WUR) with the Systems Analysis for Rice Production (SARP) project to develop and implement systems approaches in rice research. This effort led to greater understanding of weather, crop, soil and pest interactions in rice and applications of rice models in estimating potential yields, yield gaps, optimal strategies for water and nitrogen management and agro-ecological zoning. It also resulted in collaboration among scientists of different disciplines using the systems approach as a common way of thinking.

Building on the experiences with the systems research in SARP, our organizations decided in 1996 to continue their partnership to develop tools for land use analysis and planning. This was facilitated by the Systems Research Network for Ecoregional Land Use Planning in Tropical Asia (Sysnet) project, funded by the Ecoregional Fund and managed by the International Service for National Agricultural Research (ISNAR), IRRI and national agricultural research and extension systems of India, Malaysia, the Philippines and Vietnam. Additional national support for developing such tools for the Indian case study was generously provided by the National Agricultural Technology

Project (NATP) and the National Fellow Project of the Indian Council of Agricultural Research. This book reports on various tools developed in these projects to help the stakeholders explore options for future development in the form of opportunities for food production to meet the increasing demand, labour, capital and other resources required for such production levels, and the environmental impact of various production systems. The decision support system developed and its illustration for Haryana amply demonstrate that considerable progress has been made in developing newer tools for ecoregional research. This also shows that the systems approach, with its well-developed analytical framework, databases and powerful simulation models, is capable of providing answers to many of the queries of stakeholders in a relatively short time frame – an important asset in a rapidly changing world economic environment.

We appreciate the enormous efforts put in by the editors and contributors of different papers in developing the methodology and documenting the various tools in this book. H.H. van Laar of WUR and B. Hardy of IRRI edited the papers in this volume.

We hope that the framework presented will be used in other regions of the world to assist a variety of stakeholders in using knowledge for more informed decisions on planning sustainable land use. At the same time, we also hope that this example of joint research will further stimulate partnerships in agricultural research.

Panjab Singh	Ronald P. Cantrell	Rudy Rabbinge
Director, IARI	Director General, IRRI	Dean, Wageningen UR

1. Executive summary

After enjoying self-sufficiency in food during the last three decades, many Asian countries are once again at a crossroads, facing tremendous new challenges because of continued population growth, globalization, environmental degradation and stagnation in farm productivity in intensive farming areas. Rapid economic expansion in the region is increasing demands on land and associated natural resources for agriculture, housing, infrastructure, recreation and industry. The big challenge for agricultural research and development is thus to suggest solutions that best match the multiple and often conflicting development objectives of various stakeholders, such as increased income and employment, improved natural resource quality and food security. It is generally difficult to identify the best solution when there are such potentially conflicting objectives. The identification of economically viable optimal solutions should be based on consideration of the biophysical potential of the resources available and the socioeconomic constraints. A systems approach can facilitate translation of policy goals into objective functions integrated into a biophysical land evaluation model.

This book reports a methodology developed for exploratory land use analysis and planning, and applied for generating options for policy and technical changes for food security of the region as a whole, characterized by food production, income, employment and environmental impact assessment. The use of the decision support system (DSS) has been illustrated for the state of Haryana in northwestern India, which provides a typical example of many Asian regions, characterised at present by conflicts among land use objectives. Notwithstanding recent surpluses of rice and wheat production in the state, there is a continued need to increase land productivity, diversification, employment opportunities and agricultural income and to arrest and preferably reverse the deterioration of agricultural land. There is increasing competition for agricultural land by urbanization, industrial development and recreation. Haryana is thus an appropriate example of the challenge to develop production systems that lead to increased future food security and to solutions that can increase farmers' income.

This state contributed tremendously to the success of the Green Revolution in India. Haryana, located in a semiarid, subtropical environment between 27.4° and 30.6° N latitude and 74.3° and 77.4° E longitude, occupies an area of 4,421,000 ha. The agricultural area constitutes 81% of the total area and 47% of the agricultural area is sown more than once in a year. The state consists of 16 administrative regions (districts) made up of 108 blocks and 7,073 villages. Rice and wheat, commonly grown in a double-cropping rotation, are the major food crops and their current total production is 11 million t. Regional stakeholders of Haryana are interested in finding optimal agricultural land use plans that can meet preset food production goals and maximize employment and income from agriculture, while minimizing pesticide residues,

P.K. Aggarwal et al. *(eds). 2001. Land use analysis and planning for sustainable food security: with an illustration for the state of Haryana, India. IARI-India, IRRI-Philippines and WUR-The Netherlands, pp. 1-6.*

nutrient losses and groundwater withdrawal. In the decision support system, the implications of various conflicting scenarios relating to multiple goals of food production, income and environmental degradation are evaluated by the concurrent use of simulation models, geographic information systems (GIS) and optimization techniques.

The first step in the DSS is to identify stakeholders' goals for regional agricultural development. These are identified based on personal discussions with policymakers and the review of policy documents. Depending upon the goals, a detailed resource inventory is carried out for the study region, using primary surveys, GIs, remote sensing and spatial databases. Homogeneous zones are demarcated based on biophysical and socioeconomic considerations. For Haryana, these were based on characteristics of soil, weather, land use and irrigation and administrative boundaries. The basic soil map of Haryana was reclassified into 17 homogeneous soil units based on soil texture, organic carbon, sodicity and salinity, considered as critical characteristics for this study. Annual rainfall in the state varies from 300 mm in western regions to 1,200 mm in northeastern regions. A rainfall map was prepared based on data of 58 weather stations in and around Haryana. Overlaying this over the reclassified soil map yielded 58 homogeneous agro-ecological units. Rainfed area, which occurs mainly in western parts of Haryana, was mapped indirectly through satellite scans and other conventional resource inventory methods. The addition of this layer, consisting of irrigated and rainfed areas and the boundaries of the 16 districts in the state, to the ago-ecological units resulted in 257 land units. Assuming that the area under settlements and barren land will not be available for cultivation, the non-agricultural area in these units was excluded. The demarcation of the latter was based on a recent satellite inventory.

Relational databases of seasonal groundwater and surface water availability, labour, pesticides, fertilizers, costs and prices of the main farm inputs and outputs, and marketing costs (transportation costs) were developed on a district basis.

The land unit was used as the primary simulation unit. Major agricultural land use types *(lut)* in Haryana are cereal-based. In irrigated areas, rice-wheat is the dominant cropping pattern, whereas, in rainfed areas, pearl millet-fallow or fallow-wheat is the dominant land use type. Based on the current cropping pattern in different parts of the state, 14 crop-based *luts* were selected for this analysis. Livestock is an integral part of Haryana's agriculture. Most farmers keep cattle for milk production, which is used for home consumption as well as for marketing. Three major milch breeds – crossbred cows, buffalo and local cows – were considered in this analysis.

A major goal of our study is to explore options for increasing production. Considering this, we have used five technology levels: current yield, potential yield and three levels between the two for irrigated areas. The techniques for these levels were assumed to become more and more site-specific and capital-intensive. In the absence of good data, only the current level of technology is considered for rainfed areas and for livestock.

The state-level average yields of various crops in farmers' fields were allocated to different land units based on a weighting criteria dependent upon the area, approximate area of different land use types, date of sowing and level of salinity/sodicity in different land units. For each of the land units, potential yields were estimated based on partially calibrated and validated models. The models used were WTGROWS for wheat, CERES-rice for rice and WOFOST for other crops. Yields were simulated for 10 different locations within and around Haryana for which daily weather data were available. The sowing dates for different crops depended on the cropping pattern. Thus, wheat-sowing dates were different in different *luts*. Unavoidable losses in harvesting, transportation and processing of 10% were assumed, for which the simulated yields were corrected. Salinity and sodicity are common in many land units of Haryana. Potential yields were therefore further adjusted for the effects of these conditions, based on reduction factors developed for different crops and yields in the region.

The difference between the adjusted potential yield and the calculated current yield in each land unit was considered the maximum yield gap for that unit. Target yields were set at bridging 25%, 50% and 75% of these yield gaps at three different technology levels. It was assumed that the current level of input use would increase in technologies 2 and 3. Technology levels 4 and 5 were assumed to become more knowledge-based, precise and mechanized. The highest technology was targeted to produce adjusted potential yields with increased use of machinery, inputs and their use efficiencies.

Required inputs and ancillary resultant outputs of various *luts* were calculated for the specified yields. Various approaches, including simulation models, the technical coefficient generator (TCG), surveys and expert knowledge, were used in the estimates. A TCG has been developed based on current knowledge of production ecology to generate biophysical input/output tables needed for optimization. This procedure relates basic soil and weather characteristics and input use to economic yields and environmental impacts for current land use types. The basic data were collected from a literature survey.

Costs of fertilizers and farmyard manure (FYM), human and animal labour and hiring of tractors and procurement prices of produce as well as residues were derived from government statistics. The total cost of production included costs of seeds, human labour, machine labour, irrigation, fertilizers, FYM, Zn sulphate, biocides and miscellaneous (10% of operational costs) costs. Gross income is the value of main produce (grain/cane) and residue. Net income of the farmers was calculated as the difference between gross return and total costs, Since inclusion of fixed costs in the total costs resulted in negative income balances in some luts, in this analysis only operational costs were considered.

Interactive multiple goal linear programming (IMGLP) has been used in this study. The model was developed using XPRESS-MP (Dash Associates), a mathematical modelling and optimization software. The constraints set for the optimization exercise with current constraints and technologies included the availability of land, water, capital and labour. Adoption of different technologies is at present generally constrained by the size of landholdings, which indirectly relates to the farmers' capital base. Small farmers are generally not able to adopt capital-intensive technologies.

Since this constraint was not directly operational in the model, a land-based constraint was introduced into the model to restrict the use of capital-intensive technology 4 to 19.1% of the area (large and very large farms) and technology 5 to 6.3% (rich farmers with very large holdings) in Haryana. All farmers (small, medium and large) could use technologies 1 and 2, whereas only medium and large farmers (80% of the area) could use technology 3. Another similar subconstraint of land-water was introduced to restrict the quantity of water used per unit area under the various technologies.

Land and water constraints were specified per district and per land unit. Labour constraints were specified for each district on a monthly basis, whereas the capital constraint was operational on a district basis only.

Stakeholder-scientist workshops were organized twice to identify the specific goals of development and to formulate various scenarios. Stakeholders gave priority to the following objectives:

- Increasing food production for Haryana in the near future.
- Maximizing income from agriculture.
- Maximizing agricultural production while maintaining employment opportunities.
- Minimizing nitrogen losses and pesticide residues from agriculture.
- Improving water management through the design of intervention measures to reduce groundwater depletion.

Based on these objectives, we have used the DSS for the objective functions – maximizing food grain production and income and employment from the agricultural sector, and minimizing water use and pesticide residues. The results showed that Haryana is capable of producing 39.1 million tons of food (rice and wheat), provided there are no constraints. This also assumes that all farmers are capable of adopting all technologies. In this scenario, water requirements are more than three times higher than water currently available. The scenario also indicates that this situation would need more than twice the capital currently used. Milk production, employment generation and overall income also increase spectacularly in this scenario.

Since technology adoption is likely to remain a constraint, in the next round this constraint was introduced. In that situation, food production potential decreased to 28 million tons. Requirements for all resources were nevertheless still phenomenal. When the water constraint was introduced to restrict water use to the current level of availability, food production decreased to 11.4 million tons. At the same time, income, milk production and employment as well became much lower. The further introduction of capital and labour as additional constraints had a relatively small effect on food production. Irrespective of scenario, the biocide index was always within the permissible limit (< 200 is considered as permissible), although it increased as more constraints were imposed. On the contrary, N loss was very high when land and technology were the only constraints.

The primary objective of most farmers is to earn sufficient income from their farm enterprise and not necessarily to produce sufficient food. In the next scenario, we therefore focussed on this objective function, keeping current food production (10.5 million tons of rice and wheat) as the lower boundary. The results indicated that income could be increased substantially, provided irrigation water was available. This type of production at the same time can result in considerable environmental problems associated with biocide residues, since cash crops such as cotton, sugarcane and potato currently depend on considerable biocide applications. Since opportunities for increases in water resources in Haryana are limited, income has to be restricted to 56 billion rupees[1]. In that situation, food production was 10.7 million tons, indicating that some increase in income is possible through diversification involving cash crops.

In the next scenario, we focussed on minimizing water use because current water use (particularly groundwater) is causing declining water tables in many parts of the state. The results showed that it is possible to maintain current food production with almost half the irrigation water. The model does this by allocating more area to more advanced technologies, which produce more food and have higher water use efficiencies. Since a small area can produce the minimum target of food, and the model prescribed use of the total agricultural area, the remaining land was allocated to a fallow-wheat system, which does not require any irrigation water and yet produces food. The biocide index is also very low when land is the only constraint. When other constraints are gradually introduced into the model, food production is maintained at the minimum limit.

Scenarios for food security for 2000 and 2010 were identified based on the importance of the state for the country as a whole and for the development objectives of Haryana. The results indicated that options are available at an aggregated scale for the state to increase income from agriculture by diversification to less water-intensive crops. This has differential impacts on the economy and employment patterns of different districts as well as on the environment.

In conclusion, the decision support system presented in this book is a powerful tool that can accelerate knowledge integration as well as its use for agricultural development and agri-wealth creation. It provides a useful tool to explore the window of opportunities for food security and associated land use planning for a region. The key advantage is that it integrates the knowledge base of several scientists from different disciplinary backgrounds and attempts to address some real issues identified by the stakeholders. It also helps us in analysing scientifically whether many of our ambitious goals for development are feasible and at what costs.

Some constraints need to be addressed before this DSS and its results for Haryana gain wider acceptance. Our results point out that availability of water will remain a major constraint to increasing food production in Haryana. Since we considered availability of water resources at today's level, the analysis would need to be repeated more critically, with a view on the total water resources likely to become available in the future. The data for the latter are not easily available at the land unit or even district level. Therefore, availability of good quality data at the desired spatial scale is an important limitation to making progress.

The TCG, although simple in approach and easy to use, is not able to upscale critical daily events to seasonal and annual results. This semiempirical approach also has limitations to extending current knowledge to determine input/output relationships for alternative possible production activities in the future. Simple yet robust simulation

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[1] 1 US$ = 45 rupees (currency exchange rate 1998)

models are needed to facilitate this.

The results of the IMGLP model are exploratory and only a single (higher) level of stakeholders is considered, while the interests of the other stakeholders in the region (e.g., farmers, village-level managers) have been ignored. Consequently, although the model illustrates the opportunities at the regional level, these may or may not be easy to implement by the primary land use decision maker – the farmer. There will be a large capital requirement at the state level to finance the equipment needed to implement capital-intensive technologies 4 and 5. This also needs to be considered in future analyses.

There is a need to further strengthen research programmes involving biologists, social scientists, economists and stakeholders to overcome the limitations of the current methodologies. A nested modelling effort using bottom-up and top-down communication between farms and the region would be most desirable. Simultaneously, user-friendly interface programs should be developed to facilitate the direct use of the DSS by the various stakeholders. Once the DSS is expanded to overcome its current limitations and data at the desired scale become available, then the stakeholders' needs of an instrument to rapidly understand the impact of policy on food security in a changing world economic environment could be fulfilled.

2. The challenge of planning for sustainable food security

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Introduction

Food is a basic need of any society and, in the course of history, safeguarding the food supply has been a major consideration in policy development. Early humans started domesticating plants and animals to increase the availability of food. The carrying capacity of the land in the Pleistocene, when food was gathered by hunting, was probably 0.1 person km^{-2} . It increased to 1 to 2 persons with dryland farming and to 8 to 12 persons with irrigation (Bender, 1975). Today, with industrial fertilizer use, it is much higher. Food security contributes vitally to social and political stability as is evident from the numerous wars that have been fought around the world to acquire fertile land and its associated natural resources, particularly irrigation water.

Food demand of humans has increased dramatically over the last 50 years, when, mainly as the result of improved medical knowledge and extension, better nutrition and finally water quality, the world population has more than doubled. This increase in population has taken place predominantly in the less-developed regions of the world, particularly in Asia. The Indian subcontinent in South Asia is now home to almost one-fifth of the world population.

Before the Industrial Revolution, most farming throughout the world was based on organic methods and yields of grain crops were low, although the transformation of agriculture from subsistence to commercial farming started in the 16th century in Europe (Swaminathan, 1982). Under the pressure of the devastating famines that were regular phenomena, efforts started to increase staple food production in the 20th century. The introduction of the tractor and other labour-saving machinery and the use of synthetic nitrogen fertilizers revolutionized agriculture (Evans, 1998). The availability of hybrid maize that yielded at least twice that of open-pollinated varieties triggered the transition from traditional practices to modem scientifically based agricultural practices in the Unites States in the 1930s. These practices then spread to other crops as well. The introduction of dwarf wheat and rice varieties in the 1960s and ’70s through the Green Revolution changed the agricultural landscape considerably in large parts of the world, particularly in areas characterized by good soils and irrigation facilities. World grain production increased from 640 million t in 1934-38 to more than 2,000 million t in 1998 through an increase in cultivated area, cropping intensity and modem varieties and increased application of water, nutrients and pesticides.

The explosive increase in food production in the western world has led to a situation

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of supply exceeding demand. These surpluses of food were absorbed by the developing countries during the 1950s but, in the ’60s, imports by the latter shrank because of the Green Revolution. Later, demand in developing countries again increased because of rapid population growth and droughts in some parts of Asia. The 1970s and ’80s saw a stimulation of fertilizer use and irrigation expansion, once again leading to several importing nations of Asia, Africa and South America becoming self-sufficient or even transforming themselves into food-exporting countries. Massive subsidies have since been provided by the U.S. and European governments to maintain their farmers’ income despite falling world prices,

In most of Asia, during the 20th century, in particular up to 1965, food production remained stagnant, while the population increased rapidly, resulting in a decreased availability of food per capita (Randhawa, 1979). Since then, however, the production of food grains has increased spectacularly because of the Green Revolution. Total food production in India, for example, increased from 69 million t in 1965 to 208 million t in 2000 and mean cereal productivity increased from less than 1.0 to almost 3.0 t ha^{-1} . These increases were largely the result of area expansion, development and the large-scale cultivation of new high-yielding semidwarf varieties in the early 1960s and increased application of irrigation water, fertilizers and biocides. This transformation was especially successful where agricultural infrastructure was in place and environmental conditions were favourable such as in northwestern India, the island of Java in Indonesia and central Luzon in the Philippines. It is important to realize that this transformation could not have taken place without the support of governments in terms of policy (Swaminathan, 1982). Governments made available seeds, credit, irrigation, fertilizers and energy at subsidized prices and also ensured a remunerative return to the farming community by guaranteeing the prices of outputs. Massive imports of wheat seeds were ordered by the Indian government in 1965 to ensure that seeds became available to as many farmers as possible in a relatively short time frame. These subsidies, although often resulting in regional disparities, have been helpful to the region from the food security point of view. The simultaneous introduction of packages of technology, services and government policy resulted in rapid agricultural growth. Figure 1 shows that food availability per person has been rising in India during the last 40 years, as in other parts of Asia and the world as a whole. Today, on average, 2,500 calories are available per day per person in India *versus* 2,750 in the world and more than 3,700 for an average American (FAO Statistics).

Thanks to the Green Revolution, the pessimism of Malthus and of the Paddock brothers proved to be a Himalayan blunder. Malthus (1798) had expressed his pessimism on resolving poverty and hunger problems of the world. Paddock and Paddock (1967) concluded that several countries in Asia, such as India, could not be saved from widespread hunger and famines. The very severe drought of 1987 in India could be managed easily and did not lead to problems of food security because of the government policy of establishing buffer stocks. Similarly, during the recent drought of 1999-2000 in the states of Gujarat and Rajasthan, although resulting in problems of water scarcity, massive public distribution of food ensured that relatively few went to bed hungry.

Food security of the world as a whole and of various countries in particular, such as

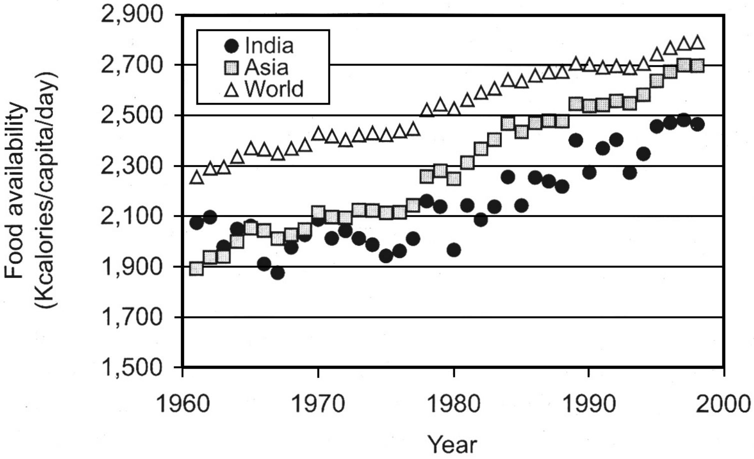

Figure 1. Average availability of food per person in India, Asia, and the world from 1960 till 1999.

those in South Asia, however, is at grave risk once again because of the continued population growth. The world population today has surpassed 6 billion, of which almost 20% live in South Asia. It is projected that about 700 million people, approximately equal to the current population of Europe, will be added in South Asia alone in the next 30 years, assuming a medium growth scenario. By 2050, India's population is expected to have grown to 1.6 billion and the country will have replaced China as the most populous country in the world (UN, 1997).

This rapid and continuing increase in population implies a greater demand for food. Although the world as a whole has sufficient food for everyone and perhaps will continue to have in the future as well, widespread poverty in many countries prevents access to this food. An analysis based on food availability per capita might therefore create a false sense of food security (Sen, 1993). Today, even after so many 'revolutions' in agriculture, almost 800 million people, almost all of whom live in the developing world, go hungry and almost 1.6 billion remain malnourished (FAO, 1999). Although the number of hungry people is currently decreasing at the rate of 8 million per year, this is too low to have any meaningful effect in the near future. In fact, from 1990 to 1995, a reduction of 100 million in undernourished people was attained, but this was confined to only 37 countries. In other countries, the number of hungry people actually increased by almost 60 million during this period. A large majority of the undernourished live in Asia, which still accounts for two-thirds of the undernourished in the world. In the 21st century, one of the great challenges will be to ensure that food production is coupled with both poverty reduction and environmental preservation. That requires greater attention to small and marginal farmers. To ensure their food security, food will have to be produced where needed, for socioeconomic and political reasons (Rabbinge, 1999). Asia may not have enough purchasing power to procure food from the western world, where it would be in surplus. Even if the capital were available, it may not be logistically feasible in physical terms to import substantial quantities of food from such long distances. Moreover, such a dependence on food imports may result in political instability in the region. It is believed that, in the 21st century, the world food situation will be strongly dominated by the changes that occur in Asia because of its huge population, changes in diet and associated demand for food (Rabbinge, 1999).

There is also likely to be a significant shift in the type of food needed in the future. It is projected that 51% of the Asian population will be living in urban areas in 2020 compared with 32% now (UN, 1997). Historical evidence shows that the per capita demand for cereals generally decreases with increasing urbanization. Yet, in absolute terms, the demand for wheat and rice will remain high. It is estimated that the total demand for cereals in Asia will increase to 10,430 million t by 2020 from a benchmark demand of 695 million t in 1993 (Garrett, 1995). Asian rice production alone must increase to more than 800 million t over the next 25 years from the 1995 level of about 5000 million t (Hossain, 1995).

For India, various projections of future food demand have been made (Rosegrant *et al.,* 1995; Kumar, 1998; Bhalla *et al.,* 1999). According to these estimates, cereal requirements by 2020 will be from 257 to 374 million t, depending on income. Kumar (Chapter 3) has made a detailed assessment of the consumption demands for various commodities in India in 2010 and 2020. This analysis takes into account projected changes in population, diet and income. The demand for rice and wheat, the predominant staple foods, is expected to increase to 122 and 103 million t, respectively, by 2020, assuming medium income growth. The demand for pulses, fruits, vegetables, milk, meat, eggs and marine products is also expected to increase sharply. This additional food will have to be produced from the same or even a shrinking land resource base because no additional land is available for cultivation. Thus, average yields of rice, wheat, coarse grains and pulses need to increase by 56%, 62%, 36% and 116%, respectively, by 2020.

The possibility of impeding food shortages in the 21st century have once again brought out the prophets of doomsday. Brown and Kane (1994), for instance, have predicted a severe shortage of food by 2030 in India and China, two countries that make up about one-third of the world’s population. According to these estimates, China and India would need to import 216 and 45 million tons of grain respectively, by 2030, assuming that current population growth rates continue and the increase in food production remains limited by the present availability of land and water. Although these figures are alarming, other recent estimates suggest that at least India would be largely able to meet its requirements (Kumar, 1998). Nevertheless, it is clear that in the coming decades food security for both India and China could be at grave risk unless population is controlled and food production increases considerably.

Although there is pressure to increase production to meet higher demand, lately the growth rate in cultivated area, production and yield has slowed significantly. The annual rate of growth in food production and yield peaked during the early years of the

Green Revolution, but has declined since the 1980s. The growth in productivity of rice and wheat shows either a decline or stagnation in several intensive-farming districts of Punjab and Haryana (Sinha *et al.,* 1998; Aggarwal *et al.,* 2000). For example, rice productivity in Punjab grew by 8.97% in 1965-74 but the growth rate has now dropped to 1.13% and in some districts to even below 1.0%. Ludhiana and Ropar exhibit negative growth rates. Many districts of Haryana also show a stagnation or slow increase in productivity.

Adding to the worries of food planners is that grain yields on experimental farms are also stagnating. The yield potential of rice in the tropics has not increased above 10 t ha^{-1} since IR8 was released 30 years ago, despite significant achievements in attaining yield stability, increasing dry matter accumulation per day and improving grain quality (Aggarwal *et al.,* 1996). A review of data of the regional statistics, agronomists' experiments, long-term trials, breeders' variety evaluation trials and simulation studies shows stagnation of yields in rice and wheat in northern India (Aggarwal *et al.,* 2000). The yields of major cereals on experimental farms in northwestern India have also not increased significantly since 1980 (Sinha, 1999), although some studies have shown that wheat yields have been increasing significantly (Rajaram, 1998; Nagarajan, 1998). Although, it has been demonstrated that hybrid rice and wheat and 'super rice' varieties being developed at the International Rice Research Institute (IRRI) have higher yield potentials, these yields have not materialized so far in farmers' fields.

The perceived gradual increase in environmental degradation, early signs of which are becoming visible in areas that benefitted largely from the Green Revolution technologies, is further compounding the problem. Great concern now exists about declining soil fertility, changes in water table depth, rising salinity, resistance of harmful organisms to many pesticides and degradation of irrigation water quality, for example, in northwestern India (Sinha *et al.,* 1998). In the major rice-wheat regions and southern parts of Haryana and Punjab, organic carbon content in the soil has declined to 0.2% from 0.5% in the 1960s. Soils low in phosphorus (P) content have increased to 73% from only 3.5% in 1975 in Haryana. Similarly, the proportion of soils high in potash (K) has declined from 91% in 1975 to 62% in 1995 (Sinha *et al.,* 1998). Nutrient removal by crops over time has exceeded application, in particular for P and K. Consequently, farmers now have to apply more fertilizer to obtain the same yield as they achieved 20–30 years ago. These signs of unsustainability must be attributed, at least partly, to the deterioration of soil quality.

The introduction of canal irrigation in Haryana has resulted in almost 0.5 million hectares of the state being affected by soil salinity (Joshi and Tyagi, 1994). Aphids, stem borers and *Heliothis armigera* have shown a tendency to increase under the rice-wheat system. False smut, sheath rot, sheath blight and grain discoloration in rice have also increased. Similarly, foliar blights, head scab and Karnal bunt have shown increasing trends in wheat. The weed *Phalaris minor* has become resistant to most herbicides in large areas under rice-wheat and is a real threat to wheat production (Sinha *et al.,* 1998).

The rapid increase in the number of tubewells during the last three decades in northwestern India and other regions has resulted in overexploitation of groundwater in

Table 1. District-wise fall in groundwater level in Punjab during 1984-94. (Source: Sinha *et al.,* 1998).

Districts (paddy predominant blocks only)	Average fall in water table during June 1984-94 (m)
Amritsar	2.3
Jallandhar	2.5
Eudhiana	1.9
Ferozpur	4.5
Kapurthala	1.8
Patiala	4.8
Sangrur	5.1
Bhatinda	1.9
Faridkot	4.5
Fatehgarh Sahib	2.7

many blocks, leading to declining groundwater levels. In Punjab, water tables have declined significantly during the period 1984-94 in most districts (Table 1). In some districts, however, the water table has risen, resulting in increased problems of salinity.

The ongoing globalization process and economic reforms associated with the World Trade Organisation are forcing many countries, including India, to make structural adjustments in the agricultural sector. Agriculture has to become more competitive and efficient and has to operate without subsidies, many of which are already being phased out. The current surplus food production in Europe and North America occurs partly thanks to the tremendous protection farmers have against lower market prices. On the other hand, in developing countries, governments are promoting reduced domestic agricultural prices through public monopolies. Once the protection is removed from agriculture, production in the developed world of today may not increase anymore, and may increase only slightly in developing countries.

Liberalization of trade is also expected to lead to greater fluctuations in the prices of agricultural commodities, which, in turn, can greatly affect the economic growth of nations. Increases in prices will particularly affect low-income, food-importing countries and major exporting countries. During the transition period from controlled markets to more open and competitive markets, many rural poor people in developing countries with limited land, capital, technology and access to markets may be adversely affected by competition from the organized, high-tech farmers of the West. This would result, at least in the short term, in increased food insecurity.

Need for integrated planning

Thus, agricultural scientists face a tremendous challenge to develop technologies for increased food production in the coming decades. Poverty reduction and food security represent major challenges to humans in the 21st century. There is an urgent need to consolidate past yield gains and further increase the yield potential of major food crops. It is very important to know how much additional cereal, responsible for more than

60% of food, particularly the staple food crops such as rice and wheat, can be produced in different regions to meet the increasing demand. For population-rich and low-income regions, such as major parts of India, it is also important to know where and at what cost this food can be produced with current technologies and/or what alternative technologies will be needed to meet the desired production targets. The future increases have to be realized on less land with less inputs such as labour, water, nitrogen and pesticides in such a way that scarce natural resources are conserved. Developmental policies are needed that directly address the issue of food security of regions and their populations for all times to come.

At the same time, today, when incomes and population are increasing, even in developing countries one can witness strong competition for land. Rapidly expanding urban settlements are gradually occupying good agricultural land. Demand is also increasing for other land uses such as for industry and recreation. Staple crops face increasing competition from cash crops such as sugarcane, cotton and vegetables. The greater awareness about possible environmental degradation, loss of forest cover in the past and possibility of CO_2 sequestration by trees is also increasing the demand for forest cover. In brief, current pressure on land is increasing and its use has to become multifunctional in any region, but ensuring food security should remain the primary goal in poor regions. A thorough quantitative assessment of the potentials and constraints of land is urgently needed, in which scientific knowledge, socioeconomic conditions and the interest of various stakeholders can be harmonized to develop efficient and sustainable land use systems.

Methodologies for assessment

Planning for sustainable development requires attention to the following major factors that affect the food security of individuals, households, regions and the world:

1. *Availability of adequate supplies* to meet each person's daily energy and nutrient needs. This depends on the physical, biological and socioeconomic resource endowments of the region.
2. *Access to sufficient food* – People should have enough purchasing power and the sociopolitical structure of the region should be conducive.
3. *Stability of supplies* – Climatic extremes such as droughts and floods and seasonal unemployment can make people vulnerable.
4. *Cultural acceptability* – People of different regions, castes and races often have certain diet sensitivities that need to be respected.

Food security is thus the availability and accessibility of sufficient food of the desired quality at all times and is the outcome of food supply and demand, modified by the socioeconomic characteristics that determine prices and purchasing power. The security of the people is ensured only when all four factors mentioned above work in harmony. Thus, besides having sufficient capacity for food production, issues such as employment, capital, infrastructure and diet also contribute directly or indirectly to the food security of regions. An equally important dimension of food security, particularly now, is the potential environmental degradation associated with food production and consequently supply.

FAO (1983) has proposed a set of indicators of food insecurity at the national level. The main purpose of these indicators is to provide a clear signal in advance of a pending food shortage that allows sufficient time to prevent its occurrence:

- Severe production problems because of unfavourable crop conditions or serious outbreaks of pests.
- Severe accessibility problems, for example, a sharp and substantial rise in domestic food prices and hoarding on a large scale.
- Severe import problems, for example, a substantial rise in the import bill of basic food, particularly in a low-income country, or a sharp deterioration in the balance of payments.
- Serious deterioration of the nutritional situation.
- A large influx of refugees.

Considerable attention has been paid to the factors controlling food security at the household, regional, national and global scale (Bindraban *et al.,* 1998; FAO, 1999). Planning for sustainable food security obviously requires an integrated assessment of biophysical, socioeconomic, political and environmental conditions. Although several studies have been carried out in the past, most of these have focussed on one or two aspects only. FAO has been involved in extensive methodology development and case studies on land evaluation. The procedures to determine the potential of different kinds of land for a variety of uses were illustrated first in the framework for land evaluation (FAO, 1976). This was largely a biophysical evaluation of the land carried out by soil survey specialists, although socioeconomic considerations were included in the framework. Subsequently, the methodology was applied in agro-ecological zoning and for estimating the population carrying capacity of the land (Higgins *et al.,* 1982; FAO, 1993). These studies formed the basis of several national-level studies on land use planning. The main components of these methodologies (Brinkman, 1994) were:

- Formulation of major land uses and their ecological requirements. This covers 25 crop species, 20 pasture grasses and four fodder grasses, eight pasture and fodder legume combinations, six livestock husbandry types and 31 species of fuelwood.
- Compilation of a national land resources and land use database dealing with edaphic and climatic features, farming systems, cash crop zones, forest zones, irrigation schemes and administrative boundaries.
- Assessment of land productivity potentials under different land uses. This used a simple crop model to match photosynthetic and phenological requirements with the available climatic inventory and the edaphic features of the region.
- Developmental planning, including assessment of potential population supporting capacities and input requirements to address policy issues.

However, such land evaluation methodologies do not relate biophysical criteria to crop productivity, intensity of input use, socioeconomic conditions and environmental impact. Land use patterns at any given time, besides being determined by the biophysical potential of the land, are also under strong control of market forces. At the same time, market-driven land use patterns often lead to unsustainable use of land and thus land degradation and decreasing profits in the long term.

The farming systems analysis approach overcomes many of these problems at the farm scale since it analyses the constraints faced by agricultural production from a multidisciplinary angle and identifies the intervention points (Fresco, 1988; Fresco *et al.,* 1992). It involves the key stakeholder – the farmer – in understanding the potentials and constraints of the land. The approach, however, is generally qualitative, operates only at the farmer's level and does not provide information on the environmental consequences of a given land use. Spatial and temporal effects of current resource use are also ignored, while promoting production strategies based on land use. Thus, different scales – global, national, regional and household – are not addressed. The existing methodologies also lack flexibility to rapidly respond to continuously changing policy environments with multiple and often conflicting goals. Adoption of research results based strictly on a biophysical evaluation has not always been very successful because of the neglect of socioeconomic considerations in the recommendations. To identify the existing and emerging constraints limiting productivity and opportunities for sustainable increases in the future, it is important to analyse the various factors constituting the production environment. This environment contains the natural resources, such as soil fertility, germplasm, level of input use, opportunities allowed by climate, interactions with climatic variability and institutional and infrastructural facilities available to the farmers. Interactions among these factors often make decision making a complex process in many production systems of today. Many earlier studies are also biased in the sense that they are based on aggregated estimates at the district level or above. The spatio-temporal differences in resource availability and constraints in any area can greatly affect the estimates of food production.

Analysis of options for regional development focuses on identifying the best development strategy. However, when there are potentially conflicting objectives with built-in trade-offs, such as maximizing production, sustaining environmental quality and maximizing farmers' income, it is difficult to define 'the best' solution. Information therefore needs to be generated to determine the consequences and trade-offs of different sets of policy aims for agriculture. The economically viable optimal solution is arrived at by considering the biophysical potential of the resources available and the socioeconomic constraints. Thus, a systems approach is needed, in which it is possible to translate policy goals into objective functions integrated into a biophysical land evaluation model. Such an approach can be used to identify production systems that are both economically viable: and agronomically efficient, minimize environmental impact or are driven by land use objectives. In most developing countries, agriculture is the biggest user of land and the largest regional employer. Therefore, the regional agricultural planning approach can be considered the most suitable for land use planning in a developing country (Hengsdijk and Kruseman, 1993).

Current availability of simulation models and other systems research tools provides an opportunity for an interdisciplinary approach to agricultural planning and development. Systems analytical tools, including simulation models, decision support systems (DSS), databases, geographic information systems (GIS) and optimization techniques, are increasingly being used for environmental characterization, agro-ecological zoning, agro-technology transfer and strategic and tactical decision making.

Interdisciplinary studies relating to land use analysis and food security are relatively recent. During the last decade, various systems research tools have been used to generate better quantitative estimates of production opportunities and analyse past, current and future land use options. Land use studies dealing with the future are generally of two types – predictive and explorative. Several examples are available now, in which both types have been applied for understanding multifunctional land use and for policy planning at different scales. Predictive studies basically extrapolate past and current trends into the future. These are useful when these trends do not change substantially and the resources and constraints remain at the same level. Such studies consider the current socioeconomic conditions as the major constraint for modification. Examples of such studies can be found in Brown and Kane (1994), Alexandratos (1995) and Veldkamp and Fresco (1996). On the other hand, explorative land use studies focus more on defining the range of developmental possibilities at different scales (Van Ittersum *et al.,* 1998). They emphasize the biophysical possibilities, assuming that socioeconomic constraints can be managed in the long run (Van Keulen *et al.,* 2000). Examples of these studies are found in WRR (1992), Penning de Vries *et al.* (1995), Veeneklaas *et al.* (1991) and Stoorvogel (1995).

The present study

Problems and policy issues in the Haryana study region

Haryana is a relatively small state to the north of New Delhi with an area of 4,421,000 ha, located in a semiarid, subtropical environment between 27.4° and 30.6° N and 74.3° to 77.4° E (Figure 2). The state consists of 16 administrative regions (districts) comprising 108 blocks and 7,073 villages (199 1 data). The agricultural area constitutes

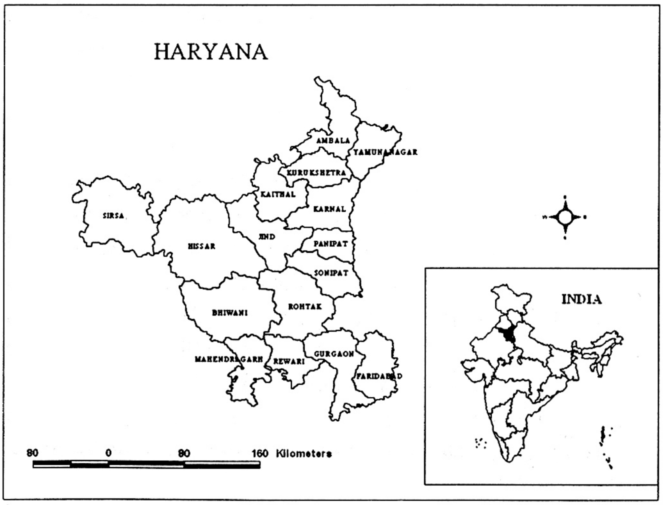

Figure 2. The districts of Haryana and its position in India (inset).

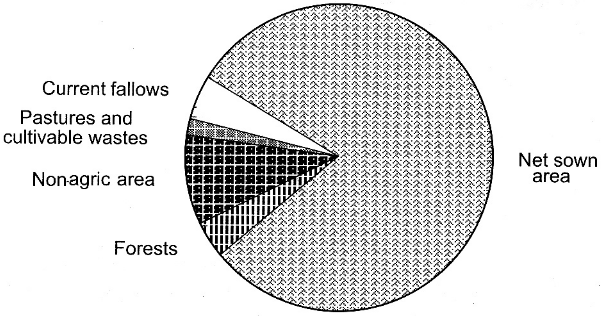

Figure 3. Current land use in Haryana.

81% of the total area (Figure 3) and 47% of the agricultural area is sown more than once annually. Almost 77% of its cultivable area is irrigated. The state has only 4% area under forests and pastures are virtually absent (Figure 3). Total population in the 1991 census was 16.5 million, 75% of whom live in rural villages.

Haryana has been and is contributing tremendously to India's food security. Together with the adjoining state of Punjab, it produced 4% of the total wheat and rice in the country in 1950-51, which rose to 8% by 1965-66 and is now almost 20%. Both states contribute enormously to central food grain procurement, which enables operation of the national public distribution system, which is crucial for the food security of the large urban and semirural population. The share of these states in total food grain procurement was 68% in 1994-95. Since the region is endowed with good soils, irrigation facilities, markets and infrastructure, these states are expected to retain tremendous importance for India's food security.

Future goals

Increasing food production

Production of rice and wheat, the dominant food grains of Haryana, is now 10.5 million tons. Both crops are commonly grown in double-cropping rotations and their average productivity ranges from 3 to 5 t ha^{-1}. Rice is grown in the rainy season (*kharif*) and wheat is grown in the winter season (*rabi*). Rice yields have shown intermittent periods of stagnation at the state level during the last three decades (Figure 4). In recent times, rice yields have shown stagnation or a small decline depending upon the district. Part of the reason for the observed stagnation/decline in rice yields could be that higher yielding but less profitable rice varieties are being replaced by lower yielding but more profitable basmati (scented) rice varieties in large parts of the state. Wheat yields have shown consistent improvement during the last three decades, except during the last 3–4 years, when some signs of stagnation appeared. The state produces 8 million tons of wheat and almost 70% of the area during the *rabi* season is allocated to wheat cultivation.

In addition to these primary staple foods, production of pearl millet and chickpea is high, particularly in the rainfed areas of southern Haryana. Cotton is another major

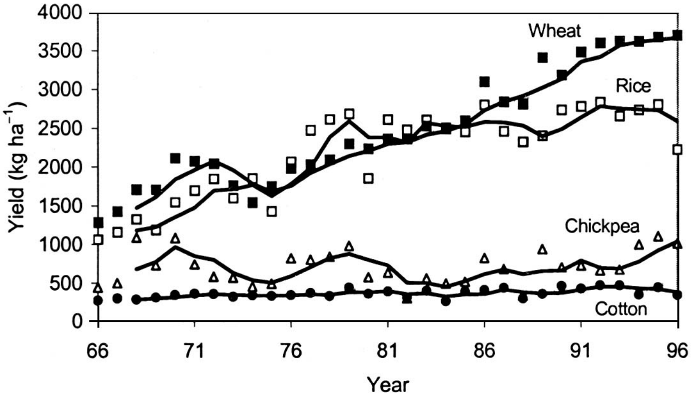

Figure 4. Trends in productivity of important crops over time (1966-96) in Haryana.

crop of the state, produced in Sirsa and Hissar districts in the west. Small areas are allocated to the cultivation of vegetables, fruits, sugarcane, potato and other minor crops. Yields of pulses and oilseed crops in Haryana, in particular chickpea, have shown strong sensitivity to annual fluctuations in weather and other production factors. Cotton yields are more or less similar to those in the 1960s (Figure 4).

Although in recent years there has been a surplus production of rice and wheat in the state, Haryana has to produce more because it is one of the largest suppliers of food to the public distribution system of the central government. Recently, a policy goal was set to double food production in the country by 2010. The Haryana government is therefore interested in determining the opportunities to increase food production in the state and the possible costs involved.

Increasing income of farmers and the region

Haryana is largely agricultural (Figure 3); therefore, much of the state's economy and many of its farmers depend on income from farming. Haryana has a considerable population of livestock, which also contributes significantly to income. Since the costs of cultivation and living are continuously going up, strategies need to be developed that enhance the income of farmers.

Employment opportunities in agriculture

Although Haryana is largely agriculturally based, a considerable proportion of the younger population migrates out to the cities for employment. The major reasons are the low income from the farms, which are generally small and cannot support many people, and the increasing employment opportunities in neighbouring metropolitan areas such as Delhi.

Another important policy goal for Haryana is equity among different regions. Because almost one-third of Haryana is rainfed, wide disparities occur in regional development and income among different districts. The rainfed areas in the southern and western regions are generally poor because of limited agricultural development.

Diversification of land use

A large part of Haryana adjacent to New Delhi has been declared the National Capital Region. Regional development in this area will have an increasingly urban bias for settlements, industry, roads and other urban uses. Hence, food production will have to be increased from the remaining areas.

At the same time, the forest area in Haryana is now almost negligible. In view of the National Forest Policy, this has to be substantially increased in the future, on a long-term basis, to 30%. It is therefore important to identify the most appropriate land for this purpose, without sacrificing other development goals of the state.

Environmental issues

Haryana's agriculture is now under moderate pressure, related to several environmental issues, in particular related to changes in water table depths, salinity/sodicity, pest profiles, pesticide use and low water use efficiency. Because of excessive withdrawal of groundwater by the rice-wheat system, problems of water table decline have become acute in the eastern districts of Karnal and Kurukshetra. On the other hand, the water table is rising in Hisar district because of the prevailing canal irrigation system and inadequate drainage. The central districts of Rohtak and Panipat have become prone to waterlogging because of their topography and inadequate drainage systems. These changes affect crop yields and thus income from fanning. The subsidies involved in water-pricing policy have aggravated the problems. Current agricultural policies have encouraged fanners to use more subsidized inputs such as nitrogen, energy and water to compensate for inefficiencies in other parts of the production system. The problem of high nitrate concentrations in the groundwater has also surfaced in a few places.

Information needs of an agricultural land use planner

The state land use planners and agricultural officials need information to formulate integrated agricultural development plans that will maximize food production, minimize environmental degradation and still attain socioeconomic goals. Since many of these goals are rapidly changing, tools are needed to rapidly assess the consequences of (lack of) policy action on agriculture in a rapidly changing policy environment.

The key stakeholders of the state (Secretary of Agriculture, Director of Agriculture and other officials) formulated the following important questions with respect to qualitative policy goals for the state in the coming years:

- How much increase is possible in food production and where?
- What inputs will be required to attain this production?
- Can some land be taken away from agriculture without losing gross agricultural production?
- What are the environmental trade-offs (water use, pesticide residues and nutrient losses) of maximizing agricultural production?
- How many people can be gainfully employed in agriculture?
- What land use will improve the water balance in different parts of Haryana?
- How can farmers' incomes be increased in view of changing terms of trade?
- What policy interventions are needed to realize multiple goals?

Overview of our approach

This monograph describes the framework of a decision support system that analyses future land use options for food security based on present technical knowledge, socioeconomic constraints and anticipated future objectives and constraints. Food security can be sustainably achieved if, apart from the availability of food, agricultural land use activities offer employment opportunities, contribute to poverty alleviation and minimize environmental effects. Technical knowledge refers to insight into the operation of biophysical systems. Implications of various scenarios have been evaluated by simultaneous use of simulation models, GIS and optimization techniques. The more specific objectives of this study were

- To develop and evaluate a quantitative land evaluation system using a GIS-based inventory of natural and other production resources, a simulation of biophysical production potentials and resource use-related environmental implications.
- To formulate a multiple criteria decision-making framework for evaluating simulated land use production options.
- To illustrate the application of this framework by generating options for land uses that can efficiently meet the agricultural production targets, deal with environmental concerns and increase regional agricultural income in Haryana.

The land use analysis in this study can be considered as both exploratory and predictive. In several scenarios, we have assumed past and current trends in resource availability and constraints, whereas in others we have explored the window of opportunities by selectively removing the constraints.

Figure 5 describes the key elements for assessing food security. Food security is basically governed by the balance between food demand and supply, both of which are primarily governed by the biophysical and socioeconomic resources and constraints of the region. Food demand is a function of population size, its income and the diet used by the average person. On the other hand, regional food production depends on the agro-technical feasibility of various land use types considering the regional resources and constraints. In combination with environmental impact assessment and socioeconomic possibilities, gross food production is assessed. Together with food stocks and possible food aid, net food supply can be determined.

This scheme has been operationalized using a systems approach (Figure 6). It essentially consists of first setting the quantitative policy goals needed for food security of the region. The policy views of the stakeholders with respect to production, income, social issues and environmental degradation are quantified on the basis of published documents or personal discussions. A detailed land evaluation is then performed based on spatial and temporal variation in soil and climatic resources of the region, using relational databases, GIS and remote sensing. This results in several homogeneous agro-ecological units. Regionally developed and tested transfer functions were used to determine soil moisture and nutrient characteristics of each agro-ecological unit. Considering the crop and livestock activities of the region, key land use types were defied. The possible production technologies and activities were defined based on the policy goals and socioeconomic resources of the region. Regionally calibrated and

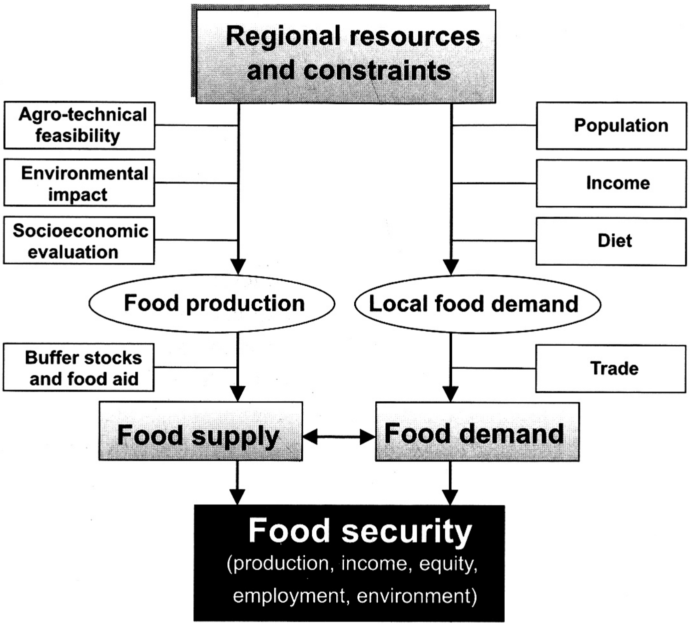

Figure 5. The key steps in the analysis of food security of a region.

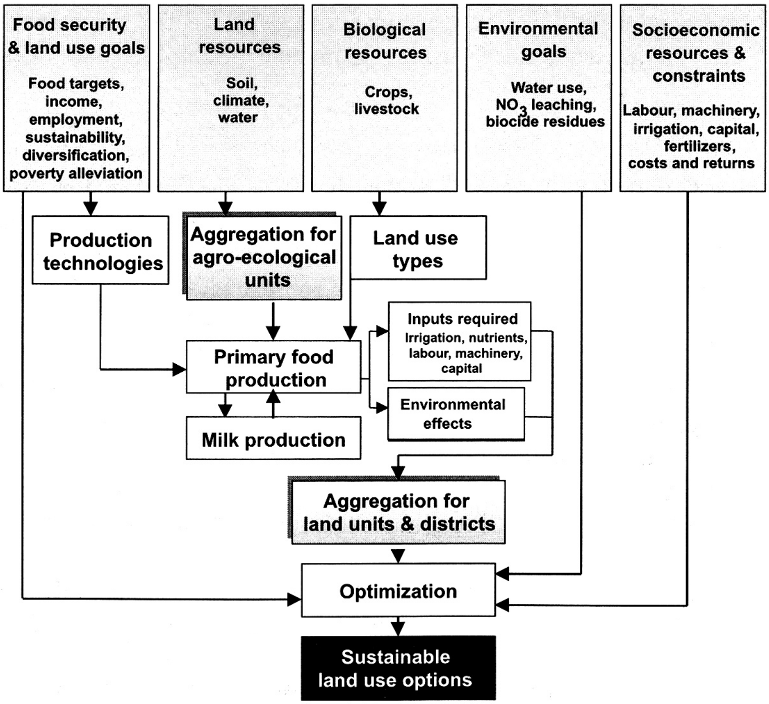

Figure 6. Operational steps followed in the DSS for land use analysis for sustainable food security of the present study.

validated crop models were then used to estimate the food production potentials of the different land use types with different production technologies for each agro-ecological unit. Potential yields were adjusted for the agro-ecological unit-specific salinity and sodicity levels.

The model also results in the assessment of environmental effects and the ancillary outputs – residues. The latter are used to provide energy to the livestock for milk production. Part of the dung produced is used as organic manure, which in turn affects crop production, and the remaining dung is used for fuel.

A technical coefficient generator (TCG), using the production function approach and based on published data for similar regions, was used to estimate the production resources required for the specified yield levels of different land use types and technologies. This provides the requirement of seed, irrigation water, N, P, K, biocides and machine and human labour for the targeted yields. The same TCG also provides estimates of N leaching from the soil profile. A biocide residue index (BRI) was calculated based on the chemicals used, their toxicity level and half-life to quantify the environmental effect of biocide use. Milk production was considered to be dependent on type of animal and feed availability.

By overlaying the district boundaries on the agro-ecological units map, the number and area of different land evaluation units in each district were determined. This is essential because all socioeconomic data are generally available at this scale only. Together with the assessment of socioeconomic resources of the region and specific goals for food security, environmental conservation and alternative land use, options for sustainable land use were determined using interactive multiple goal linear programming.

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3. Future demand for food in India and Haryana State

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Introduction

India has a very high population pressure on land and other resources to meet its food and development needs. It accounts for 20% of the world's population but has only 3% of the world's land area. Public investments in infrastructure, research and extension along with crop, livestock and fishery production strategies have significantly helped to expand food production and diversified the consumer food basket during the last three decades. As a consequence, food grain production in India increased from about 72 million tons in 1965 to 208 million tons in 2000. The increased per capita income and availability of a wide variety of food items have increased the demand for food. In many segments of society, there is an increasing demand for high quality and nutritious food. Thus, demand is shifting from coarse grains to superior grains (rice and wheat) and from grains to animal and horticultural products such as milk, meat, vegetables and fruits (Paroda and Kumar, 2000).

The coming years will bring many new developmental challenges. Food demand is likely to be formidable considering the non-availability of favourable factors of past growth, fast-declining factor productivity in major cropping systems and a rapidly shrinking resource base (Kumar, 1998). On an optimistic note, such challenges can be faced if specific development plans are drawn up that match food production with demand. This chapter provides demand projections for food grains, livestock and horticultural products from 2000 to 2020 for India and Haryana.

Demand projections

The direct household (human) food demand projections are derived from the growth in population, urbanization and income. Several demand models are available for estimating the income and price elasticities of demand for a commodity. Bouis (1996) suggested a non-econometric model based on demand characteristics known as the food characteristic demand system (FCDS). This model requires far less data than the econometric approaches and it can be implemented relatively quickly and cost effectively. It easily provides the demand elasticities of individual commodities and groups of commodities by region and expenditure groups within rural and urban areas and also takes into account the effects of structural shifts in food demand.

The demand projections in this chapter have been calculated based on the FCDS for different groups of the rural and urban population aggregated by income using the following formula:

P.K. Aggarwal et al. *(eds). 2001. Land use analysis and planning for sustainable food security: with an illustration for the stale of Haryana, India. IARI-India. IRRI-Philippines and WUR-The Netherlands, pp. 27-32.*

$$D_{ijkt} = d_{ijk0} \times N_{ijkt} (1 + y \times e_{ijk})^t$$

where

D_{ijkt} Demand for a commodity for the subgroup of ‘i’ lifestyle, ‘j’ region and ‘k’ income group and in ‘t’ period;

d_{ijk0} Per capita consumption demand for ‘i’ lifestyle, ‘j’ region and ‘k’ income group in the base year (1993-94);

N_{ijkt} Population in year ‘t’ belonging to ‘i’ lifestyle, ‘j’ region and ‘k’ income group;

y Growth in per capita income; and

e_{ijk} Expenditure elasticities for the subgroup population belonging to ‘i’ lifestyle, ‘j’ region and ‘k’ income group.

These demands are calculated for individual commodities based on lifestyle (rural, urban), region (eastern, western, northern, southern regions of India), expenditure elasticities and income group (very poor, moderately poor, non-poor lower and non-poor higher) in 2000, 2010 and 2020. Population growth is specified by region, lifestyle and income group. The demands of the commodities are then aggregated to arrive at the regional demand.

The following assumptions were made in these calculations:

- The population changes are as shown in Table 1.
- The pace of urbanization will be consistent with the recent historical trend.
- The ratio of rural to urban per caput expenditure remains consistent with past trends.
- Inequality in expenditures will remain the same as in 1987-88.
- The area elasticities for expected crop revenue and crop output price are nearly zero for rice and wheat (Kumar and Rosegrant, 1997). Thus, it is presumed that the projected crop area will not change and will remain at about the existing level.
- The share of the rural population in the total population was 74.3% in 1991, which is assumed to change to 73.4%, 72.3% and 69.9% in 2000, 2010 and 2020, respectively.
- The rural poverty ratio (the sum of population shares of the lower two expenditure groups) is 33%, 21% and 11% in 2000, 2010 and 2020, respectively, and the urban poverty ratio is 29%, 16% and 8% during the same periods.
- Expenditure elasticities are as given in Table 2.

In addition to the demand for direct human consumption, an increasingly important component is the indirect demand for seed, feed and industrial uses. Although considerable efforts are being made to reduce postharvest losses, a significant fraction of

Table 1. Projected population (in millions).

Year	India*	Haryana**
2000	1,007.3	20.0
2010	1,156.0	22.4
2020	1,279.1	24.4

* Source: UNFPA (1998). ** Source: Population Foundation of India (1999).

Table 2. Expenditure elasticities based on the food characteristic demand system (FCDS).

Item	India	Haryana
Rice	–0.016	0.101
Wheat	–0.109	–0.082
Coarse grains*	–0.147	–0.110
Pulses	0.214	0.410
Edible oils	0.176	0.532
Vegetables	0.673	0.363
Fruits	0.702	0.592
Milk	0.589	0.651
Meat, fish and eggs	0.892	0.873
Sugar	0.115	0.180

* Coarse grains are sorghum and millet.

wastage remains inevitable. Thus, domestic demand projections are arrived at by adding the direct demand (human consumption) and the indirect demand (seed, feed, industrial uses and wastage). This projected demand does not account for export, increased buffer stock needs for the rising population and risk factors. For Haryana, which contributes a very large fraction of its cereal production to the buffer stocks of the federal government, total demand would be much larger than the current calculations for domestic consumption alone. Projections are being made for two alternative scenarios of gross domestic product (GDP) growth based on recent trends and at constant prices: 3.5% (low-income growth) and 5.5% (high-income growth) growth in per capita gross domestic product (PCGDP).

Food demand for India

The domestic demand for food grains in India is estimated at 220–222 million tons in 2010 and 241–245 million tons in 2020 (Table 3). These projections are lower than earlier estimates of Kumar (1998) because of lower population projections and a steady decline in per capita cereal consumption, which has not yet stabilized. Consumption of non-cereal foods usually increases as income level rises. A deceleration in the growth rate of total domestic demand for major cereals (rice and wheat) was observed. Taking all cereals and pulses together, under the assumption of a 3.5% PCGDP growth at constant prices, annual growth in demand for food grains is likely to decline from 1.2% (2000- 10) to 1.0% during 2010-20.

Food demand for Haryana

Table 4 presents the domestic demand for food for Haryana under the two income growth scenarios. The results show that the household demand for food grains in Haryana will be 3.1–3.2 million tons in 20 10 and will grow to about 3.6–3.7 million tons in 2020. All demand is projected to further increase by 2020. A deceleration in the growth rate of total domestic demand for all commodities was observed. Under the

Table 3. Projected domestic demand for food in India.

Food item	Domestic demand (10^6 t y^{-1})		Growth rate (% y^{-1})	
	2010	2020	2000-2010	2010-2020
3.5% growth in per capita income				
Rice	95.7	105.9	1.26	1.02
Wheat	70.7	77.3	1.09	0.91
Coarse grains	35.7	38.9	1.32	0.86
Pulses	19.6	22.3	1.68	1.31
Edible oils*	9.6	10.8	1.61	1.26
Vegetables	108.5	132.2	2.67	1.99
Fruits	61.4	74.3	2.56	1.92
Milk	97.1	115.8	2.36	1.78
Meat, fish, eggs	16.9	21.0	2.90	2.20
Sugar**	29.0	32.6	1.50	1.18
5.5% growth in per capita income				
Rice	95.4	105.4	1.25	1.01
Wheat	69.0	74.9	0.98	0.83
Coarse grains	34.6	37.3	0.88	0.75
Pulses	20.6	23.8	1.90	1.46
Edible oils*	9.9	11.4	1.79	1.38
Vegetables	128.1	164.7	3.46	2.54
Fruits	71.5	90.9	3.29	2.42
Milk	110.4	137.3	2.97	2.20
Meat, fish, eggs	20.5	27.1	3.81	2.83
Sugar**	29.7	33.7	1.62	1.27

Source: Computed from Paroda and Kumar (2000).

* Divide by 0.4 to get oilseed.

** Divide by 0.1 to get sugarcane.

assumption of a 5.5% growth rate in PCGDP at constant prices, annual growth in demand for food grains is likely to decline from 0.91% in 2000-10 to 0.96% in 2010-20. The domestic demand will increase at a higher rate for non-cereals (3–5% per annum).

The current production of food grains in Haryana is 10.5 million tons, about 2.8 times the demand in 2020 (Table 4). Thus, evidently there is no problem in satisfying grain demand for local consumption in Haryana. However, the state contributes a large fraction of its cereal produce to the buffer stocks and the public distribution system of the federal government. Assuming that the state continues to contribute the same proportion to these federal schemes, total demand would be much higher than the current calculations for domestic consumption. At the same time, this provides opportunities for diversification of cereals-based agriculture in Haryana.

Table 4. Projected domestic demand for food in Haryana, India.

Food item	Domestic demand (10^6 t y^{-1})		Growth rate (% y^{-1})	
	2010	2020	2000-2010	2010-2020
3.5% growth in per capita income				
Rice	279.8	315.3	1.47	1.20
Wheat	2,852.8	3,024.4	0.86	0.59
Coarse grains	58.2	61.0	0.73	0.47
Pulses	227.8	286.2	2.58	2.31
Edible oils*	101.0	132.1	2.99	2.72
Vegetables	1,507.3	1,864.7	2.42	2.15
Fruits	374.3	500.5	3.23	2.95
Milk	5,692.6	7,763.6	3.43	3.15
Meat, fish, eggs	29.5	43.3	4.23	3.91
Sugar**	514.7	597.3	1.77	1.50
5.5% growth in per capita income				
Rice	289.8	332.9	1.67	1.40
Wheat	2,775.0	2,897.1	0.70	0.43
Coarse grains	56.0	57.4	0.53	0.25
Pulses	263.5	359.0	3.42	3.14
Edible oils*	121.6	176.3	4.06	3.78
Vegetables	1,716.4	2,282.3	3.17	2.89
Fruits	460.8	691.7	4.42	4.15
Milk	7,146.5	11,059.2	4.74	4.46
Meat, fish, eggs	39.8	69.3	5.96	5.70
Sugar**	549.4	661.1	2.14	1.87

Source: Computed based on national sample survey (NSS) data of 50th round for Haryana State, 1993-94.

* Divide by 0.4 to get oilseed.

** Divide by 0.1 to get sugarcane.

Summary and conclusions

A structural shift in dietary pattern toward milk, fruits, vegetables, meat, fish and eggs has started already and is predicted to intensify further. A decline in per capita consumption of cereals and a rapid increase in consumption of fruits, vegetables, milk, meat, eggs and fish are observed. Despite these changes, the food grain demand for India and its different states will be considerably higher in the coming decades. Average yields of most commodities are now low in the region. To meet the projected demand for 2020, national (Indian) per hectare productivity must increase to 2.7 tons for rice, 3.3 tons for wheat, 2.2 tons for coarse grains and 0.99 tons for pulses. The production of horticultural, livestock and fishery products also needs to increase by 108% to 229%.

Haryana now produces more than the required food for local consumption even for 2020. Nevertheless, food production in the state needs to increase proportionally to support the nation's food security.

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4. Evaluation of regional resources and constraints

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Introduction

Food production and hence food security of a region can be sustained only if its natural resource base consisting of soil, water and biodiversity is conserved and climatic conditions remain favourable. The amount of food that can be produced also strongly depends upon the region's socioeconomic resources such as labour, capital and credit facilities; production resources such as fertilizer, irrigation, biocides and machinery; and agricultural infrastructure such as markets, roads and storage facilities. Past successes in increasing food production in India and in many developing countries were evident only in those regions where a synergistic combination of many of these resources and infrastructure existed, of which Haryana is a typical example. The issue of sustaining production in some of these regions has now become important in view of the reported decline in the quality and quantity of their natural resource base. Haryana, for example, faces increasing problems of sustainability because of inappropriate agricultural land use and water and nutrient management practices. There is a strong need to identify appropriate land use and management options for sustaining agricultural production in the future.

Characterization of resources can be performed at different scales depending upon the major objectives of the study. To achieve greater impact of natural resource management, one needs also to (1) look at the regional level, (2) orient research toward development activities and (3) apply interdisciplinary approaches (Kam *et al.,* 2000; Agganval *et al.,* 1998; Rabbinge, 1995). Characterization of regional resources is extremely important because these dictate the potential of the land for food production and the major constraints to attaining these levels. Such characterization has to describe the spatial and temporal availability of both the natural and other biophysical resources and the various socioeconomic resources. In this chapter, we describe these resources in brief for the state of Haryana, including the databases and the methodology used for assessing resource availability.

P.K. Aggarwal et al. *(eds), 2001. Land use analysis and planning for sustainable food security: with an illustration for the slate ofHaryana, India. IARI-India, IRRI-Philippines and WUR-The Netherlands, pp. 33-59.*

Biophysical resources of Haryana

Land area

Haryana consists of 16 districts as per the 1991 census (see Figure 2, Chapter 2). The state now has 19 districts, which have been carved out by dividing and merging certain districtshlocks. Since the details needed for this analysis were not available for all of the current 19 districts, we have used the 1991 classification. Sirsa, Bhiwani, Rohtak and Hisar in the western and central parts of the state are the largest districts (Table 1). Kurukshetra and Karnal, the two fully irrigated districts, are the major rice-wheat-producing areas. Net sown area in the state is 3,615,000 ha.

Soils

The National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur, has mapped the soils of Haryana at a scale of 1:250,000 (Sachdev *et al.,* 1995). The map shows 199 units based on surface form, parent material, soil depth, particle size class, mineralogy, calcareousness, soil temperature regime, soil pH, drainage class, groundwater depth, presence of a compact layer, slope, erosion class and level; extent of salinity and sodicity; and susceptibility to flooding. The soil map was digitized and imported into a geographic information system (GIS) – IDRISI (Eastman, 1995) for reclassification and further analysis. For the present study, in which production capacity and susceptibility to degradation are the major criteria, the soil units were reclassified based on soil texture, degree and extent of salinity and sodicity and soil organic carbon content. Other soil properties were not included because either they

Table 1. Area of 16 districts of Haryana (1990-91).

District	Area (ha)
Ambala	238,500
Bhiwani	514,000
Faridabad	276,000
Gurgaon	210,500
Hisar	627,900
Jind	273,600
Kaithal	279,900
Kamal	196,700
Kurukshetra	121,700
MohinderGarh	168,300
Panipat	175,400
Rewari	155,900
Rohtak	441,100
Sirsa	427,600
Sonipat	138,500
YamunaNagar	175,600
Total	4,421,200

depended on properties selected already or were of minor importance for the analysis of agricultural land use options in Haryana.

Particle size

Haryana soils can be broadly classified into three main textural classes (Figure 1). Light-textured soils (sandy and coarse loamy) prevail in the western parts, whereas the central and eastern parts are occupied by medium to heavy textures (sandy loam and silty clay loam) suitable for rice-based cropping systems.

Organic carbon

Soil organic carbon content is an important indicator of soil fertility. Since this characteristic was not available in the original soil map of the NBSSLUP, an extensive literature search was conducted. Based on the results (data for 73 locations in Haryana) a map of organic carbon was prepared by inverse square distance interpolation. Two classes, low (< 0.3%) and high (> 0.3%) content, were distinguished (Figure 2). In general, the soils of Haryana are characterized by a relatively low organic carbon content because of intensive agricultural activity in this region. It could also be concluded that the light-textured soils have a lower organic carbon content than the medium-textured to slightly heavier-textured soils.

Salinity and sodicity

The primary cause of natural salinity in soils is the weathering of primary minerals and rocks. Surface deposition of salts through streams and surface inundation andor their interaction with carbon sources for several thousand years might be the major source of natural salinity in northern India.

Induced salinity in Haryana might be caused by human interference through irrigation including lifting underground water and modifjmg the natural water courses via roads, rails, bridges and artificial irrigation channels. Now, salinity affects 190,000 ha (nearly 14%) of the land area of the state. In addition, sodicity affects 330,000 hectares and a majority of this area is seriously affected.

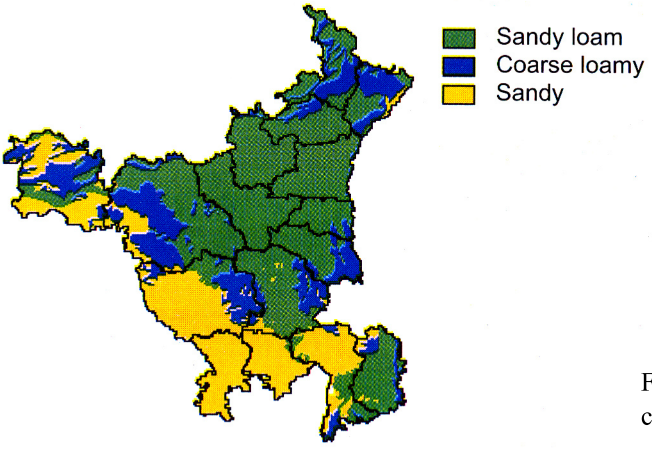

Figure 1. Soil textural classes in Haryana.

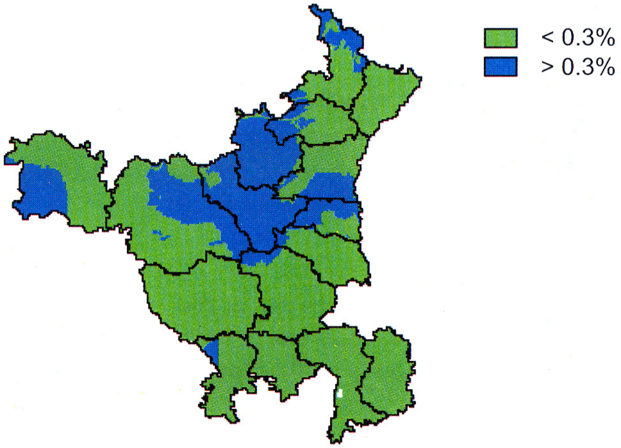

Figure 2. Organic carbon content of soils in Haryana.

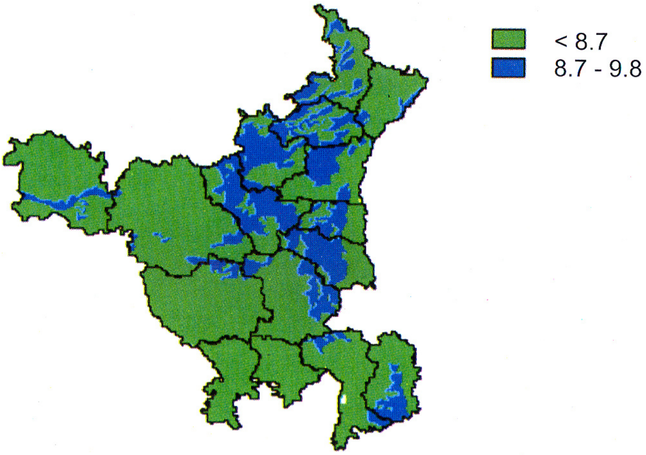

Figure 3. pH of soils in Haryana.

The original map developed by the NBSSLUP was reclassified into two pH classes (< 8.7 and 8.7–9.8) for sodicity assessment for the present study (Figure 3). To characterize salinity, the NBSSLUP map was reclassified based on electrical conductivity (EC, dS m^{-1}) into three classes (< 1.6, 1.6–2.5 and > 2.5; Figure 5). The aerial extents of sodicity and salinity were also mapped to evaluate their effects on crop yields (Figures 4 and 6, respectively).

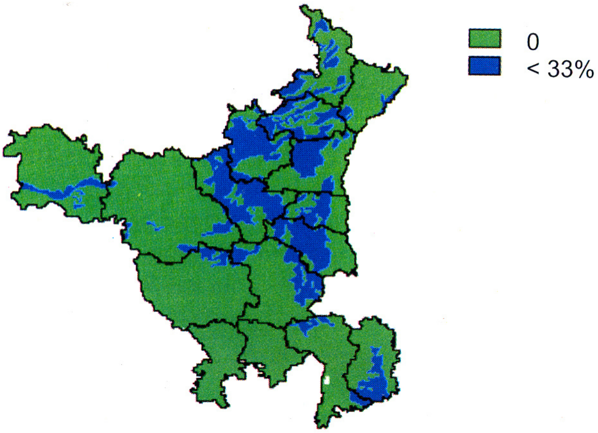

Figure 4. Extent of soil sodicity in Haryana. Percent values in the legend reflect the area affected by sodicity in that specific zone.

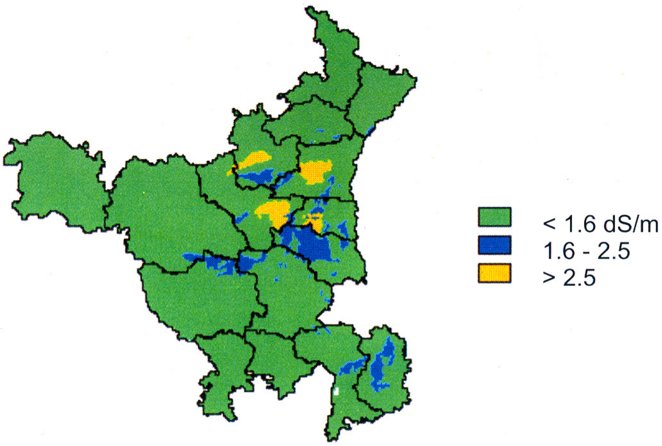

Figure 5. Electrical conductivity of soils in Haryana.

Climate

Although Haryana is a relatively small state, it has a large variation in climatic features, especially rainfall, which is unimodal and varies from 300 mm to 1,100 mm per annum (Figure 7). Almost 80% of the rainfall comes from the southwestern monsoon and is received in three months from July to September. The northern districts receive relatively higher rainfall and the western districts adjoining the state of Rajasthan the lowest rainfall. The central part of the state receives annual rainfall of 400 to 480 mm. Average rainfall of the state varies over the years – with a coefficient of variation from 30% to 40%. One can therefore observe arid, semiarid and subhumid climatic types in the state. Temperatures are generally very high during summer (reaching a maximum of 45 °C during daytime) to very low during winter (reaching a minimum of 1 °C).

For the agro-ecological analysis of this study, variation in climatic features in different regions is an important criterion for distinguishing homogeneous subregions. Our results showed that the spatial variation in temperature and solar radiation in the state could be largely related to the rainfall gradient. Preliminary analysis further indicated that the subregions based on spatial variation in rainfall in different crop seasons (winter or rubi from November to March, summer from May to June and monsoon (*kharif*) from July to October) were similar to the subregions based on annual rainfall.

A rainfall map was prepared based on annual precipitation data of 58 stations in and around Haryana. Inverse distance interpolation was used and the resultant map was classified into six zones (Figure 7). The cropping pattern in the different subregions

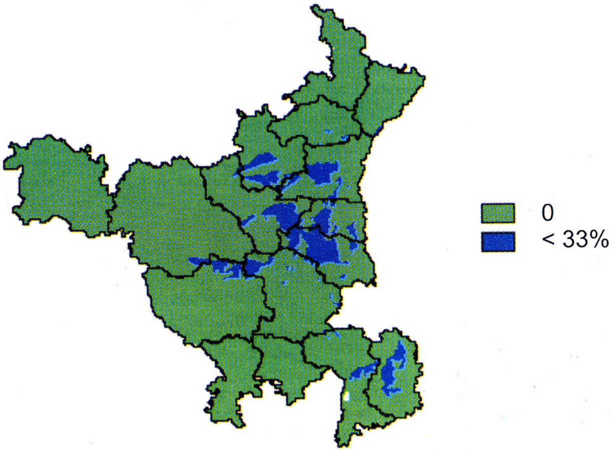

Figure 6. Extent of salinity in Haryana. Percent values in the legend reflect the area affected by salinity in that specific zone.

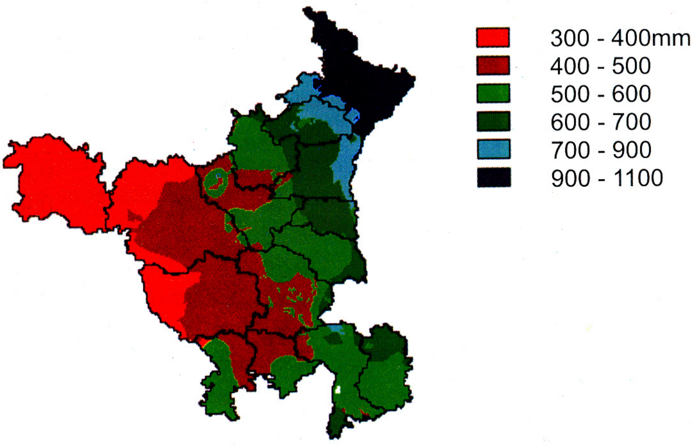

Figure 7. Annual rainfall zones in Haryana.

matches well with the rainfall pattern: the eastern parts are dominated by rice-based cropping systems, whereas rainfed crops are grown in the arid western parts.

Water

Haryana has considerable groundwater resources, which are used extensively for irrigation purposes. During the last three decades, with the introduction of the Green Revolution technology, the state has seen a major spurt in the number of tubewells and an associated increase in groundwater withdrawal. The density of tubewells has reached 0.22 per hectare in the predominantly rice-based cropping systems of Karnal, Kurukshetra and Panipat (Table 2), whereas, in eastern rainfed parts, the density is almost 25% of this.

Groundwater quality is relatively poor in the western and eastern districts of Haryana (Table 3). In Rohtak and Bhiwani, more than 20% of the wells have water with an EC exceeding 6 dS m^{-1}, whereas groundwater in Karnal and Kurukshetra has a relatively low EC.

For land use analysis, information on the availability of groundwater and canal water in different spatial units at different times is needed. Data of such fine spatial and temporal resolution on available water are not available. However, data on available groundwater per district, total area irrigated and the percentage of area irrigated by groundwater were available at the district level. In several districts, however, water is highly saline and not suitable for irrigation. The total amount of water available was therefore calculated based on groundwater availability, fraction of groundwater in the district and quality of water (water EC > 6 dS m^{-1} was not considered; only 67% of the water with EC 4–6 dS m^{-1} was included for evaluating the

Table 2. Density of tubewells, net utilizable groundwater and extraction in different districts of Haryana.

District	Density of tubewells per hectare	Net utilizable groundwater (10^9 m^3)	Net extraction (10^9 m^3)
Ambala	0.09	0.32	0.47
Bhiwani	0.06	0.10	0.41
Faridabad	0.13	0.25	0.31
Gurgaon	0.12	0.29	0.40
Hisar	0.07	0.45	1.24
Jind	0.13	0.16	0.32
Kaithal	0.16	0.55	0.46
Karnal	0.22	1.15	0.79
Kurukshetra	0.22	0.64	0.26
MohinderGarh	0.13	0.13	0.14
Panipat	0.22	0.34	0.30
Rewari	0.15	0.12	0.14
Rohtak	0.14	0.20	0.49
Sirsa	0.06	0.23	0.49
Sonipat	0.17	0.23	0.55
YamunaNagar	0.14	0.46	0.49
Haryana	0.13	5.62	7.26

Table 3. Quality of groundwater in various districts of Haryana (% of wells in different quality ranges).

	EC (d S m^{-1})			
District	0–2	2–4	4–6	>6
Ambala	99.0	0.9	0	0
Bhiwani	5.5	31.5	32.5	30.5
Faridabad	30.3	42.1	19.4	8.2
Gurgaon	53.4	22.9	12.8	10.9
Hisar	17.1	49.8	22.1	11.0
Jind	23.8	51.7	16.3	8.2
Kaithal	92.5	5.9	1.6	0
Karnal	95.5	4.5	0	0
Kurukshetra	100	0	0	0
MohinderGarh	35.8	38.7	15.1	10.4
Panipat	91.9	7.3	0.8	0
Rewari	16.5	40.7	28.0	14.8
Rohtak	19.8	39.6	20.3	20.3
Sirsa	19.5	36.6	26.9	17.0
Sonipat	32.9	38.5	18.3	10.3
YamunaNagar	8.7	91.3	0	0
Total	41.9	30.6	16.4	11.1

Table 4. Amount of water available per crop season (10^9 m^3).

	Canal			Groundwater		
District	*Kharif*	*Rabi*	*Summer*	*Kharif*	*Rabi*	*Summer*
Ambala	0.264	0.212	0.053	0.152	0.121	0.030
Bhiwani	0.099	0.079	0.020	0.018	0.015	0.004
Faridabad	0.068	0.054	0.014	0.095	0.076	0.019
Gurgaon	0.075	0.060	0.015	0.072	0.058	0.014
Hisar	1.359	1.087	0.272	0.189	0.151	0.038
Jind	0.634	0.507	0.127	0.053	0.043	0.011
Kaithal	0.602	0.482	0.120	0.258	0.206	0.052
Karnal	0.662	0.530	0.132	0.541	0.433	0.108
Kurukshetra	0.467	0.373	0.093	0.299	0.240	0.060
MohinderGarh	0.059	0.047	0.012	0.056	0.045	0.011
Panipat	0.326	0.261	0.065	0.161	0.129	0.032
Rewari	0.076	0.061	0.015	0.038	0.030	0.008
Rohtak	0.702	0.561	0.140	0.055	0.044	0.011
Sirsa	0.537	0.429	0.107	0.085	0.068	0.017
Sonipat	0.500	0.400	0.100	0.103	0.083	0.021
YamunaNagar	0.286	0.229	0.057	0.214	0.171	0.043
Haryana	6.72	5.37	1.34	2.39	1.91	0.48

impact on most of the crops grown in the region). The amount of water available per crop season was calculated from this annual water 'supply', based on sensitivity analysis and current crop demand by season (Table 4).

The gross irrigated area (which includes the area irrigated more than once in a year) in Haryana is 4.78 million ha. Out of the net irrigated area of 2.7 million ha, canals and tubewells (drawing water from groundwater) cover 50% each (Table 5). Most districts in western Haryana have large canal irrigation systems, whereas, in the eastern part, both surface water and groundwater are used for irrigation. Since the soils in the state are light- to medium-textured, relatively more irrigation water is required. As a consequence, the number of pumps and tubewells has increased dramatically during the last three decades (Figure 8). At the same time, this excessive pumping to meet the water requirements of paddy has resulted in declining water tables, particularly where the rice-wheat cropping system is used.

The availability of irrigation water is likely to increase to 21.16 billion m^3 by 2005 and to 22.5 billion m^3 by 2015 because of the increased availability of water from the rivers Rawi and Beas (Irrigation Department Haryana, 1995).

In the southwestern part of Haryana, irrigation facilities are negligible. Their spatial demarcation is essential for regional planning, but this has not been done for Haryana. As a surrogate, we have used the discrimination of wheat/non-wheat areas during the *rabi* season to demarcate irrigated areas. Wheat is the dominant crop in the *rabi* season and is largely irrigated in most of the districts of Haryana. The assumption is that, if a farmer has access to an irrigation facility, he would always grow wheat in the rabi

Table 5. District-wise area (×000 ha) covered with different irrigation systems (Statistics Handbook of Haryana, 1995-96).

District	Canals	Tubewells	Others	Total
Ambala	–	86	5	91
Bhiwani	111	88	–	199
Faridabad	37	65	–	102
Gurgaon	13	40	–	53
Hisar	378	65	–	443
Jind	131	78	–	209
Kaithal	114	71	10	195
Karnal	67	121	–	188
Kurukshetra	4	125	18	147
MohinderGarh	4	101	–	105
Panipat	26	67	–	93
Rewari	4	97	–	101
Rohtak	144	66	–	210
Sirsa	243	73	–	316
Sonipat	102	64	–	166
YamunaNagar	4	97	–	101
Haryana	1,382	1,304	33	2,719

season and the farmer who does not would grow other crops such as chickpea. Remote-sensing images of IRS-1C and 1D for the *rabi* season of 1998-99 were used to demarcate the wheat-growing areas. Kamal, Kurukshetra, Kaithal, Sonipat, Panipat and Jind districts had no rainfed area, although they did have crops other than wheat. In these districts, the entire area was considered irrigated. In other districts of Haryana,

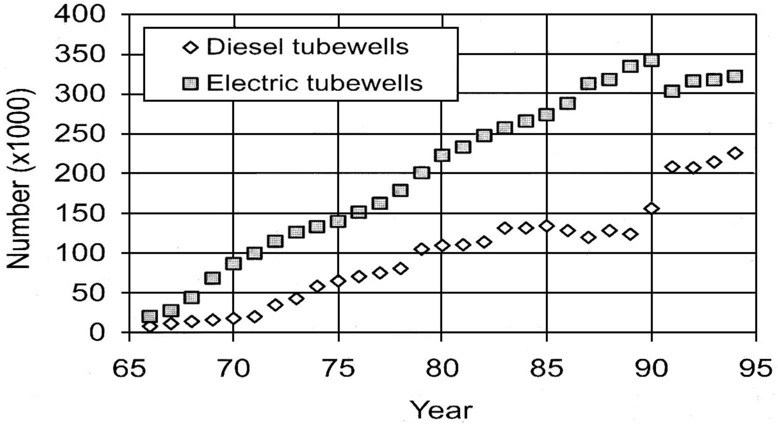

Figure 8. Change in number of tubewells in Haryana over time (1965-94).

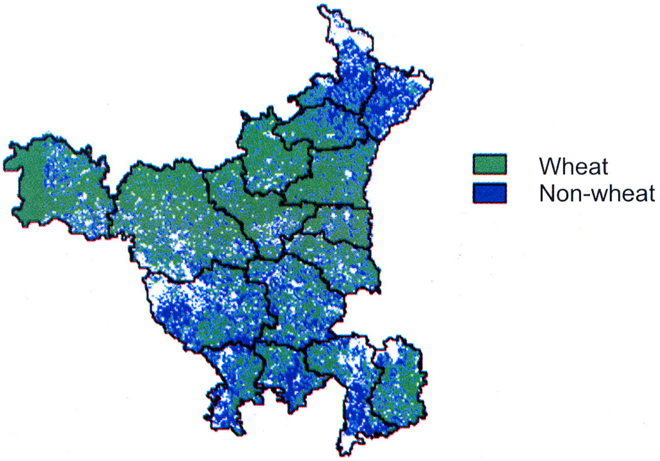

Figure 9. Wheat and non-wheat areas in Haryana mapped using IRS-1D satellite image.

areas not identified as wheat were presumed to be rainfed areas. Figure 9 shows the wheat and non-wheat coverage in Haryana, which was subsequently used to map the rainfed areas in ten districts: Rohtak, Bhiwani, MohinderGarh, Rewari, Gurgaon, Faridabad, Ambala, YamunaNagar, Sirsa and Hisar.

Fertilizers and pesticides

Consumption of plant nutrients per unit of cropped area in the state during 1997-98 was 101 kg ha^{-1} compared with the national average of 52.7 kg ha^{-1}. Only in Punjab was fertilizer consumption (133.9 kg ha^{-1}) higher. The eastern region of Haryana, where rice-wheat is the dominant cropping system, is comparable with Punjab in the amount of nutrients applied. Fertilizer consumption in the state has increased, as witnessed by the fact that, during the last decade, N application to wheat in the state has increased at 5 kg ha^{-1} y^{-1}. Table 6 shows the fertilizer consumption in the various districts. The western regions, being rainfed and with limited irrigation facilities, showed a lower application of nutrients than the eastern and central regions, which are mainly dominated by rice-based cropping systems.

Chemical control of pests is an integral part of modem agriculture. In Haryana, the use of plant protection chemicals increased from 3,608 t (1985-86) to 5,164 t (1990-91) but subsequently stagnated (5,100 t during 1995-96). However, the spectrum of chemicals used in the state has been shifting from a total dependence on organochlorine chemicals to the introduction of newer chemicals that are relatively safer and leave only degradable residues.

Some reports, nevertheless, mention an adverse environmental effect of pesticides in the region. Table 7 shows the district consumption of pesticides. Hisar and Sirsa consume the largest amounts of pesticides, mainly on cotton.

Table 6. Fertilizer consumption in the various districts of Haryana during 1997-98.

District	Fertilizer use (kg ha $^{-1}$ y^{-1})		
	N	P	K
Ambala	141.2	16.8	0.74
Bhiwani	32.3	5.7	0.05
Faridabad	136.8	16.9	0.50
Gurgaon	77.8	9.2	0.25
Hisar	67.3	8.2	0.25
Jind	114.0	11.5	0.13
Kaithal	132.0	14.5	0.56
Karnal	169.1	16.1	0.55
Kurukshetra	176.6	20.2	2.38
MohinderGarh	87.2	11.5	0.09
Panipat	149.9	18.8	0.13
Rewari	97.6	47.0	0.35
Rohtak	58.8	7.3	0.16
Sirsa	98.0	10.9	0.36
Sonipat	117.8	18.3	1.34
YamunaNagar	173.4	16.5	2.91

Table 7. Pesticide consumption by district in Haryana during 1996-97.

Districts	Pesticide (t)
Ambala	301.5
Bhiwani	285.8
Faridabad	318.2
Gurgaon	116.7
Hisar	597.5
Jind	288.9
Kaithal	427.3
Karnal	397.7
Kurukshetra	303.5
MohinderGarh	127.6
Panipat	338.7
Rewari	178.6
Rohtak	158.3
Sirsa	601.4
Sonipat	336.3
YamunaNagar	267.0
Total	5,045.0

Crops

In the northern irrigated plains of the state, the major crops are rice, sugarcane, wheat and maize. The southern part is rainfed, sandy and undulating; therefore, pearl millet, chickpea, wheat and mustard predominate. The area under rice, maize and sugarcane is negligible in this region. In most of Haryana, modern varieties of different crops are grown. The principal crops in the various districts are given in Table 8.

Livestock

Livestock is an important component of Haryana's agriculture. Most farmers keep dairy animals at the homestead for milk production. The average population of livestock per farm holding in the state is double that of the Indian average (ESO, 1996). Milk production per farm holding and per capita is 3 to 5 times the national average (Table 9). Although several different dairy animals can be found in Haryana, three types predominate – indigenous cows, crossbred cows and buffaloes. In all

Table 8. Area (× 1,000 ha) under principal crops by district during 1996-97.

Districts	Rice	Wheat	Chickpea	Pulses	Oilseeds	Sugarcane	Cotton
Ambala	66.5	83.3	1.7	7.7	15.2	13.2	0.3
Bhiwani	0.3	87.5	165.4	170.2	122.1	1.8	57.0
Faridabad	16.3	120.3	0.4	7.4	10.1	9.8	0.4
Gurgaon	4.4	104.7	5.6	7.0	63.1	0.7	0.4
Hisar	59.1	308.5	75.1	18.6	95.6	6.8	267.6
Jind	71.3	177.5	11.2	11.9	18.3	11.9	66.1
Kaithal	140.5	162.8	0.6	1.3	7.7	6.6	5.6
Karnal	153.5	163.2	0.7	3.3	14.3	10.5	0.4
Kurukshetra	107.9	95.7	0.2	1.2	24.8	14.8	0.0
MohinderGarh	0.0	36.8	17.9	18.1	93.9	0.0	13.1
Panipat	64.8	81.2	0.1	1.9	1.6	5.2	0.2
Rewari	0.1	42.2	4.0	4.5	69.7	0.1	4.9
Rohtak	16.9	146.9	13.8	25.7	64.4	22.1	16.5
Sirsa	29.1	213.9	46.6	49.6	57.3	0.5	217.8
Sonipat	53.8	133.9	1.1	22.9	8.5	14.1	2.1
YamunaNagar	47.0	58.6	0.7	4.8	5.9	43.8	0.2
Total	831.5	2,017.0	345.1	356.1	672.5	161.9	652.6

Table 9. Livestock population and milk production and availability in Haryana compared with the national average.

Item	Haryana	India
Livestock population per farm holding	8.4	4.2
Annual livestock population growth (%)	3.5	2.0
Milk production per farm holding (litres per annum)	2,516	575
Milk availability (g per capita per day)	639	196

districts, buffaloes are the most common. Haryana is home to the *Murrah* buffalo, one of the best breeds in the world. Crossbreds constitute only 5% of the total population (Table 10).

The state has 1.93 million dairy animals in the milking stage, 77% of which are buffaloes. The density of dairy animals is much higher in the districts having irrigation facilities than in the rainfed districts where fodder is scarce (Table 11). Karnal has the highest density of dairy animals (85 km^{-2}), whereas Bhiwani has only 23 animals km^{-2}. The animals are generally fed wheat straw and green millet straw supplemented by oil cakes and pulses.

Socioeconomic resources

Population and labour

The total population of Haryana according to the 1991 census was 16.4 million, with the rural population accounting for 75.4%. The current (year 2000) estimated population is approximately 20.7 million, corresponding to a growth rate of 2.62% during 1991-2000 (Statistical Handbook of Haryana, 1995-96). The population growth rate during 1981-91 was 2.74% compared with 2.38% for the country as a whole. Population density was 372 persons km^{-2} in 1991 and is estimated to be 470 now. Haryana has 2.6 million households, with, on average, 7 persons per household in rural areas and 6 in urban areas. The ratio of males to females is 1:1.15. Hisar, Rohtak and

Table 10. Number of dairy animals in the milking stage in different districts of Haryana (1992-93).

Districts	Indigenous cows	Crossbreds	Buffaloes	Total dairy animals
Ambala	24,600	8,500	75,300	108,400
Bhiwani	29,700	600	88,300	118,600
Faridabad	25,300	4,100	148,800	178,200
Gurgaon	26,500	5,000	109,600	141,100
Hisar	43,700	6,000	199,300	249,000
Jind	23,600	1,200	112,100	136,900
Kaithal	22,900	4,700	111,100	138,700
Karnal	22,600	23,900	120,300	166,800
Kurukshetra	10,700	9,000	73,000	92,700
MohinderGarh	10,100	500	54,200	64,800
Panipat	6,100	3,400	52,700	62,200
Rewari	11,900	400	45,200	57,500
Rohtak	20,800	5,300	104,200	130,300
Sirsa	28,600	13,500	72,200	114,300
Sonipat	13,800	4,800	76,400	95,000
YamunaNagar	16,600	8,700	53,200	78,500
Total	337,500	99,600	1,495,900	1,933,000

Table 11. Density of dairy animals in the milking stage (number of animals per hectare) in different districts of Haryana.

District	Indigenous cows	Crossbreds	Buffaloes	Total
Ambala	0.10	0.04	0.32	0.46
Bhiwani	0.06	0.00	0.17	0.23
Faridabad	0.09	0.01	0.54	0.64
Gurgaon	0.13	0.02	0.52	0.67
Hisar	0.07	0.01	0.32	0.40
Jind	0.09	0.00	0.41	0.50
Kaithal	0.08	0.02	0.40	0.50
Karnal	0.11	0.12	0.61	0.84
Kurukshetra	0.09	0.07	0.60	0.76
MohinderGarh	0.06	0.00	0.32	0.38
Panipat	0.03	0.02	0.30	0.35
Rewari	0.08	0.00	0.29	0.37
Rohtak	0.05	0.01	0.24	0.30
Sirsa	0.07	0.03	0.17	0.27
Sonipat	0.10	0.03	0.55	0.68
YamunaNagar	0.09	0.05	0.30	0.44
Average	0.07	0.03	0.34	0.44

Table 12. Total and rural population and number of agricultural workers in different districts of Haryana. All numbers are in 1,000s and refer to 1991 census data.

District	Total population	Rural population	Cultivators	Agricultural labourers	Total agricultural workers
Ambala	1,117	720	69	52	121
Bhiwani	1,140	943	174	41	215
Faridabad	1,477	760	112	49	161
Gurgaon	1,146	913	128	44	172
Hisar	1,845	1,455	264	130	394
Jind	963	798	141	57	198
Kaithal	821	700	112	59	171
Karnal	886	643	73	73	146
Kurukshetra	642	488	59	50	109
MohinderGarh	682	597	85	18	103
Panipat	834	607	79	51	130
Rewari	623	528	63	19	82
Rohtak	1,809	1,423	226	85	311
Sirsa	904	712	119	77	196
Sonipat	755	577	70	40	110
YamunaNagar	822	545	58	54	112
Total	16,466	12,409	1,832	899	2,731

Faridabad districts each have more than a million people. A large fraction of the population lives in urban areas in Faridabad, which is adjacent to New Delhi. Cultivators (having their own holdings) and agricultural labourers represent, on average, 15% and 7%, respectively, of the rural population, the remainder consisting of either non-actives (including children and old people) or people employed in other sectors (Table 12).

Haryana has a shortage of labour, particularly at planting and harvesting. As a result, there is a large influx of migratory labour, especially in the highly productive rice-wheat belt of eastern Haryana, mainly from densely populated eastern Uttar Pradesh and Bihar, where unemployment is higher. Data on this influx are not available. At the same time, outmigration of labour from the rural areas of Haryana is considerable at different times for (temporary) employment in the cities. Thus, it is difficult to assess the net availability of labour in different districts. The current availability of labour-days per district was therefore derived from recent surveys on cultivation costs as performed in different districts (Table 13). Based on the cropping calendar for the major cropping systems in a given district, this annual labour-day requirement was allocated to different months.

Capital and credit

Data on capital used in agriculture in different districts of Haryana were not available. These values were therefore estimated from the current costs of cultivation and the area of different crops in each district (Table 14). It was assumed that these costs represent the capital used in the various districts. Part of this could be credit and the

Table 13. Availability of total labour-days per district as used in the model.

District	Labour-days (million per annum)
Ambala	11.64
Bhiwani	23.12
Faridabad	10.93
Gurgaon	17.32
Hisar	67.30
Jind	32.52
Kaithal	30.02
Karnal	33.54
Kurukshetra	22.22
MohinderGarh	7.77
Panipat	14.00
Rewari	6.58
Rohtak	27.86
Sirsa	49.09
Sonipat	25.09
YamunaNagar	7.64
Total	386.64

Table 14. Estimates of capital used in agriculture in different districts of Haryana.

District	Capital (10^9 rupees)
Ambala	1.60
Bhiwani	2.98
Faridabad	1.52
Gurgaon	2.38
Hisar	10.50
Jind	5.20
Kaithal	4.15
Karnal	4.92
Kurukshetra	3.14
MohinderGarh	0.99
Panipat	2.10
Rewari	0.84
Rohtak	4.32
Sirsa	7.23
Sonipat	3.47
YamunaNagar	1.06
Total	56.40

remaining the farmers' own resources.

In addition to costs for crop production, the farmers also have additional income through milk. This was estimated for each district, considering the cost of milk production and its revenue. Total capital used in the model is the sum of the costs of cultivation of all crops and net revenue from milk in each district.

Energy

Consumption of electricity in the state increased from 434 million kWh (1966-67) to 7,824 million kWh (1994-95), equivalent to an increase in per capita consumption from 58 (1966-67) to 446 kWh (1994-95), whereas the national average reached only 283 units. Per capita availability of electricity for agriculture in the state was 238 units compared with the national average of 72 units. This high availability is one of the reasons for overirrigation of crops with the associated increase in salinity and waterlogging.

Machinery

Table 15 shows the agricultural machinery used in the various districts of the state. Karnal, Kurukshetra and Kaithal districts in the east and Hisar in the west had the largest density of power tillers, tractors and tubewells. The number of combine harvesters, however, was the highest in Rohtak and Sonipat. The rate of adoption of agricultural machinery has been one of the highest among all the states of India, indicating the easy acceptance of technological advances.

Table 15. Use of agricultural machinery by district (1992-93).

District	Power tillers	Tractors	Tubewells	Combine harvesters
Ambala	4,089	6,345	18,136	39
YamunaNagar	5,881	6,847	25,400	97
Kurukshetra	8,483	10,982	38,942	469
Kaithal	3,804	10,284	64,910	371
Karnal	7,210	13,884	69,424	540
Panipat	1,145	5,247	24,050	211
Sonipat	1,148	11,208	34,740	1,379
Rohtak	3,235	15,469	30,498	2,187
Faridabad	333	6,600	21,990	249
Gurgaon	409	5,548	25,487	954
Rewari	602	3,368	na*	50
MohinderGarh	357	2,361	20,909	174
Bhiwani	649	6,934	21,541	435
Jind	3,602	9,818	30,655	223
Hisar	8,313	25,015	49,722	332
Sirsa	1,575	16,300	27,327	471
Total	50,835	156,210	503,731	8,181

* not available.

Delineation of agro-ecological units and land units

There is tremendous spatial and temporal variation in the availability and use of biophysical and socioeconomic production resources in the region. Therefore, it is important to use a classification to demarcate homogeneous areas. Traditionally, soil scientists and soil survey specialists have used various soil properties to classify land into different suitability classes. Since such classes do not take into account other resources, such as irrigation water and socioeconomic profiles, it becomes difficult to use them in an operational way in the evaluation of land use systems.

For Haryana, the methodology for land unit mapping included the following activities:

- Selection of a minimum number of climatic parameters,
- Selection of suitable soil physical and chemical parameters,
- Identification of irrigated/rainfed areas, and
- Combination with administrative boundaries.

This successively resulted in areas considered to be homogeneous in soil conditions (soil units), in biophysical conditions (agro-ecological units) and in both biophysical and socioeconomic conditions (land units) (Figure 10).

Soil units

Based on soil particle size distribution, organic carbon content, salinity and sodicity (extent assumed to be 33%), 17 distinct soil units were identified (Figure 11). Table 16 describes each soil unit in terms of the soil characteristics and area occupied.

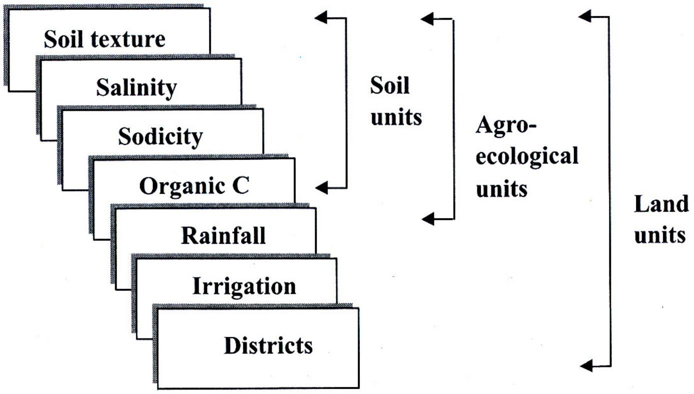

Figure 10. Parameters used in determining soil, agro-ecological and land units.

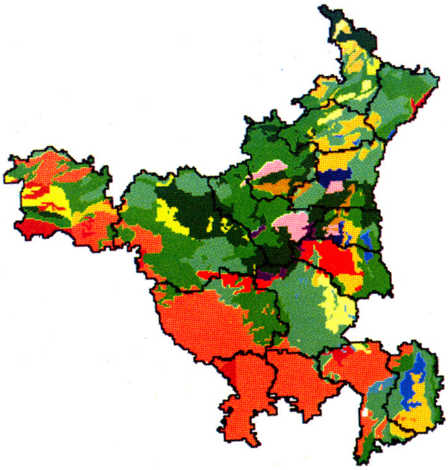

Figure 11. Pattern of soil units of Haryana. (Each colour corresponds to a soil unit class. For characterization see the Appendix.)

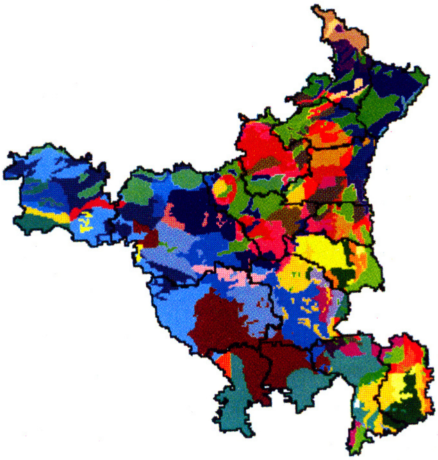

Figure 12. Pattern of agro-ecological units (58 in total) in Haryana. For characterization see the Appendix.

Table 16. Characteristics of the various soil units in Haryana.

Soil unit number	Soil texture	Organic carbon (%)	Salinity (EC, dS m^{-1})	Sodicity (pH)	Area (ha)
1	Sandy loam	< 0.3	4.6	< 8.5	818,963
2	Sandy loam	< 0.3	1.6–2.5	< 8.5	59,829
3	Sandy loam	< 0.3	4.6	> 8.5	288,185
4	Sandy loam	< 0.3	1.6–2.5	> 8.5	113,566
5	Sandy loam	< 0.3	2.5–5.0	> 8.5	31,127
6	Coarse loam	< 0.3	<1.6	< 8.5	738,795
7	Coarse loam	< 0.3	<1.6	> 8.5	99,325
8	Sandy	< 0.3	<1.6	< 8.5	983,372
9	Sandy	< 0.3	1.6–2.5	< 8.5	22,460
10	Sandy	< 0.3	<1.6	> 8.5	35,377
11	Sandy loam	> 0.3	<1.6	< 8.5	486,013
12	Sandy loam	> 0.3	1.6–2.5	< 8.5	47,617
13	Sandy loam	> 0.3	<1.6	> 8.5	345,891
14	Sandy loam	> 0.3	1.6–2.5	> 8.5	31,964
15	Sandy loam	> 0.3	2.5–5.0	> 8.5	71,955
16	Coarse loam	> 0.3	<1.6	< 8.5	107,880
17	Sandy	> 0.3	<1.6	< 8.5	72,862

Agro-ecological units

The overlay of the rainfall map (six zones) with the soil map (17 units) resulted in 58 homogeneous ago-ecological units (Figure 12). Irrigated/unirrigated area within these units was calculated by overlaying the map of wheatfnon-wheat area. The area covered by each of these units varies in size from a few hundred to more than 200,000 ha.

Land units

Overlaying the maps of 16 districts with that of 58 agro-ecological units with a demarcation of irrigated/unirrigated areas resulted in a map consisting of 257 land units (Figure 13). The properties of these land units are described in the Appendix. The area covered by these units varied in size from 18 to 98,067 ha. Frequency distribution indicated that 155 of the land units occupied a rather small area, in total covering less than 20% of the total agricultural land of the state (Figure 14).

Conclusions

The identification and demarcation of agro-ecological units and land units based on characteristics of biophysical and socioeconomic resources as presented in this chapter are major components of the interactive multiple goal linear programming (IMGLP) technique for optimizing land use at the regional level. Quantitative resource assessment is a prerequisite for determining biophysical potentials and resource constraints in the search for optimal management and land use options. Planning for

Figure 13. Land units (257) in Haryana. For explanation of the land units see the Appendix.

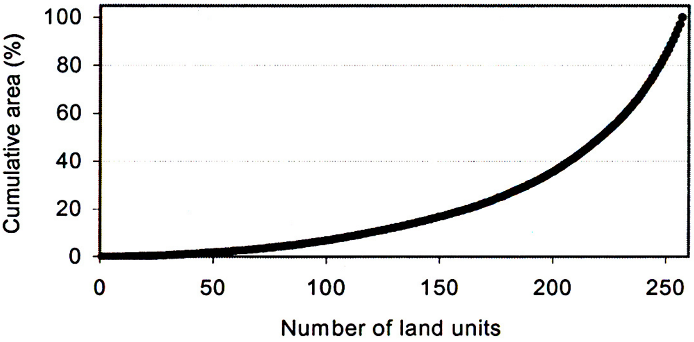

Figure 14. Cumulative area (%) of the different land units.

food security based on these considerations is likely to be more appropriate than using conventional qualitative land evaluation procedures. The land units form the basis for quantitatively describing the input/output relations of the various crop and livestock activities in the region (see Chapters 5 and 6). The more homogeneous the 'calculation units', the more accurate the land use plans and associated recommendations for changes in management practices and policy interventions. The level of aggregation chosen and the homogeneity of calculation units achieved is usually a compromise of the objective of the study, data availability and complexity of the land use model. In IMGLP models with many objectives, constraints, production activities (land use types) and technologies, the number of calculation units should be minimized as much as possible. For Haryana, this has been achieved through successive generalizations of land units based on the performance oflresults from earlier MGLP model versions for Haryana (e.g., Aggmal *et al.,* 1998).

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Appendix. Description of 257 land units for the state of Haryana. Characteristics of the soil units are described in Table 16.

Land unit	District	Agro-ecological unit (id. nr.)	Net sown area (ha)	Rainfall (mm)	Soil unit (id. nr.)
Irrigated land units					
1	Ambala	5	6,452	700-900	1
2	Ambala	6	4,153	900-1,100	1
3	Ambala	13	7,378	700-900	3
4	Ambala	14	1,715	900-1,100	3
5	Ambala	22	2,939	700-900	6
6	Ambala	23	4,492	900–1,100	6
7	Ambala	28	3,797	900-1,100	7
8	Ambala	42	641	900−1,100	11
9	Ambala	49	7,831	700-900	13
10	Ambala	56	2,287	900-1,100	16
11	Yamunanagar	6	9,739	900−1,100	1
12	Yamunanagar	9	18	900-1,100	2
13	Yamunanagar	13	3,882	700-900	3
14	Yamunanagar	23	9,719	900,1,00	6
15	Yamunanagar	36	71	900−1,100	10
16	Kurukshetra	4	18,692	600-700	1
17	Kurukshetra	5	23,052	700-900	1
18	Kurukshetra	8	2,255	600-700	2
19	Kurukshetra	12	21,187	600-700	3
20	Kurukshetra	13	21,090	700-900	3
21	Kurukshetra	21	4,933	600-700	6
22	Kurukshetra	22	7,720	700-900	6
23	Kurukshetra	27	8,133	700-900	7
24	Kurukshetra	40	7,322	600-700	11
25	Kurukshetra	47	4,623	500-600	13
26	Kurukshetra	48	28,992	600-700	13
27	Karnal	3	13,634	500-600	1
28	Karnal	4	22,894	600-700	1
29	Karnal	5	35,821	700-900	1
30	Karnal	12	34,943	600-700	3
31	Karnal	13	3,049	700-900	3
32	Karnal	17	21,493	600-700	5
33	Karnal	21	1,111	600-700	6
34	Karnal	23	3,136	900-1,100	6
35	Karnal	40	26,925	600-700	11
36	Karnal	41	14,244	700-900	11
37	Karnal	43	8,384	400-500	12
38	Karnal	44	6,236	600-700	12
39	Karnal	48	9,039	600-700	13
40	Karnal	53	8,092	600-700	15
41	Kaithal	4	6,368	600-700	1
42	Kaithal	12	3,363	600-700	3
43	Kaithal	20	3,530	500-600	6
44	Kaithal	21	4,051	600-700	6
45	Kaithal	38	5,444	400-500	11
46	Kaithal	39	31,034	500-600	11
47	Kaithal	40	18,244	600-700	11
48	Kaithal	43	16,577	400-500	12
49	Kaithal	46	11,130	400-500	13
50	Kaithal	47	72,315	500-600	13
51	Kaithal	48	8,825	600-700	13
52	Kaithal	52	16,119	500-600	15

Land unit	District	Ago-ecological unit (id. nr.)	Net sown area (ha)	Rainfall (m)	Soil unit (id. nr.)
53	Panipat	4	5,624	600–700	1
54	Panipat	8	8,326	600–700	2
55	Panipat	12	13,636	600–700	3
56	Panipat	17	5,969	600–700	5
57	Panipat	21	11,157	600–700	6
58	Panipat	39	8,419	500–600	11
59	Panipat	40	16,563	600–700	11
60	Panipat	41	2,172	700–900	11
61	Panipat	44	7,007	600–700	12
62	Panipat	48	12,623	600–700	13
63	Panipat	51	2,125	500–600	14
64	Panipat	53	5.378	600–700	15
65	Sonipat	3	9,522	500–600	1
66	Sonipat	7	5,271	500–600	2
67	Sonipat	11	27,778	500–600	3
68	Sonipat	16	61,497	500–600	4
69	Sonipat	20	23,485	500–600	6
70	Sonipat	21	38,318	600–700	6
71	Sonipat	39	5,194	500–600	11
72	Sonipat	51	6,935	500–600	14
73	Jind	2	4,676	400–500	1
74	Jind	3	10,699	500–600	1
75	Jind	38	22,373	400–500	11
76	Jind	39	27,752	500–600	11
77	Jind	40	6,255	600–700	11
78	Jind	46	70,199	400–500	13
79	Jind	47	28,804	500–600	13
80	Jind	51	8,291	500–600	14
81	Jind	52	25,101	500–600	15
82	Hissar	1	64,403	300–400	1
83	Hissar	2	49,162	400–500	1
84	Hissar	10	2,422	300–400	3
85	Hissar	15	2,903	400–500	4
86	Hissar	18	62,545	300–400	6
87	Hissar	19	47,779	400–500	6
88	Hissar	29	12,552	300–400	8
89	Hissar	30	17,808	400–500	8
90	Hissar	34	1,805	300–400	10
91	Hissar	37	20,217	300–400	11
92	Hissar	38	98,067	400–500	11
93	Hissar	39	5,742	500–600	11
94	Hissar	46	11,662	400–500	13
95	Hissar	47	1,837	500–600	13
96	Hissar	54	11,916	300–400	16
97	Hissar	55	19,923	400–500	16
98	Sirsa	1	22,555	300–400	1
99	Sirsa	10	16,219	300–400	3
100	Sirsa	18	83,116	300–400	6
101	Sirsa	29	77,312	300–400	8
102	Sirsa	34	2,725	300–400	10
103	Sirsa	37	12,036	300–400	11
104	Sirsa	45	15,057	300–400	13
105	Sirsa	54	35,581	300–400	16
106	Sirsa	57	50,176	300–400	17
107	Rohtak	2	57,999	400–500	1
108	Rohtak	3	31,569	500–600	1

Land unit	District	Agro-ecological unit (id. nr.)	Net sown area (ha)	Rainfall (mm)	Soil unit (id. nr.)
109	Rohtak	4	642	600–700	1
110	Rohtak	11	2.120	500–600	3
111	Rohtak	15	4,167	400–500	4
112	Rohtak	16	3,397	500–600	4
113	Rohtak	19	7,809	400–500	6
114	Rohtak	24	11,719	400–500	7
115	Rohtak	25	15,476	500–600	7
116	Rohtak	26	3,188	600–700	7
117	Rohtak	30	6,773	400–500	8
118	Rohtak	33	2,323	500–600	9
119	Rohtak	38	6,135	400–500	11
120	Rohtak	39	4,212	500–600	11
121	Rohtak	50	5,060	400–500	14
122	Rohtak	51	1,096	500–600	14
123	Bhiwani	2	15,461	400–500	1
124	Bhiwani	15	17,242	400–500	4
125	Bhiwani	18	2,629	300–400	6
126	Bhiwani	19	47,162	400–500	6
127	Bhiwani	29	16,107	300–400	8
128	Bhiwani	30	66,944	400–500	8
129	Mahendragarh	29	918	300–400	8
130	Mahendragarh	30	41,309	400–500	8
131	Mahendragarh	31	21,459	500–600	8
132	Mahendragarh	58	1,261	500–600	17
133	Rewari	2	3,692	400–500	1
134	Rewari	30	40,725	400–500	8
135	Rewari	31	16,887	500–600	8
136	Gurgaon	2	8,232	400–500	1
137	Gurgaon	3	9,434	500–600	1
138	Gurgaon	11	4,662	500–600	3
139	Gurgaon	19	572	400–500	6
140	Gurgaon	21	927	600–700	6
141	Gurgaon	22	107	700–900	6
142	Gurgaon	27	888	700–900	7
143	Gurgaon	30	6,457	400–500	8
144	Gurgaon	31	26,408	500–600	8
145	Gurgaon	32	5,476	600–700	8
146	Gurgaon	33	3,844	500–600	9
147	Gurgaon	35	5,882	500–600	10
148	Faridabad	3	25,126	500–600	1
149	Faridabad	4	10,110	600–700	1
150	Faridabad	7	13,386	500–600	2
151	Faridabad	8	7,382	600–700	2
152	Faridabad	11	32,447	500–600	3
153	Faridabad	12	1,467	600–700	3
154	Faridabad	20	8,631	500–600	6
155	Faridabad	21	6,319	600–700	6
156	Faridabad	31	2,264	500–600	8
157	Faridabad	32	67	600–700	8
Rainfed land units					
158	Ambala	5	7,599	700–900	1
159	Ambala	6	16,803	900–1,100	1
160	Ambala	13	9,345	700–900	3
161	Ambala	14	14,183	900–1,100	3
162	Ambala	22	4,623	700–900	6
163	Ambala	23	26,303	900–1,100	6

Land unit	District	Agro-ecological unit (id. nr.)	Net sown area (ha)	Rainfall (mm)	Soil unit (id. nr.)
164	Ambala	28	11,688	900–1,100	7
165	Ambala	42	8,450	900–1.100	11
166	Ambala	49	2,724	700–900	13
167	Ambala	56	10,595	900–1,100	16
168	Yamunanagar	6	34,345	900–1,100	1
169	Yamunanagar	9	842	900–1,100	2
I70	Yamunanagar	13	4,454	700–900	3
171	Yamunanagar	23	58,070	900–1,100	6
172	Yamunanagar	36	3,859	900–1,100	10
173	Jind	2	193	400–500	1
174	Jind	3	1,654	500–600	1
175	Jind	38	3,139	400–500	11
176	Jind	39	13,327	500–600	11
177	Jind	40	300	600–700	11
178	Jind	46	7,375	400–500	13
179	Jind	47	6,150	500–600	13
180	Jind	51	1,376	500–600	14
181	Jind	52	7,336	500–600	15
182	Hissar	1	3,870	300–400	1
183	Hissar	2	17,469	400–500	1
184	Hissar	10	87	300–400	3
I85	Hissar	15	3,789	400–500	4
186	Hissar	18	14,307	300–400	6
187	Hissar	19	21,594	400–500	6
188	Hissar	29	7,948	300–400	8
189	Hissar	30	2,427	400–500	8
190	Hissar	34	1,319	300–400	10
191	Hissar	37	1,780	300–400	11
192	Hissar	38	15,356	400–500	11
193	Hissar	39	2,951	500–600	11
194	Hissar	46	5,537	400–500	13
195	Hissar	47	139	500–600	13
196	Hissar	54	1,367	300–400	16
197	Hissar	55	5,319	400–500	16
198	Sirsa	1	2,677	300–400	1
199	Sirsa	10	2,101	300–400	3
200	Sirsa	18	18,092	300–400	6
201	Sirsa	29	32,437	300–400	8
202	Sirsa	34	1,847	300–400	10
203	Sirsa	37	128	300–400	11
204	Sirsa	45	1,005	300–400	13
205	Sirsa	54	8,082	300–400	16
206	Sirsa	57	3,855	300–400	17
207	Rohtak	2	52,704	400–500	1
208	Rohtak	3	28,403	500–600	1
209	Rohtak	4	2,384	600–700	1
210	Rohtak	11	1,627	500–600	3
211	Rohtak	15	2,449	400–500	4
212	Rohtak	16	913	500–600	4
213	Rohtak	19	7,218	400–500	6
214	Rohtak	24	7,471	400–500	7
215	Rohtak	25	1,220	500–600	7
216	Rohtak	26	7,181	600–700	7
217	Rohtak	30	6,884	400–500	8
218	Rohtak	33	1,959	500–600	9
219	Rohtak	38	2,264	400–500	11

Land unit	District	Agro-ecological unit (id. nr.)	Net sown area (ha)	Rainfall (mm)	Soil unit (id. nr.)
220	Rohtak	39	3,652	500–600	11
221	Rohtak	50	2,503	400–500	14
222	Rohtak	51	1,424	500–600	14
223	Bhiwani	2	18,219	400–500	1
224	Bhiwani	15	9,147	400–500	4
225	Bhiwani	18	3,155	300–400	6
226	Bhiwani	19	48,473	400–500	6
227	Bhiwani	29	71,637	300–400	8
228	Bhiwani	30	88,824	400–500	8
229	Mahendragarh	29	2,736	300–400	8
230	Mahendragarh	30	28,947	400–500	8
231	Mahendragarh	31	51,445	500–600	8
232	Mahendragarh	58	7,924	500–600	17
233	Rewari	2	1,409	400–500	1
234	Rewari	30	26,122	400–500	8
235	Rewari	31	38,166	500–600	8
236	Gurgaon	2	3,982	400–500	1
237	Gurgaon	3	28,597	500–600	1
238	Gurgaon	11	6,734	500–600	3
239	Gurgaon	19	1,858	400–500	6
240	Gurgaon	21	3,091	600–700	6
241	Gurgaon	22	1,136	700–900	6
242	Gurgaon	27	2,646	700–900	7
243	Gurgaon	30	2,366	400–500	8
244	Gurgaon	31	40,385	500–600	8
245	Gurgaon	32	9,131	600–700	8
246	Gurgaon	33	9,202	500–600	9
247	Gurgaon	35	6,982	500–600	10
248	Faridabad	3	9,103	500–600	1
249	Faridabad	4	5,457	600–700	1
250	Faridabad	7	5,587	500–600	2
251	Faridabad	8	6,218	600–700	2
252	Faridabad	11	13,103	500–600	3
253	Faridabad	12	641	600–700	3
254	Faridabad	20	2,213	500–600	6
255	Faridabad	21	5,307	600–700	6
256	Faridabad	31	2,059	500–600	8
257	Faridabad	32	1,112	600–700	8

5. Yield estimation and agro-technical description of production systems

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Introduction

The resource base of an agro-ecological unit (MU) described in the previous chapter needs to be related to the potential and constraints of producing economic yields of different crops and livestock for the analysis of land use options for sustainable food security. In both exploratory and predictive land evaluation studies (Van Keulen *et al.,* 2000), this requires consideration of the current farming systems and of those expected to gain importance in the future.

The agro-technical possibilities of a given crop or cropping system depend primarily on the soil and climate resource base of a location. The basis of all primary and secondary production in agriculture is photosynthesis. Analysis of photosynthesis over the crop's life cycle can help in quantifying crop performance and yield in diverse agro-environments. Each crop cultivar is characterized by a genetic limit, its potential yield, defined as the maximum yield that can be reached by a crop in a given environment under adequate water and nutrient supply and in the absence of yield-reducing factors such as weeds, pests and diseases. It is determined by atmospheric CO_2 content, radiation, and temperature conditions and their effects on crop growth and development. Following the concepts of production ecology, various growth-defining, -limiting and -reducing factors can be distinguished (Rabbinge, 1986).

This production potential in any specific situation can be limited by a shortage of nutrients or water, or by other edaphic factors. Yields can be further reduced at any given time by insects, weeds and diseases. Figure 1 schematically illustrates differences in yield levels for these production situations. Potential yield is an important reference for land evaluation. The difference between potential and actual yield determines the magnitude of improvement that is possible with the current technology in a given environment.

These production levels may be very different in the different agro-ecological units, defined in Chapter 4, depending on the variation in climatic and edaphic properties. Estimates of potential and actual yields and the extent of yield limitation through water, nutrients and other growth-limiting factors in different agro-ecological units are a prerequisite for properly quantifying the relative suitability of different production

P.K. Aggarwval et al. *(eds). 2001. Land use analysis and planning for sustainable food security: with an illustration for the state of Haryana. India. IARI-India, IRRI-Philippines and WUR-The Netherlands, pp, 61-89,*

systems. Measurement of these characteristics in (farmers') field conditions is difficult because usually several yield-reducing and yield-limiting factors interact; carrying out specific experiments for this purpose under diverse biophysical conditions would be too expensive. Crop growth simulation models, however, can provide estimates of the biophysical potential as well as of the yield limitation by water and nutrients for different land units.

Many crop simulation models have been developed during the last three decades (see, e.g., Bouman *et al.,* 1996). Models are now available for all major crops such as wheat, rice, maize, sorghum, millet, chickpea, pigeonpea, groundnut, sunflower, sugarcane and potato, as well as for some plantation and horticultural crops.

In land use analysis for food security, the production orientation of the future agricultural activities may vary for different regions. In the developed countries, where food is already in surplus, improving the quality of the natural resource base has high priority because of public concern, whereas increasing production has no priority. In developing countries such as India, where food demand is increasing rapidly, natural resource management without the explicit objective of increasing food production will not be acceptable. Thus, the focus is on increasing crop production with minimal negative environmental impact. Although targeting potential yields may be attractive, for many agro-ecological units it will not be feasible to close the current yield gap because of various soil, water and socioeconomic constraints. Aggarwal *et al.* (1995), for example, have estimated that the potential yields of wheat in eastern India are almost three times their current levels, whereas, in northwestern India, this difference is much smaller. In rainfed regions, such as southern Haryana, the lack of irrigation facilities restricts yields, whereas, in many other areas salinity and sodicity seriously limit yields.

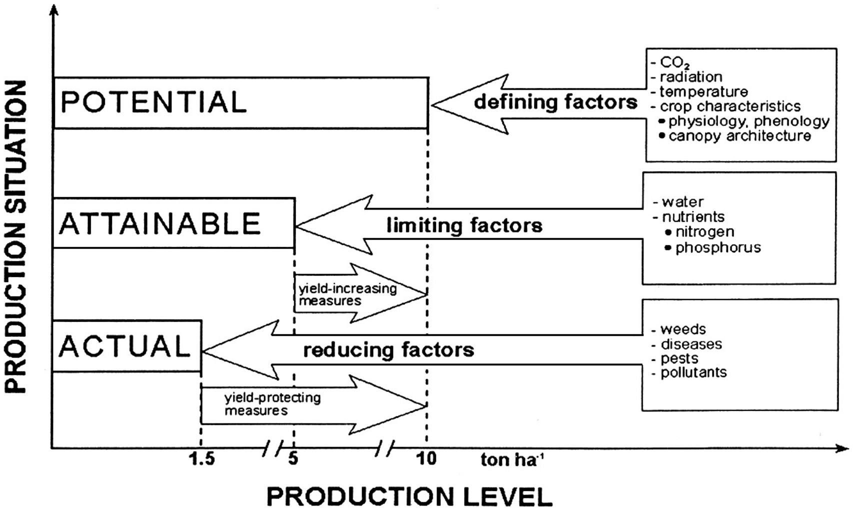


Figure 1. Factors determining crop growth. (Source: Rabbinge *et al.,* 1993.)

In our study, the so-called 'target-oriented approach' (Hengsdijk *et al.,* 1996), in which different yield levels are prefixed as desirable goals depending on production orientation and overall regional targets for food security, is applied to the different land units. These yield targets serve as a reference for calculating the required agronomic inputs and assessing their environmental effects. In earlier studies, a qualitative land evaluation was usually performed to determine the units not suitable for a given crop. FAO (1976) proposed such a framework for land evaluation, in which basic characteristics of the land, including soil and weather, were used to define agro-ecological zones (AEZ), which were then related to the possibilities of growing a specified crop or using a specific cropping system (called land use types, *lut*). The combination of an AEZ with a *lut* results in a land use system. This approach does not provide information about required changes in production technologies and/or the quantities of inputs needed to attain given production targets. Whenever biophysical land evaluation had to be linked to socioeconomic considerations, this FAO approach was inadequate. Jansen and Schipper (1995) proposed a modified approach in which different land use systems are quantitatively described at a defined technology (LUST, land use system at a defined technology) level. We have adapted this approach to quantify the target yields and input/output relations for different land use types in various agro-ecological units (see Chapter 4). Target yields of different land use types for each agro-ecological unit were predefined depending on the levels of potential yield and actual yield and the magnitude of their gap. The calculations of inputs required to attain these target yields are based on well-established eco-physiological principles and on expert knowledge.

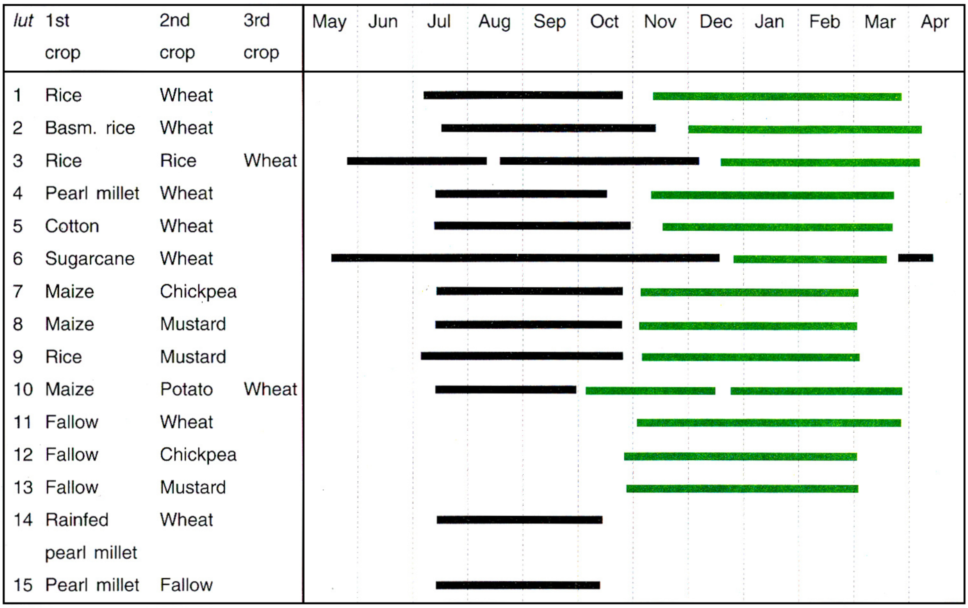
Production systems

Land use types

Temperatures and radiation levels in different parts of Haryana are fairly similar, allowing the major crops (see Chapter 4 and Table 1) to be grown at all places. Since the state has a subtropical climate, the environment is generally suitable for growing a wide range of cereals, pulses, oilseeds, vegetables, sugarcane, cotton and fruit trees. The availability of water and certain soil-specific factors may, however, restrict their cultivation in certain areas. For example, the water requirement of rice cannot be met everywhere in the state unless rainfall is supplemented by irrigation. Although the southwestern region of Haryana is rainfed and at present does not have surface irrigation, irrigation is expected to be available in the region in the future. Therefore, we assume that, in principle, all land use types are possible in different parts of Haryana.

In this study, land use types are always defined and quantitatively described on the basis of cropping systems, instead of describing individual crops, because the activities for an individual crop are generally influenced by the preceding crop. To keep the analysis technically manageable, it was important to select a limited number of key land use types. Based on current technologies, current cropping patterns and anticipated targets of food production, 15 crop-based land use types were selected. Table 1 shows these *luts* and their average planting and maturity time in Haryana. The first 10 luts are common in irrigated areas, whereas the remaining ones are predominant in

Table 1. Major agricultural land use types (*luts*) in Haryana and their average cropping calendar.



lut	1st crop	2nd crop	3rd crop
1	Rice	Wheat	
2	Basm. rice	Wheat	
3	Rice	Rice	Wheat
4	Pearl millet	Wheat	
5	Cotton	Wheat	
6	Sugarcane	Wheat	
7	Maize	Chickpea	
8	Maize	Mustard	
9	Rice	Mustard	
10	Maize	Potato	Wheat
11	Fallow	Wheat	
12	Fallow	Chickpea	
13	Fallow	Mustard	
14	Rainfed pearl millet	Wheat	
15	Pearl millet	Fallow	

rainfed areas. Other potential land use types that are theoretically possible in the state, considering its vast resource base, have been ignored to limit the size and complexity of the model. Some *luts* are now practised across the whole of Haryana, whereas some others are found only in a few subregions. With the ascent of the Green Revolution in the 1960s, sorghum and pearl millet, the traditional cereals of Haryana, were largely replaced by rice .during the *kharif* season (July to October) and winter pulses were replaced by wheat in the rubi season (November to April). Thus, the rice-wheat system has become the most common cropping pattern in the irrigated areas of the state. In areas with a reliable, year-round possibility of irrigation, such as in the districts of Karnal and Kurukshetra, some farmers also practise rice-rice-wheat cropping. These shifts in cropping pattern toward rice, wheat or sugarcane-based cropping systems were largely due to their higher yield and profitability. Dryland farming is usually practised in the southwestern part of Haryana where irrigation facilities are absent or weakly developed.

Production technology levels

Technology level in this study is defined as the complete description of a production activity, which includes the target yield level plus all inputs required to realize this target output and all additional outputs such as crop residues, and environmental impact indicators. A major goal of our research is to identify land use options that combine in the best possible way the various targets for food production, farmers' income and environmental conservation. Thus, we have selected technologies that, in the future, may exhibit higher yields than the current systems. The latter have been included as the baseline technology (technology 1). The level of potential yield in different agro-ecological zones is associated with technology 5. Since the yield gap is large between technologies 1 and 5 and the cost of bridging this gap is huge, another three levels of technologies have been defined. In terms of material input/capital use and resource use efficiency, these are intermediate between 1 and 5. For these technologies, target yields were defined in terms of the gap between actual and potential yield for the various land units. Thus, the production orientation of technologies 2–5 is primarily toward higher agricultural production. The various technologies are described in brief as follows.

Technology level 1 (current practice; baseline)

The average yield of crops in Haryana is higher than the national average. Different farmers, depending on their capital endowments, select different production techniques. In this study, however, we have used the average conditions of the state to define this technology. In general, the mechanization level is medium, tillage is usually done with a tractor and tillage implements, deep ploughing is not common and levelling of fields is done at a very rough scale. Sowing and application of fertilizers are mostly done with a drill or manually. The use of organic manure is almost absent; on average, farmers use less than one ton of farmyard manure (FYM) per hectare. Irrigation is applied to 90% of the area of the northern part of the state, whereas 50% of the southern part is under irrigation (Tomar *et al.,* 1992). Saline and sodic groundwater is used to irrigate in areas where canal water is not available (see Chapter 4 for details). Even in places where canal water availability is limited, saline and sodic groundwater is mixed with canal water for irrigation. In salinity-affected fields, farmers apply 25% higher seed rates and an additional dose of FYM to improve plant stand and yield. In sodic groundwater areas, 25% more nitrogen is applied and groundwater and canal water are usually mixed for irrigation (Manchanda, 1993). Regular plant protection measures are taken in 5–10% of the total area.

Rainfed areas Almost 33% of the area of Haryana is used for dryland agriculture, which has a low productivity because of limited rainfall, brackish underground water, low fertilizer use and the use of local and uncertified seeds (Dept. of Agriculture, 1998-99). Monocropping is generally practised. Pearl millet and sorghum are the main crops during *kharif;* while chickpea, mustard and wheat are grown during the *rabi* season. The main cropping systems are: fallow-wheat, fallow-chickpea, fallow-mustard, pearl millet-wheat and pearl millet-fallow.

Technology level 5 (potential yield level)

This technology is currently not practised in Haryana. It represents knowledge-based, intensive mechanized crop production. Target yields are set equal to potential yields. We assume that some well-endowed resource-rich farmers of Haryana might adopt this technology in the future. Concepts of precision farming may be used to maximize input use efficiency through high-tech agriculture, including site-specific (nutrient-, water-and pest-) management. Use can be made of special equipment such as tractor-mounted or hand-held global positioning systems, laser-based micro-land levellers and precision micro- and high-volume chemical applicators in combination with liquid fertilizers and simulation models. It has been assumed that the full cost of all implements will not be borne by the farmers directly, but that heavy and costly equipment will be supplied to them from a central pool and financial support for procurement of these implements/equipment will be available from the government/cooperatives/agro-service centres. The cost of hiring this equipment/tool has been included at a rate of rupees 3,000 per hectare per crop. In view of high mechanization activities, labour use is assumed to decrease by 45%. Overall, this technology is expected to result in a considerable increase in food production, income and environmental conservation (through increased input use efficiencies), although the capital requirement is also much higher.

Technology level 4 (bridging 75% of the yield gap)

Target yield for the various land use types was set to current yield +75% of the yield gap. As the input use increases assumed for technologies 2 and 3 may not be sufficient to realize these targets, a knowledge-intensive technology (similar to technology 5) with partially mechanized crop production has been assumed for technology 4. Input use efficiencies are higher than in technologies 1, 2 and 3, but slightly lower than in technology 5. Technology 4 also has a sustainable food production orientation as does technology 5, but requires relatively lower capital.

Technology level 3 (bridging 50% of the yield gap)

Target yields are set to current yield +50% of the yield gap for the land units. Again, these higher yields are supported by input intensification, in proportion to the increase in yield as illustrated later.

Technology level 2 (bridging 25% of the yield gap)

Target yields were set to the current yield +25% of the yield gap. Agricultural practices similar to these in technology 1 were assumed. The higher yields were assumed to be obtained by intensification of input use in proportion to the increase in yield. These are illustrated later in this chapter.

Yield estimation

Yield level at technology 1

Estimation of the target yields of the different land use types for the various agro-ecological units starts with the definition of the yield levels for technologies 1 and 5. Current yields of the different crops in farmers' fields (technology 1) are available as averages of the whole district and state. In our methodology, the yields need to be specified per agro-ecological unit (AEU). The yields aggregated per district and state, however, do not provide any indication of the variation in yields within these spatial units, caused by variations in yield-determining, -limiting and -reducing factors.

Therefore, a procedure is needed to allocate these yields to agro-ecologically defined spatial units. Since some AEUs can occur in two or more districts, allocation of mean district yields is not feasible. To overcome this problem, current yields of different AEUs were approximated from the state mean yield using a weighting procedure. The weighting factor for each AEU was based on the total cultivated area per crop, estimated area of different land use types by product, date of sowing and level of salinity/sodicity in different land units. For a specific crop, the total production is calculated as follows:

$$P = \Sigma\, Yi \times Ai, \qquad (1)$$

where $Yi = Y \times (1 - RFi)$, P is total production of that crop (t), i refers to AEU (identification number), Ai (ha) is the area of AEUi allocated to that crop, RF is the yield reduction factor of that crop because of salinit/sodicity and Y ($t\ ha^{-1}$) is the yield of that crop when RF = 0.

From the above equation, we can evaluate Y as

$$Y = P / (\Sigma\, Ai \times (1 - RFi)) \qquad (2)$$

The total area and production of different crops and the area of different AEUs are discussed in Chapter 4.

Soil salinity and sodicity are major yield-reducing factors in Haryana, with about 500,000 ha of land now affected (Chapter 4). Yield, as a function of average root-zone salinity/sodicity, has been described reasonably well with a threshold linear response function (Maas and Hoffman, 1977). This function is characterized as a segmented linear function containing four independent parameters: maximum yield under stress-free conditions (Ym); salinityhodicity threshold (C_t), which is defined as the maximum soil-salinity/-sodicity level without a yield reduction; the slope (S) of the function describing the fractional yield decline per unit increase in salinityhodicity level beyond the threshold; and Co, the salinityhodicity level at which crop growth is completely inhibited.

$$\begin{array}{ll} Y = Ym & O < C < C_t \\ Y = Ym \times \{1 - \Sigma(C - C_t)\} & C_t < c < Co \\ Y = 0 & C > Co \end{array} \qquad (3)$$

where Y is crop yield and C is average root zone salinityhodicity. Soil salinity and sodicity can be expressed in terms of electrical conductivity (EC, $dS\ m^{-1}$) and exchangeable sodium percentage (ESP, %), respectively, in a saturation extract of the soil. Results compiled by Maas and Hoffman (1977) showed that salt tolerance response functions are crop- and variety-specific and are dependent on soil and other environmental factors, and on water management. Fitting of this linear model to the salinity and sodicity response data for rice, wheat, maize, chickpea, mustard, potato, pearl millet, cotton and sugarcane (Gupta and Sharma, 1990; Van Genuchten and Gupta, 1993; CSSRI, 1979) yielded slope and threshold values for each crop (Table 2).

These values were used to calculate the actual crop yield for land units with salinity/sodicity problems.

Table 2. Slope and threshold values for salinity and sodicity response functions.

Crop	Sodicity reduction factor (slope)	Sodicity reduction threshold	Salinity reduction factor (slope)	Salinity reduction threshold
Rice	0.9	24.4	7.6	1.3
Basmati rice	1.8	16.0	7.6	1.3
Summer rice	0.9	24.4	7.6	1.3
wheat	2.1	16.4	4.5	7.0
Chickpea	5.0	7.7	16.7	2.0
Pearl millet	2.3	13.6	2.0	4.6
Maize	2.3	13.6	7.2	10.0
Cotton	2.3	13.6	5.6	9.0
Sugarcane	2.3	13.6	6.3	2.0
Mustard	0.8	7.6	7.4	6.6
Potato	2.1	16.4	6.3	1.7
Sorghum	2.3	13.6	3.0	3.2

Salinity affects crops differentially depending on the ability of the crop to withstand adverse effects of salts. We estimated the salinity reduction factor (SRF), i.e., the reduction in yield caused by salinity, for the various crops. For example, the following equation was used to estimate the salinity reduction factor for rice:

$$\text{SRF} = \text{rice SRF (slope)} \times 0.01 \times (\text{ECs} - \text{rice SRT}) \times \text{extent of salinity (\% area)} \qquad (4)$$

where ECs is the EC of saturation extract of soil, SRF the salinity reduction factor and SRT the salinity reduction threshold. Similar equations were developed for other crops using the coefficients in Table 2.

Many *luts* may have the same crops or products. For example, rice and wheat crops are sown in several cropping systems and their yields may vary with planting date (Aggarwal and Kalra, 1994). Therefore, it is important to estimate yields of different crops on various *luts.* For rice, four crop types have been distinguished rice sown in summer, rice sown at the normal time, rice sown after summer rice and basmati rice. To derive current yields for each of these types, first their shares in the total rice area were estimated derived from a literature review.

The relative yield factors for each type, given in Table 3, were estimated on the basis of results of field experiments conducted in the past within the state. The average yield of rice (type Ri), for instance, was then calculated as follows:

$$\begin{aligned} Y_{\text{Ri}} = {} & \text{Relative yield}_{\text{crop types}} \times \text{Mean state rice yield} \times \\ & \text{Relative area}_{\text{crop types}} / (S_{\text{crop types}}\, \text{relative yield} \times \text{relative area}) \qquad (5) \end{aligned}$$

For wheat, a similar procedure was applied to the four types distinguished, as given in Table 3.

As an example, the target yields for rice and wheat in the rice-wheat *lut* incorporated in the model for the various crop/land unit combinations are given in Table 4.

Table 3. Coefficients used for estimating yields of different rice and wheat types.

Crop type	Relative area	Relative yield
Rice		
Rice sown in summer	0.10	0.70
Rice sown at normal time	0.50	1.0
Rice sown after summer rice	0.10	0.95
Basmati rice	0.30	0.65
Wheat		
Wheat planted at normal time	0.50	1.00
Wheat planted late in basmati rice-wheat system	0.30	0.90
Wheat planted late in rice-rice-wheat system	0.15	0.80
Wheat planted very late in sugarcane-wheat system	0.05	0.73

Yield level at technology 5

Since measured yields at this level of technology in different agro-ecological units are scarce, we have used a variety of crop growth simulation models for the different crops (Table 5) to estimate the potential yields that can be attained in the different AEUs. Limited parameterization/calibration of these models was performed based on experiments conducted at several locations in India including Haryana and similar environments. The models were able to simulate reasonably well the yields at different management levels. The results of calibration and validation for rice, wheat, sorghum, maize and chickpea are given in Aggakal *et al.* (1994), Mall and Aggarwal (2001), Chatterjee (1998) and Mandal (1998). A complete standard calibration and validation was impossible for mustard, cotton, sugarcane and potato because of a lack of required data sets. For these cases, the simulated potential yields were further judged on the basis of expert knowledge and accepted when considered 'reasonable' or corrected when not considered reasonable.

Potential yields of different crops were simulated for 11 locations in or near Haryana, located between 73° and 79° E and 26° and 32° N, based on availability of weather data. These locations were Agra, Delhi, Gwalior, Hisar, Jodhpur, Karnal, Kapurthala, Kota, Ludhiana, Saharanpur and Pantnagar. Weather data for 10 to 20 years for each location were used for this purpose. Sowing dates for the different crops were selected depending on the prevailing cropping pattern. Thus, wheat-sowing dates were different for the different *luts.* On the basis of the simulated point data, potential yield surfaces were developed for the whole state using IDRISI (Eastman, 1995).

Figure 2 illustrates the distribution of the three major classes of wheat yield interpolated over Haryana.

In general, even under the best management, marketable yield is lower than potential yield because of unavoidable losses through pests and diseases and during harvesting, transportation and processing. These losses were assumed to result in a 10% reduction in potential yield. Therefore, realizable potential yield (RYP) of an area has been set at 90% of potential yield. These yields were allotted to different AEUs by

Table 4. Target yields (t ha^{-1}) for rice and wheat in rice-wheat systems in different ago-ecological units (AEU).

AEU	Rice					Wheat				
	Tech 1	Tech 2	Tech 3	Tech 4	Tech 5	Tech 1	Tech 2	Tech 3	Tech 4	Tech 5
1	3.56	4.70	5.85	6.99	8.13	3.88	4.52	5.15	5.79	6.42
2	3.56	4.71	5.86	7.01	8.16	3.88	4.56	5.23	5.91	6.58
3	3.56	4.64	5.73	6.82	7.91	3.88	4.54	5.20	5.85	6.51
4	3.56	4.62	5.68	6.74	7.80	3.88	4.52	5.15	5.79	6.42
5	3.56	4.61	5.67	6.73	7.19	3.88	4.50	5.12	5.74	6.36
6	3.56	4.61	5.67	6.73	7.19	3.88	4.46	5.04	5.61	6.19
7	2.84	3.73	4.62	5.51	6.40	3.66	4.34	5.02	5.69	6.37
8	2.84	3.73	4.62	5.51	6.40	3.66	4.31	4.95	5.59	6.24
9	2.84	3.73	4.62	5.51	6.40	3.66	4.25	4.84	5.42	6.01
10	3.40	4.51	5.74	6.92	8.09	3.44	4.05	4.65	5.25	5.86
11	3.40	4.48	5.56	6.64	7.12	3.44	4.06	4.69	5.31	5.93
12	3.40	4.46	5.53	6.60	7.66	3.44	4.04	4.64	5.25	5.85
13	3.40	4.46	5.53	6.60	7.66	3.44	4.03	4.61	5.20	5.78
14	3.40	4.46	5.53	6.60	7.66	3.44	3.99	4.55	5.10	5.65
15	2.84	3.82	4.81	5.79	6.78	3.44	4.09	4.75	5.40	6.05
16	2.84	3.75	4.66	5.58	6.49	3.44	4.05	4.65	5.25	5.86
17	2.24	2.95	3.65	4.35	5.06	3.28	3.85	4.43	5.00	5.58
18	3.56	4.71	5.87	7.03	8.19	3.88	4.54	5.20	5.86	6.52
19	3.56	4.71	5.87	7.03	8.19	3.88	4.57	5.25	5.94	6.62
20	3.56	4.63	5.69	6.76	7.83	3.88	4.52	5.15	5.78	6.41
21	3.56	4.62	5.68	6.74	7.81	3.88	4.53	5.17	5.81	6.45
22	3.56	4.62	5.69	6.75	7.82	3.88	4.52	5.16	5.79	6.43
23	3.56	4.61	5.67	6.73	7.19	3.88	4.46	5.04	5.62	6.20
24	3.40	4.53	5.66	6.80	7.93	3.44	4.05	4.66	5.27	5.88
25	3.40	4.53	5.66	6.80	7.93	3.44	4.05	4.66	5.26	5.87
26	3.40	4.53	5.66	6.80	7.93	3.44	4.05	4.65	5.25	5.86
21	3.40	4.48	5.57	6.66	7.75	3.44	4.06	4.69	5.31	5.93
28	3.40	4.46	5.53	6.60	7.66	3.44	4.00	4.56	5.12	5.68
29	3.56	4.73	5.91	7.08	8.26	3.88	4.55	5.22	5.89	6.56
30	3.56	4.69	5.81	6.94	8.07	3.88	4.55	5.21	5.87	6.53
31	3.56	4.63	5.70	6.78	7.85	3.88	4.55	5.22	5.89	6.56
32	3.56	4.62	5.69	6.75	7.82	3.88	4.56	5.24	5.92	6.60
33	2.84	3.75	4.66	5.57	6.48	3.66	4.35	5.03	5.71	6.40
34	3.40	4.60	5.79	6.99	8.19	3.44	4.07	4.69	5.32	5.94
35	3.40	4.53	5.66	6.79	7.92	3.44	4.10	4.75	5.41	6.06
36	3.40	4.46	5.53	6.60	7.66	3.44	3.99	4.55	5.10	5.65
31	3.56	4.71	5.86	7.02	8.17	3.88	4.52	5.15	5.79	6.42
38	3.56	4.71	5.87	7.02	8.17	3.88	4.54	5.19	5.84	6.49
39	3.56	4.65	5.75	6.85	7.95	3.88	4.52	5.15	5.78	6.42
40	3.56	4.61	5.67	6.73	7.19	3.88	4.52	5.15	5.78	6.41
41	3.56	4.61	5.67	6.73	7.19	3.88	4.52	5.15	5.78	6.41
42	3.56	4.61	5.67	6.73	7.19	3.88	4.46	5.04	5.61	6.19
43	2.84	3.74	4.64	5.54	6.45	3.66	4.30	4.95	5.59	6.23
44	2.84	3.73	4.62	5.51	6.40	3.66	4.30	4.95	5.59	6.23
45	3.40	4.53	5.66	6.80	7.93	3.44	4.05	4.65	5.25	5.86
46	3.40	4.53	5.66	6.80	7.93	3.44	4.05	4.66	5.27	5.88
41	3.40	4.49	5.59	6.68	7.78	3.44	4.05	4.65	5.25	5.86
48	3.40	4.46	5.53	6.60	7.66	3.44	4.05	4.65	5.25	5.86
49	3.40	4.46	5.53	6.60	7.66	3.44	4.05	4.65	5.25	5.86
50	2.84	3.78	4.73	5.67	6.62	3.44	4.09	4.73	5.37	6.02
51	2.84	3.76	4.68	5.60	6.52	3.44	4.05	4.65	5.25	5.86
52	2.24	2.96	3.69	4.41	5.13	3.28	3.85	4.43	5.00	5.58
53	2.24	2.95	3.65	4.35	5.06	3.28	3.85	4.43	5.00	5.58
54	3.56	4.69	5.83	6.97	8.11	3.88	4.53	5.17	5.81	6.45
55	3.56	4.73	5.90	7.08	8.25	3.88	4.56	5.23	5.90	6.58
56	3.56	4.61	5.67	6.73	7.79	3.88	4.46	5.04	5.61	6.19
57	3.56	4.68	5.81	6.93	8.06	3.88	4.52	5.15	5.78	6.41
58	3.56	4.68	5.81	6.93	8.06	3.88	4.52	5.16	5.79	6.43

Table 5. Crop growth simulation models used for potential yield estimation in various agro-ecological units of Haryana.

Crop	Potential yield estimation technique	Reference
Rice	CERES-Rice	Singh *et al.* (1993)
Basmati rice	CERES-Rice	Singh *et al.* (1993)
Wheat	WTGROWS	Aggarwal *et al.* (1994)
Maize	CERES-Maize	Singh *et al.* (1991)
Pearl millet	CERES-Millet	Singh *et al.* (1991)
Sorghum	CERES-Sorghum	Singh *et al.* (1991)
Mustard	WOFOST	Van Diepen *et al.* (1988)
Cotton	WOFOST	Van Diepen *et al.* (1988)
Sugarcane	WOFOST	Van Diepen *et al.* (1988)
Gram (chickpea)	WOFOST	Van Diepen *et al.* (1988)
Potato	DSSAT-SUBSTOR	Griffin *et al.* (1993)

appropriate map overlay procedures. RYPs of the various crops for different agro-ecological units of Haryana are given in Table 6.

Yields at technologies 2, 3 and 4

The difference between the adjusted potential yield and the calculated current yield in each land unit was considered as the attainable yield gap for that unit. Target yields were set at bridging 25%, 50% and 75% of the yield gap for the three technology levels, respectively. As an illustration, Table 4 shows the target yields for a rice-wheat system at different technology levels.

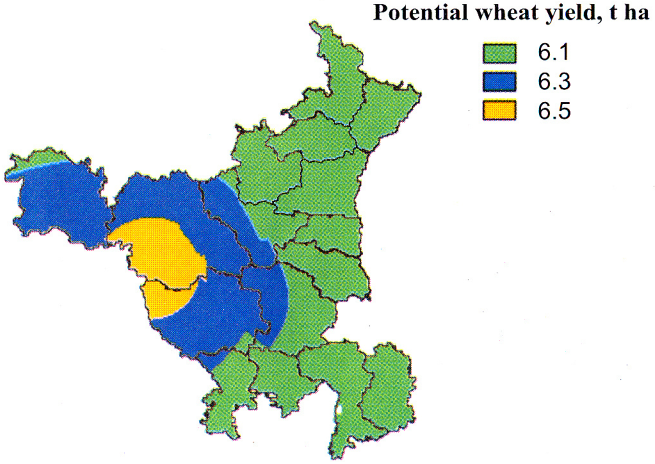


Figure 2. Potential wheat yields (at technology level 5) in Haryana.

Table 6. Realizable potential yields (t ha $^{-1}$) of different crops in different land use types (*luts*) for various ago-ecological units in Haryana (*lut* numbers are as in Table 1).

Agro-ecological unit	Rice	Basmati rice	Rice 1 in *lut* 3	Rice 2 in *lut* 3	Wheat in *lut* 1,4, 5, 11, 14	Wheat in *lut* 2	Wheat in *lut* 3	Wheat in *lut* 6, 10
Planting	1 Jul	5 Jul	1 May	1 Aug	10 Nov	25 Nov	20 Dec	25 Dec
1	8.13	5.65	5.76	8.06	6.42	6.23	5.99	5.31
2	8.16	5.63	5.76	7.93	6.58	6.38	6.13	5.43
3	7.91	5.53	5.73	8.03	6.51	6.31	6.13	5.38
4	7.80	5.49	5.85	8.00	6.42	6.23	6.07	5.45
5	7.79	5.49	5.94	7.77	6.36	6.17	6.00	5.40
6	7.79	5.49	5.94	6.42	6.19	6.00	5.87	5.27
7	6.40	4.51	4.65	6.52	6.37	6.20	5.96	5.15
8	6.40	4.51	4.72	6.38	6.24	6.05	5.92	5.20
9	6.40	4.51	4.88	7.86	6.01	5.87	5.70	5.11
10	8.09	5.58	5.67	7.73	5.86	5.72	5.48	4.86
11	7.72	5.40	5.60	8.01	5.93	5.75	5.60	4.86
12	7.66	5.40	5.84	7.81	5.85	5.67	5.57	5.00
13	7.66	5.40	5.85	7.64	5.78	5.70	5.44	4.88
14	7.66	5.40	5.82	6.72	5.65	5.48	5.35	4.81
15	6.78	4.69	4.73	6.69	6.05	5.87	5.60	4.97
16	6.49	4.51	4.88	5.34	5.86	5.68	5.60	4.97
17	5.06	3.57	3.86	8.08	5.58	5.50	5.33	4.86
18	8.19	5.71	5.76	8.10	6.52	6.40	6.06	5.35
19	8.19	5.74	5.76	7.93	6.62	6.42	6.13	5.44
20	7.83	5.49	5.79	7.93	6.41	6.22	6.10	5.37
21	7.81	5.49	5.77	7.98	6.45	6.25	6.11	5.37
22	7.82	5.49	5.91	7.78	6.43	6.24	6.01	5.37
23	7.79	5.49	5.94	7.86	6.20	6.01	5.87	5.27
24	7.93	5.40	5.67	7.86	5.88	5.70	5.60	4.97
25	7.93	5.40	5.71	7.86	5.87	5.69	5.60	4.97
26	7.93	5.40	5.67	7.86	5.86	5.75	5.60	4.97
27	7.75	5.40	5.78	7.69	5.93	5.80	5.52	4.93
28	7.66	5.40	5.79	8.09	5.68	5.60	5.37	4.81
29	8.26	5.71	5.76	7.96	6.56	6.36	6.08	5.39
30	8.07	5.59	5.75	7.82	6.53	6.34	6.13	5.36
31	7.85	5.49	5.67	7.87	6.56	6.36	6.13	5.27
32	7.82	5.49	5.69	6.45	6.60	6.30	6.12	5.27
33	6.48	4.53	4.67	7.96	6.40	6.21	5.96	5.17
34	8.19	5.66	5.67	7.86	5.94	5.87	5.53	4.88
35	7.92	5.40	5.67	7.64	6.06	5.88	5.60	4.85
36	7.66	5.40	5.85	7.99	5.65	5.48	5.35	4.81
37	8.17	5.67	5.76	8.07	6.42	6.23	6.01	5.35
38	8.17	5.67	5.79	8.14	6.49	6.20	6.09	5.44
39	7.95	5.57	5.91	8.17	6.42	6.23	6.11	5.45
40	7.79	5.49	5.94	8.21	6.41	6.22	6.12	5.54
41	7.79	5.49	5.94	7.76	6.41	6.22	6.13	5.51
42	7.79	5.49	5.84	6.70	6.19	6.00	5.86	5.27
43	6.45	4.51	4.88	6.75	6.23	6.04	5.95	5.31
44	6.40	4.51	4.88	7.86	6.23	6.04	5.96	5.46
45	7.93	5.58	5.67	7.93	5.86	5.78	5.48	4.81
46	7.93	5.50	5.77	7.89	5.88	5.71	5.56	4.97
47	7.78	5.46	5.79	7.96	5.86	5.72	5.52	4.96
48	7.66	5.40	5.84	7.86	5.86	5.72	5.53	5.03
49	7.66	5.40	5.84	6.72	5.86	5.72	5.48	4.86
50	6.62	4.66	4.74	6.70	6.02	5.84	5.60	4.97
51	6.52	4.57	4.86	5.28	5.86	5.68	5.60	4.98
52	5.13	3.57	3.86	5.34	5.58	5.50	5.30	4.74
53	5.06	3.57	3.86	8.02	5.58	5.41	5.33	4.87
54	8.11	5.68	5.76	8.14	6.45	6.26	6.02	5.30
55	8.25	5.75	5.76	7.76	6.58	6.38	6.13	5.45
56	7.79	5.49	5.92	7.99	6.19	6.00	5.86	5.27
57	8.06	5.67	5.76	7.99	6.41	6.32	6.00	5.27
58	8.06	5.60	5.76	7.99	6.43	6.30	6.13	5.28

Table 6. Continued.

Agro-ecological unit	Maize	Pearl millet	Cotton	Sugarcane	Chickpea	Potato	Mustard
Planting	10 Jul	15 Jul	20 Jul	20 May	5 Nov	10 Oct	10 Nov
1	6.91	4.85	4.25	83.89	3.06	63.47	3.38
2	7.01	5.09	4.32	88.33	3.33	67.58	3.30
3	7.06	5.14	4.50	95.01	3.58	68.63	3.30
4	7.24	5.13	4.84	99.08	3.52	68.85	3.33
5	7.26	5.13	4.80	96.34	3.47	67.55	3.42
6	7.18	5.09	4.48	91.33	3.70	65.52	3.59
7	6.97	4.91	4.35	82.19	2.39	59.21	3.11
8	7.12	4.94	4.59	84.44	2.33	59.21	3.12
9	7.18	5.02	4.24	74.15	2.43	59.21	3.41
10	6.12	4.29	3.77	75.65	2.03	58.76	3.12
11	6.21	4.49	3.92	84.11	2.42	62.87	3.12
12	6.53	4.57	4.48	90.09	2.28	62.87	3.14
13	6.37	4.51	4.17	83.75	2.31	61.09	3.28
14	6.30	4.41	4.10	83.69	2.27	57.80	3.42
15	6.24	4.44	3.78	72.36	2.03	58.59	3.11
16	6.41	4.57	4.27	83.30	2.20	59.21	3.11
17	6.38	4.57	4.49	75.04	0.91	49.37	2.56
18	6.91	4.87	4.25	81.19	3.06	63.13	3.35
19	7.02	4.97	4.25	82.80	3.24	66.76	3.30
20	7.07	5.08	4.58	94.83	3.53	67.98	3.31
21	7.11	5.11	4.59	95.40	3.55	68.44	3.32
22	7.14	5.03	4.64	94.50	3.47	64.95	3.43
23	7.18	5.07	4.43	90.65	3.67	65.32	3.59
24	6.36	4.57	4.02	83.69	2.31	62.87	3.12
25	6.35	4.57	4.06	83.69	2.31	62.87	3.12
26	6.36	4.57	3.90	83.69	2.44	62.87	3.12
27	6.27	4.48	4.02	83.69	2.35	60.25	3.21
28	6.28	4.39	4.06	83.69	2.28	57.51	3.36
29	6.91	4.92	4.25	80.73	3.07	63.32	3.33
30	6.91	5.01	4.25	88.33	3.36	66.82	3.30
31	6.91	5.08	4.25	94.05	3.66	68.84	3.30
32	6.91	5.14	4.25	94.50	3.78	68.85	3.30
33	6.97	5.00	4.32	8 1.90	2.39	59.2 1	3.11
34	6.12	4.35	3.77	72.3 1	2.03	58.76	3.12
35	6.12	4.57	3.77	83.69	2.51	62.87	3.12
36	6.36	4.56	3.71	75.72	2.51	61.41	3.42
37	6.91	4.85	4.25	84.73	3.06	64.33	3.32
38	6.98	4.99	4.35	85.19	3.13	65.22	3.30
39	7.21	5.11	4.79	95.50	3.39	67.85	3.31
40	7.39	5.15	5.10	102.2	3.42	68.50	3.31
41	7.45	5.16	5.15	103.5	3.42	68.85	3.30
42	6.99	4.93	4.33	93.74	3.42	61.31	3.61
43	7.26	4.99	5.02	86.27	2.20	58.79	3.11
44	7.45	5.02	5.14	89.70	2.20	59.2 I	3.11
45	6.12	4.29	3.77	75.72	2.03	58.76	3.12
46	6.33	4.45	4.14	81.09	2.18	60.65	3.14
47	6.35	4.46	4.22	83.76	2.24	60.02	3.20
48	6.45	4.50	4.36	87.35	2.27	60.86	3.19
49	6.36	4.43	4.16	83.69	2.27	58.76	3.27
50	6.36	4.44	3.95	75.1 1	2.20	59.21	3.11
51	6.47	4.54	4.35	84.78	2.20	58.77	3.11
52	6.19	4.52	4.30	70.52	0.91	48.49	2.57
53	6.38	4.57	4.49	75.04	0.91	49.37	2.56
54	6.91	4.85	4.25	83.81	3.06	63.72	3.31
55	6.95	4.92	4.29	80.12	3.07	64.64	3.30
56	7.10	4.99	4.66	94.50	3.42	63.07	3.61
57	6.91	4.85	4.25	85.50	3.06	63.71	3.31
58	6.91	5.01	4.25	85.50	3.42	65.67	3.30

Estimating inputs required for the target yields and other ancillary outputs

For land use analysis in the framework of planning for food security, all inputs required to realize these target yields have to be specified, as limited availability of natural and socioeconomic resources may constrain the implementation of a certain activity. In terms of outputs, in addition to the (desired economic) yield, other consequences of carrying out a certain activity should be considered. That refers to the production of crop residues, but equally to undesirable outputs, such as emissions of nutrients (volatilization, denitrification, leaching) and/or emissions of biocide (residues) into the environment and/or excessive groundwater withdrawal. In our approach, a unique combination of all inputs results in a unique output in a given physical environment. The combination of inputs needed to obtain a particular yield (output) are calculated based on knowledge of the underlying processes (Van Ittersum and Rabbinge, 1997). Target yields act as the independent variable that dictates the inputs, i.e., nutrients water, labour, pesticides and machinery required to attain this yield (Figure 3). Certain outputs, such as nitrate leaching and residual pesticides, are then calculated on the basis of input use and its related output generation mechanism.

Input/output relationships are expressed per hectare. The calculation procedure is based on earlier measurements at a field/farm scale and reported in the literature. For simplicity, it has been assumed that these relationships can be extrapolated to larger areas, although the rate of return from a particular input can change with scale. In our approach, inputs and outputs for a given land use system are determined by the physical environment and the production technology. Soil and climate represent the physical environment and production technology specifies how the target yield is attained and includes the required inputs.

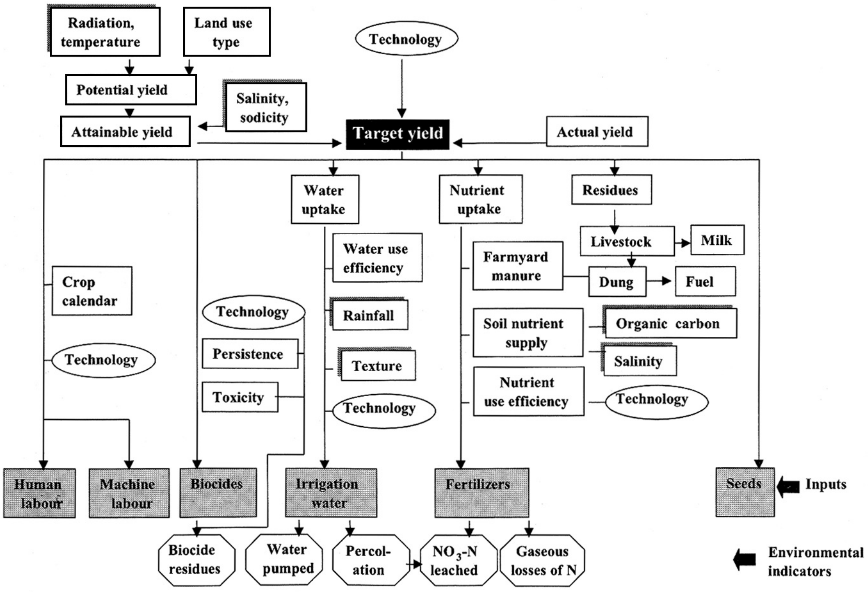


Figure 3. Schematic representation of calculation procedure of technical coefficients.

Estimates of fertilizer requirement

Recommendations based on soil classification of low, medium and high fertility and cost–benefit analysis are often inadequate when the goal is to sustain high yields, to maintain or improve soil fertility at a level that ensures maximum efficiency from investment in nutrient inputs and to limit losses to the environment. We therefore used a soil test-based approach for estimating fertilizer requirements for a yield target (Figure 4).

Nitrogen (N), phosphorus (P) and potassium (K) requirements of crops

The first step in calculating fertilizer requirements is estimating the requirement for a particular nutrient for a target yield. Nutrient removal by a crop depends on the composition of main products and by-products (economic yield and residues). Considerable uncertainties exist about N, P and K requirements of crops because the internal nutrient efficiencies (kg economic yield kg^{-1} plant nutrient) vary greatly depending on nutrient supply, crop management practices and climatic conditions. For example, estimates of total nutrients per ton of wheat grain ranged from 15 to 60 kg N, 2.5 to 8.0 kg P and 10 to 55 kg K (Van Duivenbooden *et al.,* 1996; Tandon and Sekhon, 1988). To overcome this problem, a modelling approach such as in the QUEFTS model is advocated to estimate nutrient requirements (Janssen *et al.,* 1990). Using this model, N, P and K requirements of rice (Witt *et al.,* 1999), wheat (Pathak *et al.,* 2001) and maize (Janssen *et al.,* 1990) were estimated. These estimates have been used in this study. For nutrient requirements of other crops, the values reported by Van Duivenbooden *et al.* (1996) and Tandon and Sekhon (1988) were used (Table 7).

Nutrient supply from soil

In most of the soil-testing laboratories in India, organic carbon, Olsen P (0.5 M $NaHCO_3$ with pH 8.5) and neutral normal ammonium acetate extractable K are used as indicators of soil N, P and K supply, respectively. On the basis of published data (e.g., Pathak *et al.,* 2001), relationships were established for estimating nutrient supply of soils for rice and wheat (Table 8). The relationships of soil nutrient supply for wheat were used for all upland crops after adjusting for crop duration.

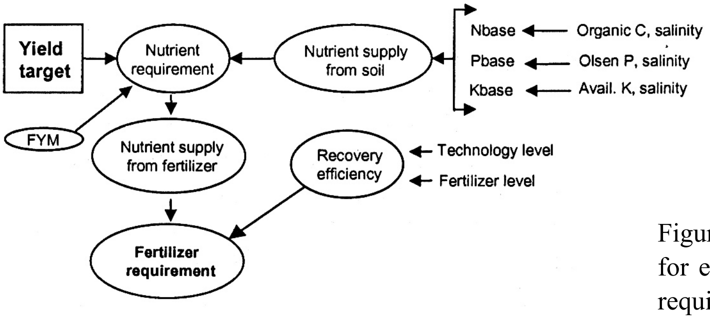


Figure 4. Components for estimating fertilizer requirements. FYM = farmyard manure.

Table 7. N, P and K requirements of crops per ton of grain yield.

Crop*	Produce	Requirements		
		N	P	K
		kg t^{-1} grain		
Rice[a]	Paddy	14.7	2.6	14.5
Basmati rice[a]	Paddy	14.7	2.6	14.5
Summer rice[a]	Paddy	14.7	2.6	14.5
Wheat[b]	Grain	23.1	3.5	28.5
Gram[c]	Grain	46.3	3.7	41.3
Pearl millet[d]	Grain	34.6	5.0	48.8
Maize[d]	Grain	23.4	3.5	16.6
Cotton[c]	Seed	44.5	12.4	62.2
Sugarcane[c]	Cane	1.7	0.1	1.7
Mustard[c]	Grain	32.8	7.2	34.8
Potato[c]	Tuber	3.9	0.6	4.1
Sorghum[d]	Grain	30.7	3.7	26.0

* Source: [a]Witt *et al.* (1999), [b]Pathak *et al.* (2001), [c] Tandon and Sekhon (1988), [d] Van Duivenbooden *et al.* (1996).

Table 8. Relationships of soil nutrient-supplying capacity and soil test parameters for rice and wheat.

Nbase-wheat*	$2.49 + 102 \times \text{OC}$
Pbase-wheat	$4.88 - 0.01 \times \text{Olsen P} + 0.02 \times (\text{Olsen P})^2$
Kbase-wheat	$2.73 + 0.93 \times \text{AAK} - 0.001 \times (\text{AAK})$*
Nbase-rice	$9.5 + 104 \times \text{OC} - 23 \times (\text{OC})^2$
Pbase-rice	$2.21 + 0.91 \times \text{Olsen P} - 0.01 \times (\text{Olsen P})^2$
Kbase-rice	$2.93 + 0.95 \times \text{AA K} - 0.0013 \times (\text{AA K})^2$

* Nbase, Pbase and Kbase are soil supply of N, P, and K in kg ha^{-1} ; OC, organic carbon (%); Olsen P in kg ha^{-1} ; AA K, ammonium acetate extractable K in kg ha^{-1} .

Nutrient supply from farmyard manure (FYM)

The average quantities of FYM used by farmers in Haryana are low (Table 9). It has been assumed that the cattle population and demand of dung for fuel will not change and thus the use of FYM will remain at the same level in the near future. Therefore, the same quantity of FYM for all the technology levels was used. However, it should be noted that higher technology levels, particularly technology levels 4 and 5, require the use of larger quantities of organic manure. Gaur (1994) recommended about 25 t FYM ha^{-1} under intensive irrigated-cropping conditions for sugarcane, potatoes and rice and 12.5 t for other irrigated crops. In the present study, the nutrient-supplying function of FYM can be compensated for with chemical fertilizers if FYM is not available in sufficient quantities.

Farmyard manure contains 0.5% N, 0.1% P and 0.4% K (Tandon, 1994). Leelavati

Table 9. Current use of farmyard manure (FYM, t ha $^{-1}$) in Haryana (Source: Survey conducted by Haryana Agricultural University during 1997-98, unpublished).

Crop	Use of FYM
Rice	1.0
Basmati rice	1.7
First rice in rice-rice-wheat	2.0
Wheat	1.0
Chickpea	0.5
Pearl millet	1.7
Maize	1.2
Cotton	1.7
Sugarcane	8.7
Mustard	0.8
Potato	2.5

(1986) estimated that in northern India 1 kg N from fertilizer was equivalent to 0.34 t FYM during a single cropping season of 120 days. Taking the proportional content of N, P and K, we calculated that 1 t FYM would supply 3 kg N, 0.5 kg P and 2.5 kg K per cropping season.

Effect of salinity on soil nutrient supply

Soil salinity reduces the nutrient-supplying capacity of the soil. Mineralization steadily decreases with an increase in salinity level, but the decrease varies with soil type. Also, N use efficiency is low in salt-affected (sodic) soils because of high losses caused by ammonia volatilization. Based on published data (Sharma *et al.,* 1992), the following relationship between soil EC at saturation and nitrogen availability from natural sources (Nbase) was derived:

$$\text{Nbase in a salt-affected land unit} = \text{Nbase in a normal unit} / (\text{soil EC in salt unit} - \text{soil EC in normal unit}) \times 0.84 \qquad (6)$$

For Pbase and Kbase, the same relationship was used.

Apparent recovery efficiency of applied fertilizer nutrients

The apparent recovery efficiency of fertilizer nutrients is an important aspect of calculating fertilizer requirements. It is defined as

$$\text{RENu} = (\text{UNu} - \text{UNu0}) / \text{Fnu} \qquad (7)$$

where RE is the apparent recovery efficiency of applied fertilizer nutrient (kg nutrient in plant dry matter kg $^{-1}$ nutrient applied), Nu is the nutrient under consideration, UNu is plant nutrient accumulation in total above-ground plant dry matter at maturity (kg ha $^{-1}$) in plots receiving the respective fertilizer nutrient at the rate of FNu (kg ha $^{-1}$) and UNu0 is total nutrient accumulation without nutrient addition (Cassman *et al.,* 1998). Tandon (1994) compiled data on nutrient removal by crops and estimated that the

Table 10. Apparent recovery efficiencies of N, P and K fertilizers (kg kg $^{-1}$) in different crops at the various technology levels.

Crop	Technology levels 1,2,3			Technology level 4			Technology level 5		
	RE_N	RE_P	RE_K	RE_N	RE_P	RE_K	RE_N	RE_P	RE_K
Rice	0.35	0.25	0.50	0.40	0.28	0.55	0.45	0.30	0.60
Wheat	0.50	0.25	0.50	0.55	0.28	0.55	0.60	0.30	0.60
Chickpea	0.50	0.25	0.50	0.55	0.28	0.55	0.60	0.30	0.60
Pearl millet	0.42	0.25	0.50	0.46	0.28	0.55	0.50	0.30	0.60
Maize	0.42	0.25	0.50	0.46	0.28	0.55	0.50	0.30	0.60
Cotton	0.42	0.25	0.50	0.46	0.28	0.55	0.50	0.30	0.60
Sugarcane	0.42	0.25	0.50	0.46	0.28	0.55	0.50	0.30	0.60
Mustard	0.50	0.25	0.50	0.55	0.28	0.55	0.60	0.30	0.60
Potato	0.50	0.25	0.50	0.55	0.28	0.55	0.60	0.30	0.60
Sorghum	0.42	0.25	0.50	0.46	0.28	0.55	0.50	0.30	0.60

recovery efficiency of N in rice was 35% and for other crops it was 42–50% (Table 10). For P and K, the estimated values were 25% and 50%, respectively. According to Tandon (1994), the production technologies that were applied correspond to our technologies 1–3. Thus, we assume that the compiled efficiency values apply to our technologies 1–3. For technologies 4 and 5, we assume increasingly improved growth conditions (presence of less/less severe yield-limiting factors). In such situations, according to De Wit (1994), the law of the optimum applies, which results in efficiency gains at higher yields. The applicability of this law under field conditions has been demonstrated repeatedly – most recently also for rice (Dobermann *et al.,* 2000) and wheat (Pathak *et al.,* 2001) cultivated in Asia. Since fertilizer recovery efficiencies are higher in technologies 4 and 5, RE_N, RE_P and RE_K have been assumed to increase by 15%, 10% and 10%, respectively, in technology 4 compared with technologies 1 to 3. At technology level 5, 30%, 20% and 20% increase in RE_N, RE_P and RE_K, respectively, has been assumed.

Fertilizer requirements

Fertilizer requirements (FR) were calculated by subtracting the supply of nutrients (soil – Nbase, Pbase and Kbase, and FYM) from crop nutrient requirements (NR) using the equations given in Table 11.

Using the procedures discussed above, the requirements of N, P and K fertilizers were calculated for all land use systems for the various agro-ecological units. A few examples for the rice-wheat cropping system are given in Table 12. At technology level 1, fertilizer-N requirements in different agro-ecological units varied from 9 to 104 kg ha $^{-1}$ and at technology level 5 from 180 to 243 kg ha $^{-1}$. These large variations are due to differences in organic carbon content and salinity status of the soils and yields. Fertilizer-N requirements at technology levels 4 and 5 were about 30 and 50 kg ha $^{-1}$, respectively, higher than at technology level 3, with average yields at technology levels 3,4 and 5 of 5.4, 6.5 and 7.5 t ha $^{-1}$.

Table 11. Relationships to estimate fertilizer requirement (FR) of crops for N, P, and K based on nutrient supply from soil and farmyard manure (FYM), and apparent recovery efficiencies (RE) of applied fertilizers.

Technical coefficient*	Relationship*
FR_N	$(NR_N$ – N through FYM – Nbase) / RE_N
FR_P	$(NR_P$ – P through FYM – Pbase) / RE_P
FR_K	$(NR_K$– K through FYM – Kbase) / RE_K

* FR_N, FR_P and FR_K, fertilizer requirements for N, P and K in kg ha $^{-1}$; RE_N, RE_P and RE_K, recovery efficiencies of fertilizer N, P and K in kg kg $^{-1}$; Nbase, Pbase and Kbase, soil supply of N, P and K in kg ha $^{-1}$; NR_N, NR_P and NR_K, nutrient requirements of crops in kg ha $^{-1}$ (from Table 7); contributions of N, P and K through FYM are in kg ha $^{-1}$.

Table 12. Ranges of fertilizer-N requirements for rice and wheat in various agro-ecological units.

Technology level	Fertilizer-N requirement (kg ha $^{-1}$)	
	Rice	Wheat
1	9–104	28–139
2	70–161	58–169
3	132–217	88–202
4	161–228	98–197
5	180–243	105–193

Cautionary remarks

In quantifying the fertilizer requirements for the various crop/agro-ecological unit combinations, indigenous nutrient supply has been taken into account. For N, the major proportion of that supply originates from the decomposition of soil organic matter. When through crop residues and FYM the organic matter store is insufficiently replenished, soil organic carbon (SOC) will decline and consequently the N-supplying capacity of the soil. Similar processes are taking place for P and K, though with different components. Phosphorus is mainly stored in inorganic components of low solubility and K predominantly in clay (minerals). It has also been observed that the P and K status of soils under intensive agriculture declined (Sinha *et al.,* 1998).

In our approach to quantifying fertilizer requirements, this aspect of sustaining the long-term quality of the soil resource base has not been considered and the calculated requirements therefore cannot be extrapolated easily into the future (next 10–20 years).

Irrigation requirements

Soil, plant and atmospheric characteristics should be taken into account for estimating irrigation requirements of crops. A plant characteristic, related directly or indirectly to crop water requirements, that readily responds to the integrated influence of soil-water, plant factors and evaporative demand of the atmosphere may also serve as a criterion of irrigation requirements (Hagan and Laborde, 1964). Crop yield, which is an integrated expression of soil, plant and atmospheric interactions, has often been related directly to irrigation requirements (Prihar and Sandhu, 1987). This relationship has been used in the present study and it has been assumed that it does not change with technology level. The amount of water available through rainfall and in the soil moisture profile at sowing is subtracted from the gross irrigation water requirement. For rice, an upper limit of 1,500 mm of irrigation requirement was set, assuming that larger amounts will result in runoff.

A soil texture-based correction factor (CFTx) has been used to account for percolation losses. CFTx values are 1.12 for coarse loam and 1.25 for sandy soil relative to sandy loam soils (CFTx = 1.0). For convenience, silty clay loam soil is pooled with the sandy loam category.

The following relationship describes the estimation of irrigation requirements of different crops:

$$\text{Irrigation required}_{lut,aeu} = \text{Yield}_{lut} \times \text{IW}_{aeu} \times \text{CFTx}_{aeu} \qquad (8)$$

where IW is irrigation required in mm water per ton dry matter yield, CFTx is an agro-ecological unit-specific soil texture-related correction factor and IW is irrigation requirement per ton of economic yield (dry weight basis) for different crops (Table 13).

As an example, total irrigation water requirements of rice and wheat at various technology levels of rice-wheat systems for AEU1 are given in Table 14. The irrigation amount for a given crop for convenience is distributed equally in different months of the growing period.

Biocide use

Chemical control of insect pests is an integral part of modem agriculture. In Haryana, the use of plant protection chemicals has increased dramatically over the last two

Table 13. Irrigation requirements of various crops for normal sandy loam class (Source: Prihar and Sandhu, 1987).

Crop	Irrigation (mm t^{-1} yield)
Rice	254
Basmati rice	270
First rice in rice-rice-wheat system	270
Second rice in rice-rice-wheat system	254
Wheat	63
Chickpea	82
Pearl millet	81
Maize	68
Cotton	271
Sugarcane	7
Mustard	105
Potato	20
Sorghum	80

Table 14. Irrigation requirements of rice and wheat in rice-wheat systems in AEU1 at various technology levels.

Crop	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Grain yield (t ha^{-1})					
Rice	3.6	4.7	5.8	7.0	8.1
Wheat	3.9	4.5	5.2	5.8	6.4
Irrigation water required (mm)					
Rice	903	1,193	1,483	1,500	1,500
Wheat	244	284	328	365	403

decades. Information on total pesticide use in Haryana in general and Karnal district in particular was collected from the literature. Currently, nearly 5,100 metric tons of technical-grade biocides are used in Haryana annually and Karnal, with 193,000 ha of net sown area, consumes nearly 422 million t. Per hectare, the consumption of biocides in Karnal is 2,184 g ha^{-1}, which is significantly higher than the national average of 400. Biocides are mainly used to eradicate Phalaris minor and rice weeds. The chemical, which is mostly applied to control this weed, is isoproturon. Other chemicals, used to control rice weeds, are butachlor and anilofos. In Karnal, 70–80% of pesticide use pertains to these three chemicals (Table 15).

Exact figures on the consumption of various chemicals on the basis of crops, region and crop season are not available. It is clear from the table that, out of more than 120 chemicals registered for use in the country, only 11 are listed as used in Haryana. The two most popular and also most toxic chemicals, DDT and BHC, are not mentioned. Using this information, we estimated biocide use in the various land use types in

Table 15. Biocide consumption in different crops in Haryana.

Pesticide	Use of pesticides (g ha^{-1})									
	Rice	Wheat	Sugar-cane	Chick-pea	Maize	Cotton	Mustard	Potato	Pearl millet	Sorghum
Chlorpyrifos	0	25	48	74.7	0	1,120	0	448	0	0
DDVP	8	2	19	0	59.4	446	0	178	0	0
Endosulfan	29	0	56	0	0	1,315	0	527	0	0
Malathion	11	3	26	0	82	616	0	246	0	0
Monocrotofos	24	0	47	47	0	1,102	0	441	0	0
Methylparathion	12	0	23	0	73	548	0	220	0	0
Phosphamidon	21	0	41	128	64	960	64	384	0	0
Anilofos	238	0	0	0	0	0	0	0	0	0
Butachlor	282	0	0	0	0	0	0	0	0	0
Isoproturon	0	775	0	0	0	0	0	0	0	0
Dithane M-145	0	0	0	0	0	0	2,135	4,270	0	0
Total (a.i.kgha^{-1})	625	805	260	250	278	6,107	2,199	6,714	0	0
Cost (Rs. ha^{-1})	293	430	130	121	132	3,053	687	2,554	0	0

Haryana at the current level of technology (technology 1). Biocide use at the other technology levels was based on the target yields.

Seed requirement

The seed rate needed for good establishment of a crop is known for Haryana (Table 16) and was used in the current analysis. It was assumed that the same seed rate is applied for all technologies.

Labour requirements

Labour requirements depend on land use system, crop type, yield level and technology level. This requirement is defined in terms of time required to carry out an operation under standard conditions by a labourer working at a normal pace, with standard equipment and with maximum efficiency. For field operations, tractor hours to perform an activity for one hectare of land have been used. A survey conducted by Haryana Agricultural University provides information on human labour and machine labour used at the current technology level (Table 17). In Haryana, oxen and male buffaloes are also used for field operations, transport and on-farm processing of the produce. For crops such as rice and wheat, however, most operations are carried out with machine labour and hardly any animal labour is used. Therefore, in the present analyses, the requirements for machine labour were considered.

Farm operations have to be carried out in a certain period to ensure timeliness of soil and crop management. Based on interpretation of information from the literature and expert judgment, monthly labour requirements were derived for various activities to be performed during the cropping season (Table 18).

Table 16. Seed rates per hectare and prices (1998-99) of seeds.

Crop	Seed rate (kg ha^{-1})	Seed price (Rs kg^{-1})
Rice in rice-wheat system	25	7.6
First rice in rice-rice-wheat	25	7.6
Second rice in rice-rice-wheat	45	7.6
Basmati rice	25	16
Wheat in rice-wheat	110	7.6
Wheat in basmati rice-wheat	115	7.6
Wheat in sugarcane-wheat	120	7.6
Wheat in other systems	100	7.6
Chickpea	45	14
Pearl millet	5	6.2
Maize	20	6.4
Cotton	20	23.6
Sugarcane	8,000	1
Mustard	5	17.2
Potato	1,500	2.8
Sorghum	10	6.2

Table 19. Cost of various inputs used in the current analysis.

Item	Cost (Rs)
Nitrogen (kg) as urea	9.2
Phosphorus (kg) as di-ammonium phosphate	14.6
Potassium (kg) as muriate of potash (KCl)	7.0
Labour (d)	55.0
Tractor (hr)	100.0
Farmyard manure (t)	80.0
Zinc sulphate (kg)	10.0

for mechanization (technology cost) have been set at Rs. 1,500 per hectare at level 4 and at Rs. 3,000 per hectare at technology level 5.

Costs and returns

Production costs, including those for fertilizer, human labour, animal labour, hiring of tractor, and FYM, and procurement prices of products and residues for 1999 were taken from the Department of Agriculture, Government of Haryana (Table 19). Miscellaneous costs were set at 10% of operational costs. We calculated total income by adding revenues from the main produce and from residues (Figure 5). Net return was calculated as the difference between gross production value (prices multiplied by total production) and costs.

Returns from outputs

Returns from outputs included the price of products (yields) and harvested residue of various crops (Table 20).

Crop residues

Amounts of residue produced from the various crop activities were estimated from the target yield and crop-specific harvest indices (HI). Average values, for different crops

Table 20. Prices (1998-99) of products and residues.

Crop	Product price (Rs kg $^{-1}$)	Residue price (Rs kg $^{-1}$)
Rice	3.8	0.1
Basmati rice	8.0	0.1
Wheat	3.8	1.0
Chickpea	7.0	0.1
Pearl millet	3.1	0.2
Maize	3.2	0.2
Cotton	11.8	0.1
Sugarcane	0.5	0.1
Mustard	8.6	0.1
Potato	1.4	0.0
Sorghum	3.1	0.1

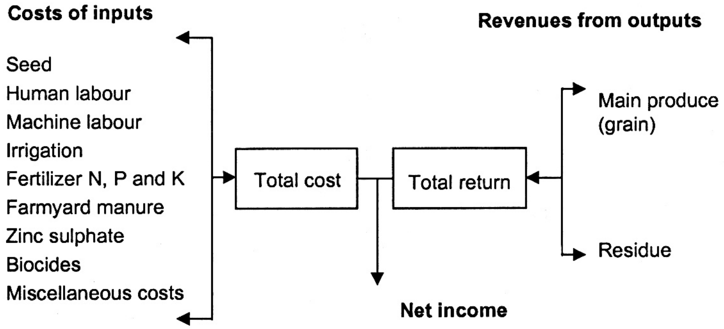


Figure 5. Costs and returns used to estimate net income from cropping activities.

appear in Table 2 1. A 20% fraction of the total residues was assumed to be lost during harvesting and transportation and thus was not available for use:

Residues = Target yield × 0.8 / HI

Livestock production activities

Livestock is an integral part of Haryana's agriculture. Most farmers keep some cattle to produce milk that is used for home consumption and partially marketed. Three major livestock activities were considered in this analysis: (1) crossbred cows, (2) buffaloes and (3) local cows. These activities are not considered as separate land use types because in Haryana animals are kept in the farm area and stall-fed; thus, there is no competition for land. Instead, cattle are part of the homestead where they are reared for milk and to some extent for traction. Goats, horses, sheep and donkeys are limited in number and of minor importance. Poultry production was also excluded because it is indirectly related to land use and has limited importance in Haryana's agriculture.

In the livestock production activities, only milk and dung production were considered, excluding beef production and other associated activities because of their restricted importance in India. Animal and crop production activities are interlinked (Figure 6). The feed required by animals originates from crop activities. Manure produced in animal activities is applied to crops as a source of nutrients. Male cattle and buffalo are used as draft animals for land preparation, sowing of crops, and transportation of manure and agricultural products.

Table 21. Harvest indices of various crops.

Crop	Harvest index	Crop	Harvest index
Rice	0.40	Cotton	0.50
Wheat	0.37	Sugarcane	0.70
Gram	0.20	Mustard	0.25
Pearl millet	0.40	Potato	0.60
Maize	0.40	Sorghum	0.40

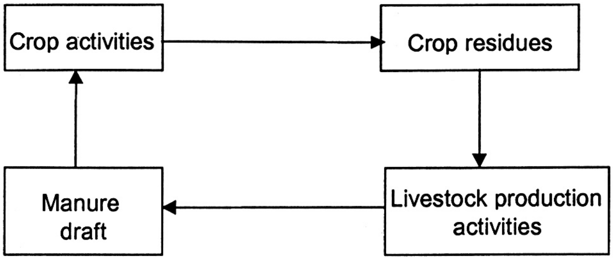


Figure 6. Interactions of cropping and livestock production activities.

Feed requirements for various livestock activities are expressed in terms of digestible energy and digestible crude protein. For each animal activity, it is assumed that a diet is selected that meets the minimum requirements for energy and protein using the target-oriented approach. Available feeds include crop residues, grass, cakes of oil crops and concentrates purchased from the market. Availability of crop residues as feed is set at 80% of their harvested yields. Only residues from wheat, millet and sugarcane are considered as consumables. Forage from natural grassland is used for grazing.

Conclusions

We have developed a framework that can be used for quantifying potential yields as a function of climatic features of various land units. In combination with actual yields, technology and land degradation status, these estimates are needed for setting target yields. The technical coefficient generator integrates the knowledge base of several sciences and provides relatively easily the inputs required for different target yields of various land use systems. Most of the relations are based on data collected from the region; no additional validation studies for the technical coefficient generator were carried out. A Visual Basic-based user-friendly interface with Microsoft Access in the backend has been developed that can help users generate the various coefficients for their situations. It also allows adaptation of the relationships used in the generator. We hope that these procedures will be useful for other scientists to estimate input/output relationships.

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6. Environmental impact assessment

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Introduction

In South Asia, agro-ecosystems have been modified increasingly during the last three decades by introducing crops with considerably higher yield potential and using high amounts of external production inputs. This did raise cereal production to such an extent that even the rapid population growth was outpaced. Over time, however, it has been realized that such external interventions also negatively affect various other properties of agro-ecosystems (Sinha *et al.,* 1998; Ladha *et al.,* 2000). The sustainability of food production systems is under increasing threat in regions where the technological interventions have been and continue to be intense. There are, for instance, serious concerns about the sustainability of continuous (high input–high output) rice cultivation (Cassman *et al.,* 1995). In some regions, environmental degradation caused by intensive agricultural practices has now started to reduce productivity itself. Yield trends from long-term continuous cropping experiments conducted in several locations in tropical countries indicate that, even with the best available cultivars and scientific management, cereal yields either have become stagnant or have started to decline (Aggarwal *et al.,* 2000; Dawe *et al.,* 2000; Duxbury *et al.,* 2000). The major reasons for such a response are believed to be the decline in the supply of soil nutrients because of organic matter depletion, deterioration of soil physical properties because of puddling, increased pest and disease infestation because of continuous monocropping, depletion of surface water and groundwater deterioration in the quality of irrigation water. In India, such changes are seriously affecting the country's productive resource base and thus threatening its capacity to increase food production. The area affected by soil salinity has increased from 7.0 million ha in the 1970s (Abrol and Bhumla, 1971) to 10.9 million ha in the 1990s (Sehgal and Abrol, 1994). On about 7 million ha, waterlogging/accumulation of excess water for a significant part of the year is the main factor reducing the productivity of the otherwise productive soils.

Increasingly intensive agriculture since the 1960s has resulted in problems of a declining water table in rice-wheat areas and of a rising water table and waterlogging

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in canal-irrigated areas of central and parts of western Haryana. There are now also reports of declining nitrogen (N) use efficiencies, NO_3-leaching, increasing salinity and pesticide residues. Planning for future food security therefore requires that environmental effects of current and future agricultural production technologies be assessed before any recommendation is made.

In the previous chapters, we have assessed the opportunities for increasing crop production for various land use systems and technologies in different land units of Haryana. Some of these technologies imply higher requirements of water for irrigation, fertilizers and biocides. In this chapter, the methodologies used to assess the environmental impact of the various production technologies are described.

Two different groups of environmental quality indicators are evaluated. The first group is related to losses of N into the environment because of leaching, volatilization and denitrification. In the absence of comprehensive and detailed measurement programmes, these processes are difficult to quantify. In our study, we used published data to estimate the various losses as a fraction of total N input, differentiated by soil type. The second group of environmental quality indicators is related to the use of crop protection agents that prevent or restrict crop damage caused by weeds, pests and diseases. The use of these agents may result in pollution of water and soil through the product itself or through transformation products, and may directly affect human health. The common denominator to combine various types of biocides is their content of active ingredient. Furthermore, in this chapter, the problems associated with waterlogging, groundwater depletion and soil salinity are briefly touched upon.

Losses of N

A shortage of nutrients, particularly of N, is often the factor that most limits crop growth. In addition to their uptake by crops, nutrients are also constantly being emitted from the soil system by various mechanisms (Figure 1). Denitrification and leaching are the major processes involved in N loss into the environment. These two processes account for approximately 75–80% of the total loss from acid to neutral types of soils, whereas, in alkaline soil, volatilization loss is more substantial. However, ammonia volatilization following urea application may also lead to significant losses in neutral to slightly acid soils (Wetselaar and Ganry, 1982). The recovery efficiency of N fertilizers seldom exceeds 50% and the losses are costly economically and they imply a waste of energy and cause environmental pollution. For example, during denitrification, nitrous oxide is emitted, which is one of the important greenhouse gases (Houghton *et al.,* 1995), and it plays an important role in the destruction of the stratospheric ozone layer (Crutzen, 1981; Bach, 1989). Nitrate leaching losses contaminate groundwater and surface water. This may result in high nitrate concentrations in drinking water, thus making it unfit.

The calculation procedure for assessing the N balance was as follows:

$$\text{N balance} = \Sigma\,(\text{fertilizer N, manure N, rain N, irrigation water N}) - \Sigma\,(\text{N uptake, losses of fertilizer N}) \qquad (1)$$

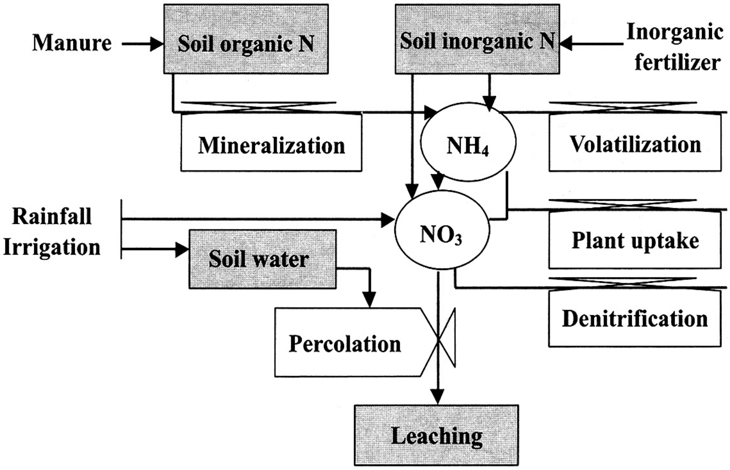

Figure 1. Schematic diagram showing the various N sources and sinks as used in the current study to estimate N losses.

Estimation of N inputs

N supply through mineral fertilizer and organic manure was estimated in our study based on a survey conducted by the Haryana Agricultural University, Hisar, Haryana. The contributions of irrigation water plus rainfall were based on the data reported by Mishra (1980) for Pantnagar, India (29° N and 79°5′ E and altitude 244 m). Plant uptake of N was estimated using the QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) model calibrated for rice (Witt *et al.,* 1999) and wheat (Pathak *et al.,* 2001). For an illustration, various inputs and outputs of N have been shown for the agro-ecological unit 4 in Table 1. The apparent net gain in N for rice-wheat systems in the current technology level (technology level 1) is 28 kg N ha $^{-1}$. In technologies 2, 3, 4 and 5, the balance ranged from 55 to 84 kg N ha $^{-1}$.

In the next section, the procedures and equations used for estimating the different N loss components are described.

Denitrification

The basic processes underlying denitrification have been studied extensively and are well understood. However, quantification in the field remains a major problem. Direct measurement is logistically difficult and therefore such data are scarce. No such measurements have been reported from India (Srivastava and Singh, 1996) and N losses through denitrification are estimated through the difference method, e.g., the unaccounted-for N is considered to be lost through denitrification. The denitrification loss of N was estimated based on published information (Tandon, 1994; Krishnappa and Shinde 1980; Sarkar and Uppal, 1994; Hengsdijk *et al.,* 1996): denitrification was set at 25% of applied fertilizer N for upland crops and at 30% for rice crops.

Table 1. Illustration of inputs and outputs of N in the rice-wheat land use system in agro-ecological unit 4.

Technology	Land use type	Inputs (kg N ha^{-1})					outputs (kg N ha^{-1})				Net balance (kg N ha^{-1})
		Fertilizer	Manure	Irrigation	Rain	Total	Uptake	Leaching	Gaseous loss	Total	
1	Rice	115	5	18	3	141	71	9	37	117	24
	Wheat	123	5	5	1	134	95	0	35	130	4
2	Rice	175	5	23	3	206	93	12	58	163	43
	Wheat	154	5	6	1	166	111	0	43	154	12
3	Rice	236	5	29	3	273	114	16	78	208	65
	Wheat	185	5	6	1	197	126	0	52	178	19
4	Rice	260	5	30	3	298	135	15	86	236	62
	Wheat	197	5	7	1	210	142	0	55	197	12
5	Rice	278	5	30	3	316	157	14	92	263	53
	Wheat	206	5	8	1	220	157	0	58	215	5

Volatilization

Using published data of Sharma *et al.* (1992), the following relationship was established between soil pH and ammonia volatilization loss:

$$\text{Volatilization loss of N (kg ha}^{-1}\text{)} = \text{Max}\,(0, 0.55 \times \text{pH}^2 - 1.72 \times \text{pH} - 18.1) \tag{2}$$

This relationship implies that volatilization losses occur only when soil pH is more than 7.5; at pH 10, for example, loss of N from volatilization would be 20 kg ha^{-1}.

Leaching of N

In India, some recent studies have reported high nitrate concentrations (more than 10 mg 1^{-1}) in the groundwater in a significant number of samples (Bijay-Singh, 1996; Majumdar and Gupta, 2000). A rapid reconnaissance study on nitrate concentrations in the shallow groundwater showed that the samples from Haryana and Punjab, the states where fertilizer consumption is the highest, contained high amounts of nitrate in the groundwater (Lunkad, 1994). Earlier, Kumar and Singh (1988) reported that the groundwater samples from Mohindragarh District of Haryana contained high concentrations of nitrate (> 45 mg 1^{-1}) in 75% of the samples. Handa (1987) and Pathak (1999) reviewed the work done on nitrate pollution in India and reported that in the tubewell (confined aquifer) water samples, about 60% of the samples had less than 1 mg nitrate-N 1^{-1} and less than 5% had more than 5 mg nitrate-N 1^{-1}. The remaining 35% of the samples were in between. But a considerable number of water samples from dug wells had high (> 50 mg 1^{-1}) nitrate content.

The magnitude of N through leaching depends upon soil conditions, agricultural practices, agro-climatic conditions and type of fertilizer and methods of application. The time taken by nitrate to move from the root zone to the water table therefore varies considerably. In sandy soils with a high water table and a high rate of fertilizer application, it may reach the water table in a matter of days, whereas, in heavy soils and a deep water table and in areas with low rainfall and/or low fertilizer use, it may take years. A limited number of studies correlate the nitrate pollution of groundwater with the use of N fertilizers. Bajwa *et al.* (1993) studied the influence of fertilizer application on nitrate content of groundwater in some districts of Punjab, where the fertilizer application rate is the highest in the country. They observed that 78.4% of the tubewell (21 to 38 m deep) water samples contained less than 5 mg nitrate-N 1^{-1} and the remaining ranged from 5 to 10 mg nitrate-N 1^{-1}. In the groundwater samples collected from 9 to 18-m-deep hand pumps located at homesteads/villages in Punjab, 64% of the samples contained 5–10 mg 1^{-1} and 2% of the samples more than 10 mg nitrate-N 1^{-1}. They concluded that animal wastes dumped in the inhabited areas could be the possible cause of higher nitrate concentrations in the hand-pump samples than in the tubewell samples. Nitrate concentrations in the groundwater were also higher under rice, maize, orchards and vegetables than for other crops. These higher concentrations were nevertheless less than the World Health Organization (WHO) limits. Bijay-Singh *et al.* (1991) have reported that in extensively irrigated coarse-textured, highly percolating soils of central Punjab, where appreciable amounts of applied N were lost because of leaching, only 10% of the samples contained nitrate-N concentrations of more than 10 mg 1^{-1}. Lunkad (1994) observed that the high nitrate concentrations in some groundwater samples reported from Haryana, Punjab and Uttar Pradesh in the north, Tamil Nadu in the south, Orissa (Ganjam District) and Bihar in the east and Gujarat in the west of India are associated with high N-fertilizer consumption. For the three basic physiographic-geologic divisions of India – the Indo-Gangetic plain, peninsular plateau and north and northeast India – nitrate pollution risk for groundwater is the highest for the Indo-Gangetic plain as it is almost flat and consists of a thick pile of unconsolidated and permeable alluvial sediments. Lunkad suggested that in this region fertilizer application must be accompanied by good drainage facilities, which, unfortunately, are lacking in Punjab and Haryana.

Nitrate-N leaching from soil in various land use systems was estimated with the assumption that only NO_3-N will be leached and ammonium-N will be retained in the soil through ammonium fixation or adsorbed to the exchange complex of soils. However, ammonia in upland soils will be readily nitrified so that concentrations tend to be relatively low. In our study, we assumed that NO_3-N translocated deeper than 150 cm in the soil is leached. We estimated NO_3-N leaching by multiplying the NO_3-N content in the soil solution by the amount of percolating water. The following equation was applied:

$$\begin{aligned}\text{N leached} = {} & [\{(N_{fert} + N_{FYM} + NO_3\text{-}N_{min} + NO_3\text{-}N_{soil}) - N_{plant}\} \times \\ & (1 - N_{denitrification} - N_{volatilization})] \times \\ & Water_{percolation} / (Water_{irrigation} + Rain \times RfUE + Water_{soil} \times 0.5)\end{aligned} \tag{3}$$

where

N_{fert}	fertilizer N applied,
N_{FYM}	N through FYM,
NO_3-N_{min}	NO_3-N mineralization during crop season,

NO_3-N_{soil}	NO_3-N content in soil profile,
N_{plant}	uptake of N by plant,
$N_{denitrification}$	loss because of denitrification of N,
$N_{volatilization}$	loss because of volatilization,
$Water_{percolation}$	percolation of water,
$Water_{irrigation}$	irrigation water,
Rain	rain during crop season,
RfUE	rainfall use efficiency (for *kharif* and *rabi* seasons, the values are 0.7 and 0.9, respectively),
$Water_{soil}$	available water in soil.

This equation, in a way, represents seasonal N balances, which account for the sources and sinks of N.

When applying this approach, results from land use optimization for different production technologies showed that loss of N through leaching in rice-wheat systems varies with land unit and technology. At technology level 1, leaching loss varies from 0 to 15 kg N ha^{-1} (Figure 2A). The highest leaching (up to 25 kg N ha^{-1}) was calculated at technology level 3. Because of higher N-use efficiencies assumed for higher technology levels, it was slightly reduced at technologies 4 and 5 (Figure 2B). Increased water use efficiency reduced percolation, resulting in relatively small leaching losses. A similar influence of the technologies was found for other land use systems (not shown).

Biocide residues

Chemical control of weeds, pests and diseases is an integral part of modern agriculture. Although in 1950 only 2,000 tons of biocides were applied, India now consumes 115,000 tons of biocides per annum. The cropped area receiving pesticides in India was only 2.4 million ha during the 1950s. This has now risen to 137 million ha. The major use of pesticides in India is in the form of herbicides and not insecticides as in most other parts of the world (Table 2).

Although per unit area of agricultural land, consumption of biocides in India is one of the lowest in the world, there are reports of pollution. This is restricted to some pockets, areas that are small in size but that receive very high application rates. Besides contamination of food and feed, translocation of biocides into the various components of the environment and their harmful effects on the non-target organisms inhabiting the soil and aquatic systems have been brought into sharp focus. In the past, soil has been considered to be a buffer sink of unlimited capacity for biocides. However, it has now been realized that the soil can be loaded with chemicals only up to a limit beyond which the undesirable effects will occur. It is therefore of prime importance to develop methods for estimating the adverse effects of biocides on the environment and means to reduce these effects.

In Haryana, the use of plant protection chemicals has been steadily increasing over the last two decades. The spectrum of chemicals used has been shifting from total dependence on organo-chlorine chemicals to the introduction of alternatives that are

Table 2. Percentage consumption of different pesticides in India in 1992.

Biocides	Consumption (%)	
	World	India
Herbicides	47.5	15.8
Insecticides	29.5	80.5
Fungicides	17.5	1.5
Others	5.5	2.3

Source: Agnihotri (1999).

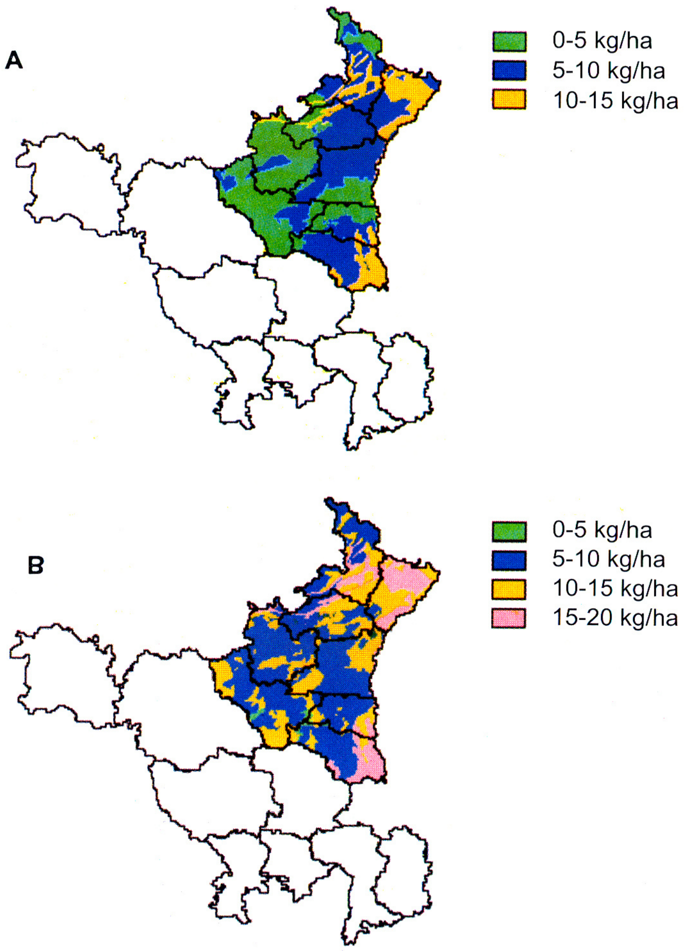

Figure 2. NO_3-leaching from different land units in Haryana at technology level 1 (A) and at level 5 (B). Leaching is shown only for those districts where rice-wheat currently occupies at least 10% of the total cultivated area.

less harmful and leave only degradable residues (Chapter 5). Currently, nearly 5,100 metric tons of technical-grade biocides are used annually in Haryana. Cotton, followed by potato, consumes the highest amounts of pesticide. The herbicide isoproturon is mainly applied for eradication of *Phalaris minor* in wheat and butachlor and anilophos are used for controlling weeds in rice. According to information from state agricultural officials, biocide retailers and farmers, the herbicide Sencor, a chemical, less toxic and less persistent, is fast replacing isoproturon for control of *Phalaris minor*.

We have described the potential environmental impact of biocide use by applying a biocide residue index (BRI) for the various land use types in Haryana. This is calculated based on per hectare consumption of each chemical, its toxicity index and half-life in soil as given in the *Agrochemicals Handbook* (1991):

$$\text{BRI} = (\text{Chemical use in g ha}^{-1} \times \text{Toxicity index} \times \text{Persistence index})/100 \qquad (4)$$

The total BRI for a given land use type is calculated by adding the BRI of the individual chemicals applied to the land use type.

The Food and Agriculture Organization (FAO) of the United Nations distinguishes four toxicity classes for biocides (I, II, III and IV) with toxicity indices of 10, 5, 2 and 1, respectively, based on their LD_{50} (lethal dose 50, the dose at which 50% of the target pests are killed) (Table 3).

Over the years, most of the persistent organo-chlorine insecticides have been replaced by less persistent organo-phosphorus insecticides such as monocrotofos, phosphamidon and malathion, which degrade relatively fast in the soil. Chemicals such as anilofos and butachlor, which are relatively more persistent, have a very low toxicity. Chlorpyrifos is the only chemical that has moderate toxicity combined with a relatively high persistence. Its continued use has contributed to environmental problems that arise from the increase in pesticide use.

A chemical with a toxicity index of 1.0 and a persistence index of 1.0, if applied at

Table 3. Toxicity and persistence indices of major pesticides applied in Haryana.

Pesticide	EPA/WHO* toxicity class	Toxicity index (1–10)	Half-life in soil (months)	Persistence index (1–10)
Chlorpyrifos	II	5	2–4	4
DDVP	I	10	< 0.5	1
Endosulfan	II	5	< 0.5	1
Malathion	III	2	< 0.5	1
Monocrotofos	I	10	< 0.5	1
Methyl parathion	I	10	< 0.5	1
Phosphamidon	I	10	< 0.5	1
Anilofos	III	2	1–1.5	1.5
Butachlor	IV	1	1.5–2.5	2.5
Isoproturon	III	2	1	1
Dithane M-145	IV	1	< 0.5	1

* Environmental Protection Agency – World Health Organization.

the rate of 10 kg ha^{-1} y^{-1} will almost disappear from the soil within one year. The biocide residue index for such an application would be 100, which is considered safe. However, a similar application rate for a moderately toxic chemical with a toxicity index of 2 would yield a BRI value of 200. These two BRI values can be designated as thresholds that delimit desirable (for BRI < 100) and permissible (for BRI < 200) in terms of environmental safety. Biocide residue indices for different crops and land use types (Tables 4 and 5) do not suggest any alarming situation for the environmental impact of biocide use in rice- and wheat-based systems. However, for cotton- and potato-based land use systems, biocide residue indices attain dramatically high values mainly because of the use of toxic and persistent insecticides on cotton and potato even at technology level 1 (Table 4). For this reason, maize-potato-wheat and cotton-wheat systems had the highest BRI at all technology levels (Table 5).

Since the spatial distribution of pesticide use in different land units cannot be estimated, we have assumed that, irrespective of the soiVclimate in Haryana, the BRI for a given level of technology depends only on land use type.

Table 4. Biocide residue index for different crops at different technology levels.

Technology	Biocide residue index							
levels	Rice	Wheat	S/cane	Gram	Maize	Cotton	Mustard	Potato
1	22	21	26	32	21	317	28	286
2	36	33	42	52	34	443	39	400
3	42	40	49	62	41	507	45	457
4	49	46	57	71	47	570	50	515
5	67	67	78	97	64	634	56	572

Table 5. Biocide residue index for different land use types at different technology levels.

Land use type	Technology level				
	1	2	3	4	5
Rice-wheat	43	69	82	95	134
Basmati rice-wheat	43	69	82	95	134
Rice-rice-wheat	65	105	124	144	201
Irrigated pearl millet-wheat	21	33	40	46	67
Cotton-wheat	338	476	547	616	701
Sugarcane-wheat	47	75	89	103	145
Maize-chickpea	53	86	103	118	161
Maize-mustard	49	73	86	97	120
Rice-mustard	50	75	87	99	123
Maize-potato-wheat	328	467	535	608	703
Fallow-wheat	21	33	40	46	67
Fallow-chickpea	32	52	62	71	97
Fallow-mustard	28	39	45	50	56
Rainfed pearl millet-wheat	21	33	40	46	67
Pearl millet-fallow	0	0	0	0	0

Waterlogging

The increased use of irrigation has resulted in waterlogging and salinity at a few places. The rise in the water table in some areas has made irrigated lands unfit for cultivation of any upland crop during the rainy season. For example, parts of Rohtak District in Haryana, where decades ago the water table was more than 20 m deep, experienced a rise in the water table of 0.6 m per year, reaching an average depth of 3.0 m in recent years. On the Haryana Agricultural University farm, in 1967, the water table was at 15.6 m below the surface. Today, it has gone up to 2.0 m below the surface. Singh *et al.* (1992) observed that, once canal irrigation is introduced, a rise in the water table is inevitable.

Groundwater depletion

The soils of Haryana are generally light- to medium-textured soils and thus not very suitable for growing rice. Repeated puddling of the soils is done to make them more suitable for rice cultivation. However, since rainfall is not sufficient to meet the water requirements of rice-based cropping systems, frequent irrigations are needed. A majority of the farmers have access to pumps and electricity subsidies and therefore draw out water from the groundwater acquifers. This has resulted in a decline in water tables in many regions, particularly in Karnal and Kurukshetra districts where rice-wheat systems predominate (Table 6). Some districts, such as MohinderGarh, were exceptions where the decline in the water table because of rice-wheat cropping intensity was relatively very low. The reason for this exception was that the water tables were already deep in these areas, which already showed signs of water table depletions. Now, some farmers have started growing rice-rice-wheat, which requires even more irrigation. There is a strong need for the adoption of proper water management techniques to prevent further groundwater depletion.

Soil salinity

Soil salinity problems in irrigation command areas develop whenever soil and hydrological conditions favour the accumulation of soluble salts in the rooting zone. The rise in the water table in semiarid and arid areas mobilizes the salts present in the soil profile and groundwater. Once the groundwater table rises to between 2 and 3 m below the soil surface, it contributes substantially to evaporation from the soil and water uptake by plants and results in a gradual concentration of salts in the rooting zone. In the initial years, crop yield may be reduced because of salinity, but, as the severity of the problem increases with time, the lands may have to be abandoned of cultivation.

Out of several environmental problems discussed, we have taken into account leaching of NO_3-N and biocide use in the current study because of growing concerns about these two aspects of environmental pollution. Other aspects such as salinity and declining water table depth in Haryana's agriculture were omitted because of the lack of appropriate data.

The study showed that in general leaching of NO_3-N and biocide residues are not serious problems at the current technology and production levels in most land units. Cotton- and potato-growing areas have problems of biocide residues; therefore,

Table 6. Rise/fall in water table as related to rice-wheat area in various districts of Haryana (Anonymous, 1994).

Districts	Rise/fall in water table (from data of 1974 to 1993) (m y^{-1})	Water table depth during June 1993 (m)	Rice-wheat area as % of gross cropped area
Ambala	–0.17	10.9	63.1
Bhiwani	0.21	18.7	12.7
Faridabad	–0.12	7.6	56.5
Gurgaon	–0.28	10.8	39.0
Hisar	0.25	10.2	34.5
Jind	0.12	8.8	50.5
Kaithal	–0.15	9.8	73.9
Karnal	–0.24	10.2	84.6
Kurukshetra	–0.51	18.2	82.3
MohinderGarh	–0.55	31.0	13.6
Panipat	–0.27	10.4	80.7
Rewari	–0.20	16.8	22.5
Rohtak	0.02	6.1	38.3
Sirsa	0.30	6.0	37.1
Sonipat	–0.13	6.3	63.7
YamunaNagar	–0.14	9.5	55.6

steps should be taken to develop and use safer biocides and integrated pest management. Leaching of NO_3-N is not a serious problem except in some sandy soils. At higher technology levels with high amounts of N application, care has to be taken to improve N use efficiency and minimize N losses.

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7. Linking socioeconomics to the biophysical evaluation: The MGLP model

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The need for integrated evaluation

In previous chapters, we have described the procedures for a biophysical evaluation of natural resources for land use analysis. However, in agro-ecosystems that are equal to or bigger than a farm, socioeconomic processes become equally important (Conway, 1987; Stomph *et al.,* 1994; Stoorvogel *et al.,* 1995). It is therefore also important to capture the dynamics of change in socioeconomic components of the system that determines the realizable production capabilities of the region. Regional land use analysis and planning for food security should be oriented toward maximization of the welfare function of society from the non-renewable resource land. It should recognize land as a resource that provides space, is indestructible and can be viewed as a source of flow of production/consumption services whose composition depends on the use to which the space is allotted. This spatial pattern is variable over time, depending on human activity and, therefore, intertemporal allocations of these services have their consequences. Land use planning is thus an interdisciplinary task that needs both biophysical and land economics evaluation.

A regional land use planning model framework should contain, implicitly or explicitly, the following five elements (Hazel and Norton, 1986):

- Definition of the resource endowments held by each group of producers.
- Description of production functions and technologies available to producers in each region.
- Description of producers' economic behaviour.
- Specification of the market environment in which the producers operate.
- Specification of the policy environment of the sector.

The approach of multiple goal linear programming (MGLP) used for the current study provides such a framework for considering biophysical and socioeconomic resources, and constraints. An optimization framework, consisting of linear programming or other techniques, represents a normative approach that is often used to search for the best solution with limited resources. In this approach, an objective function is maximized or minimized by selecting from different possible activities and subject to several regional constraints. Prior knowledge of the decision makers' choices has

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prime importance in formulating objective functions. Their preferences are expressed as objective functions and targets in the model. Decision making for many real-world problems is often the responsibility of a group of individuals, each with its own goals and aspirations, rather than of a single individual. Besides, in any society, preferences of the people are likely to be multidirectional. Therefore, it is necessary to develop a land use planning model for food security in a multi-objective framework.

The MGLP approach has been used in several studies for land use analysis and planning at the farm level (Schans, 1991), village level (Huizing and Bronsveld, 1994), subregional and regional level (Schipper *et al.,* 1995; Veeneklaas *et al.,* 1991) and even at the continental level (WRR, 1992). It requires decision makers to specify maximum allowable levels for the (n–1) objectives to solve the n-dimensional multi-objective problem. This method can be used to generate the non-inferior set for all types of objectives. The result of each iteration is presented to decision makers to seek their preferences and then articulated back to the model through modified values of objective functions and targets. The process continues till the decision makers are satisfied with their choices and an optimal solution is obtained. This implies that this approach needs a series of iterations to arrive at the desired output. In the first iteration, all targets are set to a minimum value, resulting in an optimal solution that satisfies the entire minimum requirement simultaneously. This process is repeated sequentially for all objective functions, which will result in the definition of technically feasible objectives, targets and constraints. Moreover, the maximum attainable value for each objective function is also achieved. In the next step, the target values are further tightened, reflecting the aspirations of the decision makers. This will reduce the technically feasible solution space. The process continues till the decision makers reach a Pareto optimal solution, that is no further feasible solution can be achieved with the same or better performance for all criteria under consideration.

A multiple goal linear programming (MGLP) model for Haryana

The MGLP model for Haryana covers 16 districts (as per the 1991 census database), which can be viewed as a combination of various land units. A land unit is delineated by overlaying agro-ecological units and district boundaries (Chapter 5). Model outputs are discussed in Chapter 8. The model contains

- Five resources: land, water, labour, capital and fertilizer. More discussion on these resources is given in Chapter 4. Land and water resources have been defined in two dimensions – administrative and agro-ecological – because of the distinct heterogeneity in different properties of land units in the same district. Since the district is the basic planning and production unit, labour, capital and fertilizer resources have been defined at the district level.
- Various production functions have been specified through input-output relations for 15 land use types at 5 technology levels. Land use types represent different farming regimes (irrigated versus non-irrigated). These are summarized in Table 1. Each land use type is characterized by a specific technology level through its uniqueness in input-output combinations. Input-output combinations are determined by several factors related to land use and technology level.

- Milk is also an important product related to land use in Haryana. Therefore, besides cropping activities, livestock activities with three animal types, cow, buffalo and hybrid cow, are also considered in the model.
- These land use types result in 11 products, including milk from each animal type.
- The behaviour of the producers is described by assuming that they aim at maximum returns from the land unit under existing resource constraints. Five farm types varying in the size of landholding are considered. This is used as a proxy variable to represent the technology adoption capability of producers.
- Since the livelihood of most of the population of Haryana basically depends on agriculture, it was assumed in all analyses that at least 98% of the land has to be used for agriculture.
- The market for agricultural products is assumed to be unaffected by producers' decisions at the district level. Irrespective of the quantities, all products can be sold or purchased at a fixed price for a district. This may not always be true but this assumption allows us to keep the model simple and explore all possible opportunities for the future irrespective of trade scenarios so that finally a limited policy environment can be explored in different scenarios.
- Table 2 shows the number of combinations of land units, land use types and technology levels. Table 3 shows the indices and abbreviations used in the equations of the MGLP model.

Table 1. Districts, land use types, technologies, products and farm types in Haryana used for land use analysis.

Districts	Land use types	Technologies	Products	Farm types
Ambala	Rice-rice-wheat	Current	Rice	Small
Bhiwani	Rice-wheat	Potential	Basmati rice	Medium
Faridabad	Basmati rice-wheat	Current +	Wheat	Medium-large
Gurgaon	Rice-mustard	25% yield gap	Sugar	Large
Hissar	Cotton-wheat	Current +	Mustard	Very large
Jind	Maize-chickpea	50% yield gap	Pearl millet	
Kaithal	Maize-mustard	Current +	Cotton	
Karnal	Maize-potato-wheat	75% yield gap	Maize	
Kurukshetra	Sugarcane-wheat		Gram	
MohinderGarh	Irrigated pearl millet-wheat		Potato	
Panipat	Rainfed pearl millet-wheat		Milk	
Rewari	Fallow-wheat			
Rohtak	Fallow-chickpea			
Sirsa	Fallow-mustard			
Sonipat	Pearl millet-fallow			
YamunaNagar				

Table 2. Number of combinations related to land use in Haryana. In irrigated land units, all 15 land use types (*luts*) were considered, whereas, in rainfed land units, only 5 *luts* were considered (see Chapter 5).

Item	Abbreviation	Size
Number of agro-ecological units	NAE	58
Number of land units (District agro-ecological combinations)	NDU	257
Number of land unit−land use type combinations	NDULut	2,855

Table 3. Indices and abbreviations used for defining land use types and input/output relationships in the MGLP model.

Index	Description	Classes
u	Agro-ecological units	58 ago-ecological units as defined in Chapter 4
d	District	16 districts as defined in Chapter 4
du	Land unit	257 land units (combinations of district, agro-ecological units and irrigated/unirrigated areas)*
lut	Land use type	15 land use types defined in Chapter 5
P	Product	11 products, including milk from each animal species
t	Technology level	Five technology levels defined in Chapter 5
m	Month	12 months
a	Animal	Three types of animals: cows, buffaloes, hybrid cows
at	Combinations of an animal and livestock technology level	Two technology levels (current and improved) for each animal
F	Type of fertilizer	Three types of fertilizer: N, P, K
S	Season code	Three seasons: summer, *kharif* (monsoon), *rabi* (winter)

* Land unit (du) is used as a basic unit in the model, but a variable can vary either by district (d) or by agro-ecological unit (u) of this combination (du).

Land use activities

Two types of activities are included in the MGLP model for Haryana: cropping activities and livestock activities. For each activity, only those items of input-output that are needed for objective functions and constraints considered in the model are quantified.

Cropping activities are expressed as land use types (lut) applied at a certain technology level (t). We defined 15 land use types for Haryana (Table 1). Inputs and outputs of these cropping activities are differentiated by land unit (u) and technology (t) and they also may vary by month or season. Inputs required for cropping activities are fertilizers, labour force, water and capital. Outputs from cropping activities are main products and by-products of the crop and residues used as feed for animals.

Animal types specify livestock activities. Inputs required for livestock are feed and capital. Livestock activities are linked to cropping activities through the availability of crop residues for feed in each land use type. The number of animals per hectare is calculated as

$$\text{NoAnimal}_{u,lut,t,a,at} = \Sigma_{p} (\text{Residue}_{u,lut,t,p} \times \text{Lut-Product}_{lut,p} \times \text{FractionMilk-Anim}_{a,at}) / \text{DryFeed}_{a,at} \qquad (1)$$

where $\text{NoAnimal}_{u,lut,t,a,at}$ is the number of animals per hectare that can be fed from residues of a cropping activity and $\text{Residue}_{u,lut,t,p}$ is the amount of residues available to feed the animals. Residues from pearl millet and wheat are considered as only animal feed. The residues from other crops are not used as feed in the state. $\text{Lut-Product}_{lut,p}$ is the relationship between 14 products (p) and 15 land use types (lut) given in a matrix. Since some land use types may generate more than one product, the value of 1 or 0 is used in the matrix to express whether a product (p) is produced by a specific land use type (lut) or not. $\text{FractionMilk-Anima}_{a,at}$ is the share of milking animals in the total livestock population and $\text{DryFeed}_{a,at}$ is the amount of residues required annually for each animal (a) under a specific livestock technology (at).

Livestock activities also provide the dung that can replace a part of the chemical fertilizers used in cropping activities. The requirement of fertilizer N, a major nutrient required for crop production (per ha), is calculated as the total N fertilizer requirement by crops minus the N supply from dung:

$$\text{Fertilizer}_{u,lut,t,f} = \Sigma_{p} (\text{Fertilizer-Ha}_{u,lut,t,p,f,} \times \text{Lut-Product}_{lut,p}) - (\text{No Animal}_{u,lut,t,a,at} \times \text{NDun}_{a,at,f}) \qquad (2)$$

where $\text{Fertilizer-Ha}_{u,lut,t,p,f}$ is the fertilizer requirement for a specific product, $\text{NoAnimal}_{u,lut,t,a,at}$ is the total number of animals per hectare and $\text{NDung}_{a,at,f}$ is the inorganic fertilizer equivalence supplied from the dung of one animal and is calculated from the wet dung by the following expression:

$$\text{NDung} = \text{Wet dung} \times 0.15 \times 0.83 \times 0.005 \times 120 \qquad (3)$$

where 0.15 is the factor for converting wet dung to dry dung, 0.83 is a factor representing the share of cow dung used for manure (the remaining is used as fuel in the state), 0.005 represents 0.5% N content in dry dung and 120 days is the average number of days in a cropping season.

Because both cropping activities and livestock activities generate outputs for objective functions, a land use activity is defined as a combination of a cropping activity (lut, t) and a livestock activity (a, at). The variable $\text{LU-Aread}_{u,lut,t,a,at}$ used in the MGLP model is the area allocated to each land use activity in each land unit (du).

$\text{LU-Promising}_{du,lut,t}$ is applied in the MGLP model as a promising land use indicator, which enables the model to handle different policy scenario analyses in a simple way and improves efficiency by reducing the size of the matrix. The value of this indicator is switched between 1 and 0 to identify whether a land use type (lut) can be applied in a land unit (du) or not.

Objective functions

Objective functions for the model were formulated considering social, economic and environmental aspects of development for Haryana.

Social objective functions: Food grain production and employment

Haryana is one of the major food-producing states in India and it contributes significantly to the public food distribution system of the federal government. Therefore, food grain production (Food) is one of the social objective functions to be maximized:

$$\text{Food} = S_{du} S_{lut} S_t\, S_a S_{at}\ (\text{Productivity}_{u\ in\ du,lut,t} \times \text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at}) \tag{4}$$

where $\text{Productivity}_{u,lut,t}$ is the yield of grains (rice, basmati rice, summer rice and wheat) in each land unit by various land use types at different technology levels.

Creating more gainful employment in the agricultural sector is essential for sustaining the development of the state. To realize this objective, we selected ‘Employment’ as another social objective function to be maximized:

$$\text{Employment} = S_{du} S_{lut} S_{ca} S_{at}\ (\text{Labor}_{u\ in\ du,lut,t,a,aat} \times \text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,at}) \tag{5}$$

where $\text{Labor}_{u,lut,t,a,at}$ is the total labour required in a year for land use activities calculated from the labour requirement in each month.

$$\text{Labor}_{u,lut,t,a,at} = \Sigma_m \Sigma_p\ \text{Monthly Labor}_{u,lut,t,p,m} \times \text{Lut-product}_{lut,p} \tag{6}$$

However, the labour input for livestock activity was not considered because in Haryana this homestead activity is generally taken care of by the family members in their spare time.

Economic objective function: Income

Income from agriculture is a major factor that determines crop and technology selection. This was selected as an objective function to be maximized to express the goal of economic development of the farmers and the region:

$$\text{Income} = S_{du} S_{lut} S_t S_a S_{at} \times \text{LU-Promising}_{lut,p} \times \text{LU-Area}_{du,lut,t.a,at}) \tag{7}$$

where Income-Ha is the net revenue from both cropping and livestock activities and is equal to the total revenue from the sale of all products, including milk, after subtracting the production cost of all inputs.

Income-Ha was calculated from operational costs and gross returns per hectare. Operational cost per ha does not include the fixed cost of the land and was derived by the following expression:

$$\text{Operational Cost}_{du,lut,t,a,at} = S_p\ [(\text{VariableCost}_{u\ in\ du,lut,t,a,at,p} + \text{PumpCost}_{du,lut,t,a,at,p}) \times \text{Lut-Product}_{lut,p}] + (\text{NoAnimal}_{u\ in\ du,lut,t,a,at} + \text{MilkCost}_{a,at}) \tag{8}$$

In the model, the cost of pumping water (PumpCost) is separated from other input costs because it varies over seasons and across crops depending on the amount of water pumped:

$$\text{PumpCost}_{du,lut,t,a,at,p} = S_m\ \text{Month-Pump}_{u\ in\ du,lut,t,a,at,p,m} \times \text{Month-Pump-Priced}_{du,m} \tag{9}$$

$\text{Month-Pump}_{u,lut,t,a,at,p,m}$ is the amount of water pumped for irrigation for a specific crop and month and Month-Pump-Price$_{du,m}$ is the unit cost of pumping water in a month. VariableCost$_{u,lut,t,a,at,p}$ is the cost for crops excluding the costs of water pumping and rearing livestock, NoAnimal$_{u,lut,t,a,at}$ is the number of animals per hectare and MilkCost$_{a,at}$ is the annual cost of producing milk from one animal. This leads to

$$\begin{aligned}\text{GrossReturn}_{du,lut,t,a,at} = {} & (\text{NoAnimal}_{u \text{ in } du,lut,t,a,at} \times \text{MilkIncome}_{a,at}) + \\ & \Sigma_p ((\text{Productivity}_{u \text{ in } du,lut,t,p} \times \text{FGPrice}_{u \text{ in } du,lut,t,p} \times \\ & \text{PriceAdjust}_{d \text{ in } du,p}) \times \text{Lut-Product}_{lut,p}) + \\ & (\text{RevResidue}_{u \text{ in } du,lut,t,a,at}) \times \text{Lut-Product}_{lut,p}) \qquad (10)\end{aligned}$$

where Productivity$_{u,lut,t,p}$ is the yield level of a product, FGPrice$_{u,lut,t,p}$ is the farm-gate price of a product and PriceAdjust$_{d,p}$ is a factor used to adjust the price across districts for different products. This price difference occurs mainly because of changes in market accessibility. RevResidue$_{u,lut,t,a,at}$ is the income from crop residues except for wheat and pearl millet (which have been used for livestock).

Net income is calculated as the difference between gross returns and costs:

$$\text{Income-Ha}_{du,lut,t,a,at} = \text{GrossReturn}_{du,lut,t,a,at} - \text{Operational Cost}_{du,lut,t,a,at} \qquad (11)$$

Environmental objective functions: Agricultural area, water use and biocide residue index and N leaching

The pressure on land is increasing because of the increase in population, industrialization and the requirements for various other non-agricultural activities. Moreover, there is concern that, ideally, about one-third of the land should be left for forest for environmental sustainability. Therefore, agricultural area in Haryana is considered as an objective function to be minimized:

$$\text{AgriArea} = \Sigma_{du}\Sigma_{lut}\Sigma_t\Sigma_a\Sigma_{at} (\text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at}) \qquad (12)$$

There are also concerns in Haryana about sustainability as the state moves into the post-Green Revolution era. The environmental goals for agricultural development in Haryana are to minimize two other environmental objective functions – water use and the biocide residue index:

$$\text{WaterUse} = \Sigma_{du}\Sigma_{lut}\Sigma_t\Sigma_a\Sigma_{at} (\text{ET}_{u \text{ in } du,lut,t} \times \text{LU-Promising}_{lut,p} \times \text{LU-Area}_{du,lut,t,a,at}) \qquad (13)$$

where ET$_{u,lut,t}$ is the total water needed in a year for each land use activity calculated from its monthly water requirement. Drinking water required for animals is a relatively low amount compared with the water required for crops and has therefore been ignored.

$$\text{ET}_{du,lut,t} = \Sigma_m \text{MonthlyET}_{du,lut,t,m} \qquad (14)$$

$$\begin{aligned}\text{Biocide Residue Index (BRI)} = {} & \Sigma_{du}\Sigma_{lut}\Sigma_t\Sigma_a\Sigma_{at} (\text{BRI-Ha}_{u \text{ in } du,lut,t} \times \\ & \text{LU-Promising}_{du,lut,p} \times \text{LU-Area}_{du,lut,t,a,at}) \qquad (15)\end{aligned}$$

where BRI-Ha$_{du,lut,t}$ is the biocide residue index per ha of a specified land use type (Chapter 6).

Besides the biocide residue index, N loss from leaching is used as another indicator of environmental quality. The model provides total nitrogen leached out (NLoss) at different levels of nitrogen application:

$$\text{NLoss} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\Sigma_{p}\,(\text{NLeaching}_{u\ in\ du,lut,t,p} \times \text{LU-Promissing}_{du,lut,p,t} \times \text{LU-Area}_{du,lut,t,a,at}) \tag{16}$$

where $\text{NLeaching}_{u,lut,t,p}$ is leaching of nitrate-N below 150 cm of the soil profile.

Constraints and targets of development

Many biophysical characteristics and socioeconomic factors constrain regional land use. These can be broadly grouped into natural resource constraints and external input constraints. In the model, a target of development, such as total production of certain products to satisfy the demand of the local population, has the same formulation as a constraint.

Natural resource constraints: Land and water resources

As mentioned earlier, the land resource has been defined with two dimensions – agro-ecological unit (u) and district (d) – to enable the model to capture biophysical homogeneity at the land unit level and homogeneity in socioeconomic variables at the district level. The first constraint in land resource is that the total area of all land use types in each land unit (DUArea_{du}) should not be greater than the available land resource (AvLand_{du}):

$$\text{DUArea}_{du} = \Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(\text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at}) <= \text{AvLand}_{du} \tag{17}$$

where AvLand_{du} is the available land in all land units (du).

In Haryana, 20.4% of the land is made up of small holdings (< 2 ha) and 35.5% of the holdings are from 2 to 5 ha (Table 4). Only 6.3% of the holdings are larger than 20 ha. Resource availability can greatly vary depending upon the size of the landholding and other production resources of farmers. Since household modelling is not directly considered in our model, we have restricted, as a surrogate, the land area that can be used for different technologies depending upon the size of the landholdings. Thus the entire area of Haryana, irrespective of size of landholding, can use 1st (current) and 2nd levels of technologies. The adoption of higher technologies requires more capital

Table 4. Categories of farmers in Haryana by area and size of landholding.

Category	Size of land-holding (ha)	Number of landholdings (%)	Area (ha)	Area (%)
Small	<2	60.5	757,731	20.4
Medium	2–5	27.5	1,318,110	35.5
Medium-large	5–10	9.0	925,968	25.0
Large	10–20	2.5	476,677	12.8
Very large	>20	0.5	232,729	6.3

Table 5. Capability of farmers of Haryana to adopt different technologies.

Technology level	Farmers	Total area (%)
1	Small, medium, medium-large, large and very large	100
2	Small, medium, medium-large, large and very large	100
3	Medium, medium-large, large and very large	79.6
4	Large and very large	19.1
5	Very large	6.3

and a larger knowledge base. It was assumed that small farmers cannot adopt the 3rd, 4th and 5th level of technologies, whereas large and very large farmers can adopt the 4th level of technology. Only very large farmers can adopt the 5th level of technology (Table 5).

The share in total area in Table 5 is used to estimate the maximum land resource available to each technology level ($AvTechLand_{du,t}$):

$$AvTechLand_{du,t} = AvLand_{du} \times CF_{d,t} \qquad (18)$$

where $CF_{d,t}$ is the share of a technology level in the total area.

Thus, another land constraint is that the total area of all land use types by each technology level ($DUTAread_{du,t}$) should not be greater than the land resources available for that level ($AvTechLand_{du,t}$):

$$DUTArea_{du,t} = \Sigma_{lut}\Sigma_{a}\Sigma_{at}(LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) <= AvTechLand_{du,t} \qquad (19)$$

Water resources

Both groundwater and surface water are considered when estimating total water available for irrigation. The water constraint was defined spatially and temporally at the land unit level (Chapter 4). The model assumes that different land use types within it can share the water available within a land unit. A total of four constraints relating to seasonal and annual availability of water are considered in the model:

a. Total water use in a year in each land unit ($Water_{du}$) should not be greater than the available water resources in that land unit ($AvWater_{du}$):

$$Water_{du} = \Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}(ET_{du,lut,t} \times LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) <= AvWater_{du} \qquad (20)$$

where $ET_{du,lut,t}$ is the total water requirement of a land use type in a year aggregated from water requirements in each month.

b. Total water use in each season in each land unit ($SeasonWater_{du,s}$) should not be greater than the available water resources ($AvWater_{du,s}$) in that land unit:

$$SeasonWater_{du,s} = \Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}(Season\text{-}ET_{du,lut,t,s} \times LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) <= AvWater_{du,s} \qquad (21)$$

where $SeasonET_{du,lut,t,s}$ is the total water requirement of a land use type in a season aggregated from water requirements in each month.

c. Since the assumption of water sharing may not be suitable in some land units with a very large area (the largest land unit was 98,067 ha), a lower level of spatial extent was defined by the area available by technology level. The water resource was allocated to different technology levels with the same ratio as used in the land area constraint. Total water use in a year for area available to each technology level ($\text{TechWater}_{du,t}$) was restricted to available water ($\text{AvTechWaterd}_{du,t}$):

$$\text{TechWater}_{du,t} = \Sigma_{lut}\Sigma_{a}\Sigma_{at}\,(\text{ET}_{du,lut,t} \times \text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at)} \\ <= \text{AvTechWater}_{du,t} \tag{22}$$

d. Constraint c of water resources was also applied for each season: the total water use in a year for the area available to each technology level ($\text{SeasonWater}_{du,t,s}$) should not be greater than the available water ($\text{AvTechSeasonWater}_{du,t,s}$):

$$\text{TechSeasonWater}_{du,t,s} = \Sigma_{lut}\Sigma_{a}\Sigma_{at}\,(\text{SeasonET}_{du,lut,t,s} \times \text{LU-Promising}_{du,lut,t} \times \\ \text{LU-Area}_{du,lut,t,a,at}) <= \text{AvTechSeasonWater}_{du,t,s} \tag{23}$$

Socioeconomic constraints: Labour, capital and input supply

Similar to water, the constraint in labour availability by month is considered. However, different scenarios of sharing the labour force are analysed: (i) within each district, (ii) within the entire state and (iii) with no constraint in labour because of migration from surrounding states at the peak period.

The following constraints are applied for scenarios (i) and (ii):

(i) Labour use ($\text{Labor}_{dist,m}$) in each district in each month should not be greater than the available labour force ($\text{AvLabor}_{dist,m}$)

$$\text{Labor}_{dist,m} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}(\text{MonthlyLabor}_{u,lut,t,a,at,m} \times \text{LU-Promising}_{du,lut,t} \times \\ \text{LU-Area}_{du,lut,t,a,at} \mid \text{with d in du = dist}) <= \text{AvLabor}_{dist,m} \tag{24}$$

where $\text{MonthlyLabor}_{u,lut,t,a,at,m}$ is the labour requirement in each month.

(ii) Labour use in the entire state in each month (SeasonLabor_{m}) should not be greater than the available labour force in that season (AvSeasonLabor_{m})

$$\text{SeasonLabor}_{m} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(\text{MonthlyLabor}_{u,lut,t,a,at,m} \times \text{LU-Promising}_{du,lut,t} \times \\ \text{LU-Area}_{du,lut,t,a,at} \mid \text{with d in du = dist}) <= \text{AvSeasonLabor}_{m} \tag{25}$$

It was assumed that capital could be shared or borrowed within the district. The constraint in capital was therefore formulated as the total capital requirement (Capital_{dist}) should not be greater than the available capital (AvCapital_{dist}):

$$\text{Capital}_{dist} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(\text{Capital-Ha}_{du,lut,t,a,at} \times \text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at} \\ \mid \text{with d in du = dist}) <= \text{AvCapital}_{dist} \tag{26}$$

where $\text{Capital-Ha}_{du,lut,t,a,at}$ is the total cost for land use activity. The latter was calculated as

$$\text{Capital}_{dist} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(\text{Capital-Ha}_{du,lut,t,a,at} \times \text{LU-Promising}_{du,lut,t} \times \text{LU-Area}_{du,lut,t,a,at} \\ \mid \text{with d in du = dist}) <= \text{AvCapital}_{dist} \tag{27}$$

where $AnimCost_{a,at}$ is the operational cost for raising one animal in a year, including the cost of protein and energy diet supplements.

Fertilizer availability is also considered as a major constraint to agricultural production. Therefore, the total fertilizer requirement ($Fertilizer_{dist,f}$) should not be greater than the available fertilizer ($AvFertilizer_{dist,f}$):

$$Fertilizer_{dist,f} = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(Fertilizer\text{-}Ha_{u\ in\ du,lut,t,f} \times LU\text{-}Promising_{du,lut,t} \times LUArea_{du,lut,t,a,at} <= AvFertilizer_{dist,f} \quad (28)$$

where $Fertilizer\text{-}Ha_{u,lut,t,f}$ is the total fertilizer required for a land use activity.

Targets of development and limits

The production of various commodities such as rice, wheat and sugarcane can be set as the targets of development to satisfy demand. These were set in the model for all products. The target of sugarcane production in the model is illustrated as

$$Sugarcane = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(Sugarcane\text{-}Ha_{u\ in\ du,lut,t} \times LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) >= SugarcaneTarget \quad (29)$$

where $Sugarcane\text{-}Ha_{u,lut,t}$ is sugarcane productivity per hectare and SugarcaneTarget is the target of production calculated from the demand of the population and the market (Chapter 3).

Milk production was also used as a target. To calculate this, a ratio of milking versus total livestock population ($MARatio_{a,at}$) in Haryana (it is currently 0.5) is used. In many scenarios, when an objective function is optimized, upper limits and/or lower limits are determined for other non-optimized object functions as the targets of development. For example, targets of food production and biocide residue index are set up while optimizing income as follows:

$$Food = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(Productivity\text{-}Ha_{u\ in\ du,lut,t} \times LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) >= LowerBound\ (\text{'Food'}) \quad (30)$$

$$BRI = \Sigma_{du}\Sigma_{lut}\Sigma_{t}\Sigma_{a}\Sigma_{at}\,(BRI\text{-}Ha_{u\ in\ du,lut,t} \times LU\text{-}Promising_{du,lut,t} \times LU\text{-}Area_{du,lut,t,a,at}) <= UpperBound\ (\text{'BRI'}) \quad (31)$$

where LowerBound (‘Food’) and UpperBound (‘BRI’) are the lower limit of food production and the upper limit of biocide residue index, respectively.

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8. Exploring the limits of agricultural production, resource requirements and environmental impact

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Introduction

The carrying capacity of a region depends on the amount of food that can be produced to meet the basic diet requirements of its population (Higgins *et al.,* 1982). However, it also needs to be recognized that, at the same time, a region needs to generate enough income from agriculture and other vocations to invest in food production and fulfil other cash needs of society. Since the population in India is already high and continues to increase rapidly, there is a need to examine the limits of food production in different regions. Ideally, to ensure food security for a population largely dependent on agriculture, a region should be able to produce sufficient food and other commodities to meet the energy and cash demands of its population.

The basic potential of the land to produce food largely depends on its biophysical characteristics. The actual production of food and its accessibility for people depend on the biophysical potential of the land and the effective purchasing power of the people, and other socioeconomic factors that determine food demand. Food security of the population is ensured only when sufficient food production and accessibility to food for all can be provided. Thus, issues such as employment, capital, infrastructure and diet, and political stability, also contribute directly or indirectly to the food security of a region. An equally important dimension of food security, particularly now, is the environmental degradation associated with agricultural production practices. Since the objectives of maximizing food production, sustaining environmental quality and maximizing farmers' income are potentially conflicting, information needs to be generated to determine the consequences and trade-offs of different sets of policy views related to the agricultural sector. The goal of this chapter is to quantify the upper limits of production of food and other commodities in the state of Haryana and to identify production systems that are both economically viable and agronomically efficient and have a minimal impact on the environment. The resources required to meet these upper limits and the income and employment generated with such land uses are also quantified.

Six objective functions for Haryana were considered:

a. Maximizing food grain production,

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b. Maximizing farm income,
c. Maximizing employment,
d. Minimizing agricultural area,
e. Minimizing water use, and
f. Minimizing biocide residue index.

Each objective function comprises six cases each of which is characterized by a combination of constraints:

1. Land resource (is always a constraint)
2. Land + water resources
3. Land + technology adoption levels applicable by farm size groups
4. Land + technology adoption + water resources
5. Land + technology adoption + water resources + capital availability
6. Land + technology adoption + water + capital + labour availability.

In all cases, however, the production of crops and milk was not allowed to drop below the current (1996-97) level. This was ensured by using the current level of production as a lower bound in the multiple goal linear programming (MGLP) model as mentioned in Chapter 7. Moreover, since the majority of the population of Haryana depends on agriculture for its basic livelihood, the model was forced to cultivate all agricultural land of the state in all cases except in the scenario in which agricultural land use was minimized. The upper limits of different objective functions were determined by optimizing each one separately and deriving the ‘extreme points’ to identify the feasible solution space under the specified restrictions. Thus, the model first calculates the value of each objective function by imposing land as a constraint plus the lower bounds for production of the different commodities, defined as the production figures for 1996-97 (Table 1, last column). Subsequently, all other constraints were introduced successively in the subsequent rounds of optimizations to evaluate the effect of each constraint on the feasible solution space. In the final run, all constraints and current targets for other crops were imposed concurrently.

Maximizing food grain production

The results of the first case in this scenario showed that the maximum attainable food production (rice + wheat) in Haryana was 39.1 million t when land was the only constraint and the current targets for other products were met (Table 1). Corresponding milk production was 6.8 billion litres. To produce this, however, Haryana would need, besides arable land, 56.4 billion cubic meters of water, 1.5 million t of N fertilizer, 666 million labour days and 114.2 billion rupees of capital for operational costs. These requirements are several times higher than what is currently (1996-97 level) available in the state. This case also indicated that, if such resources were made available, farmers could generate an income of 109.9 billion rupees per annum. The associated land use would result in a loss of 61.4 thousand tons of N through leaching. The environmental impact in terms of biocide residues would still be within the safe limits at the aggregated level (< 100 is safe, Chapter 5).

Rice-rice-wheat, the largest food production system among all land use types (*luts*), occupied 50.4% of the area (73% of the irrigated land) in this scenario. The remaining irrigated area was allocated to rice-mustard, cotton-wheat, maize-chickpea and sugarcane-wheat. In rainfed areas, pearl millet-wheat and fallow-chickpea systems were selected. This satisfied the condition that all land should be used and the demand targets of chickpea and pearl millet were realized (Table 2).

In terms of technology level, as expected in the absence of any constraint in the model, the highest technology level was used at all places (in rainfed areas there was only one technology used in the model) (Table 3).

This case provides information on the maximum food production possibilities in Haryana. However, it is not considered a feasible solution because of the extremely high amount of resources needed to produce these levels. These resources are neither currently available nor do they appear to become available in the next 10 to 20 years.

Table 1. Production of different commodities, income, resource requirements and environmental impact at an aggregated level when maximizing food production in Haryana.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Food**	**Million tons**	**39.1**	**17.4**	**28.0**	**11.4**	**11.4**	**11.1**	**10.5**
Rice	Million tons	27.3	5.1	19.0	2.8	2.7	2.5	2.5
Wheat	Million tons	11.8	12.2	9.0	8.6	8.7	8.6	8.0
Oilseed	Million tons	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Chickpea	Million tons	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Cotton	Million bales*	1.53	1.53	1.53	1.53	1.53	1.53	1.53
Sugar (jaggery)	Million tons	0.90	0.9	0.90	0.90	0.90	0.90	0.90
Milk	Billion litres	6.8	6.3	5.5	5.4	4.5	4.6	4.2
Income	Billion rupees	109.9	73.8	77.8	54.3	56.3	54.9	46.1
Land used	%	100	100	100	100	100	100	100
Irrigation	Billion m^3	56.4	17.8	51.2	16.3	16.2	15.5	18.2
N fertilizer	Million tons	1.51	0.79	1.25	0.64	0.64	0.61	0.65
Employment	Million labour days	666	384	674	364	361	347	387
Capital	Billion rupees	114.2	56.9	92.1	54.1	53.7	52.0	56.4
N loss	Thousand tons	61.4	37.6	62.5	39.6	39.1	37.4	31.6
Biocide index	–	95	94	97	132	129	125	81

[*] Each bale of cotton = 170 kg.

[*] Objective function maximized.

Table 2. Area (% of agricultural land) under different land use types when food grain production was maximized.

Land use type	Constraints					
	Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
Rice-rice-wheat	50.4	1.7	45.2	4.8	3.8	1.6
Rice-wheat	0.0	19.4	0.0	8.1	8.7	9.5
Basmati rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-mustard	8.3	3.5	10.8	2.6	3.1	5.7
Cotton-wheat	6.7	7.1	8.6	20.0	19.6	19.6
Maize-mustard	0.0	4.75	0.0	10.2	9.9	7.7
Maize-chickpea	0.3	0.0	0.3	3.1	3.2	3.3
Maize-potato-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane-wheat	3.0	2.58	3.7	3.9	3.9	4.0
Irrigated pearl millet-wheat	0.0	4.6	0.0	9.8	10.3	10.2
Rainfed pearl millet-wheat	18.0	0.0	18.0	0.0	0.0	0.0
Fallow-wheat	0.0	56.3	0.0	37.5	37.5	38.5
Fallow-chickpea	13.4	0.0	13.4	0.0	0.0	0.0
Fallow-mustard	0.0	0.0	0.0	0.0	0.0	0.0
Pearl millet-fallow	0.0	0.0	0.0	0.0	0.0	0.0

Table 3. Area (% of agricultural land) under different technology levels when food grain production was maximized.

Technology level	Constraints					
	Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
1	0.0	57.2	31.4	42.6	43.1	46.6
2	0.0	0.24	0.0	45.5	45.3	42.6
3	0.0	0.03	51.2	8.1	7.9	7.1
4	0.0	0.05	13.1	2.7	2.7	2.7
5	100.0	42.5	4.3	1.1	1.0	1.0

The availability of irrigation water was imposed as the next constraint, in addition to land, to determine the maximum possible food production in Haryana with only the natural resources as constraints. Food grain production in the second case decreased to 17.4 million t. Rice production, being the largest consumer of water, dropped to 5.1

million t from 19.0 million t. Production of other commodities was maintained at their minimum demand level (Table 1). These results indicate that the spatial and temporal availability of water is now the major limiting factor for increasing food grain production in Haryana. In spite of this drastic reduction in food production, milk production decreased only marginally to 6.3 billion litres (Table 1). To realize these levels of production, all land available for agriculture was used and 17.8 billion cubic metres of water were needed. It is interesting to note that 2% of the water available now was still not used. The available water in the *kharif* season was completely used, whereas that of the *rabi* and summer seasons was not fully used. With food production as the main goal, the model allocated all area to rice in the *kharif* season the only food grain crop in that season, whenever water availability allowed. Since the minimum targeted demand of less water-consuming crops, such as chickpea and mustard in the rabi season, had to be fulfilled as well, a considerable area was allocated to these land use systems and hence some water remained unused.

Fertilizer, labour and capital requirements as well as farm income also decreased drastically (Table 1). Biocide residues, however, were the same as when land was the only constraint. A reduction in nitrogen loss could be observed compared to the first case. This is the result of a drastic shift in cropping pattern from rice-rice-wheat, the cropping system that consumes the highest amount of nitrogen fertilizer, to rice-wheat and fallow-wheat. The demand for rice, which was met earlier by the rice-rice-wheat system, was now met by the rice-wheat system because of the constraint imposed on water (Table 2). Other land use patterns also changed, with 56.3% of the area occupied by fallow-wheat and 7.1% by cotton-wheat (Table 2). Since 98% of the arable land had to be used in adoption of technology, a clear shift toward the current level (57.2%) and highest level (42%) of technology could be observed (Table 3).

In the third case, in addition to land, the constraint of technology adoption was introduced to mimic the limited capacity of small and medium farmers to adopt capital-intensive technologies. Water availability was not included as a constraint in this scenario. Optimal food grain production decreased to 28 million t and corresponding milk production to 5.5 billion litres. Production of all other commodities was at their 1996-97 levels (Table 1). Relative to the land constraint, the requirements of water, fertilizer and capital decreased and total farm income decreased by 30% (Table 1). The land use pattern was not much different from the first case, except that in irrigated areas the rice-rice-wheat area was smaller (Table 2). Because the area restriction to applying higher technologies became effective (see Chapter 7), a major share of the area was allocated to technologies 3 and 4 (51%) and only a small area (4.3%) to level 5 (Table 3).

When land, water and technology adoption were simultaneously introduced as constraints in the fourth case, food grain production decreased further to 11.4 million t. Rice production declined to 2.8 million t, which was very close to the minimum targeted demand. For wheat, the situation was almost the same. Production of other commodities was maintained at their minimum demand level (Table 1). To achieve this level of production, all land available for agriculture was used and 16.3 billion litres of water were used. Almost 10% of the available water remained unused, largely in the *rabi* and summer seasons, possibly because the technology adoption constraint limits the use of higher level technologies that efficiently use water.

Fertilizer, labour and capital requirements also decreased drastically and were lower than their current (1996-97) level of use in the state (Table 1). This is perhaps because now the primary goal of farmers is to maximize income and not necessarily food production, as aimed at in this scenario. Biocide residues, however, increased compared to the first case because of the expansion of the area under cotton-wheat (Table 1). Cotton, the largest consumer of biocides, left more residues. The demand for rice, which was met earlier by the rice-rice-wheat system, was now met by the rice-wheat system, mainly because of the constraint imposed on water (Table 2). Other land use patterns also changed, with 37.5% of the area occupied by fallow-wheat and 10.2% by maize-mustard (Table 2). Since all arable land had to be used, adoption of technology shifted toward the lower levels, with 45.5% of the area under level 2 and 42.6% under the current level (Table 3).

The introduction of capital and labour availability as additional constraints in the fifth case resulted in similar total food grain production (11.4 million t), but milk production dropped to 4.5-4.6 billion litres. The use of all inputs for production as well as outputs remained similar to the third case (Table 1). Land use pattern and percentage of area by technology level were also similar to the third case (Tables 2 and 3).

Our results indicate that, at the aggregate state level, even with all constraints (land, technology, water, capital and labour) imposed in the sixth case, production and income could be somewhat higher than what are currently (1996-97) achieved.

Maximizing farm income

If availability of land were the only constraint as in the first case, maximum farm income from agricultural activities in Haryana would reach 236.7 billion rupees, more than 5 times the current (1996-97) level. This would also ensure that production of all commodities, including milk, were higher than in 1996-97 (Table 4). As expected, to generate that level of income, resource use in terms of capital, water, fertilizer and labour would also be much higher. This scenario at the same time is associated with tremendous quantities of biocide residues, the BRI being 739 (< 200 is acceptable, Chapter 5). At the district and land unit level, residue levels could be even much higher because 50% of the land is allocated to the maize-potato-wheat system. Although this results in the highest income, it is at the same time capital- and pesticide-intensive. Maize production in this system reached 12 million t. Other land use systems for the irrigated areas were rice-rice-wheat, rice-mustard, cotton-wheat, maize-chickpea and sugarcane-wheat (Table 5). In rainfed areas, fallow-chickpea and pearl millet-wheat were the only two systems. Since in this run the technology adoption constraint is not yet effective, all land is used at the highest technology level (Table 6).

Inclusion of the technology adoption constraint in the third case reduced maximum farm income to 145.9 billion rupees, with corresponding food and milk production of 11.4 million t and 5.0 billion litres, respectively (Table 4). All input requirements and ancillary outputs also decreased, except that leaching loss of N was slightly higher.

Land allocated to different land use types was more or less similar to that of the first case (Table 5). There was a small reduction in the area under maize-potato-wheat, which was largely taken up by the cotton-wheat and rice-mustard systems. There was, however, a major shift in the adoption of technology in this scenario. The area under the highest technology was drastically reduced in favour of technologies 3 and 4 (Table 6).

Similar to the scenario of maximizing food grain production, when irrigation water availability was introduced as a constraint in the second case in addition to land, farm income decreased to 102.6 billion rupees and food grain production to 13.7 million t. This again showed that water is the major limiting factor for increasing income in Haryana. Nevertheless, almost 2% of the available water remained unused because of its suboptimal spatial and temporal distribution for the cropping systems considered in the model. Fertilizer, labour and capital requirements also declined drastically as did leaching of N and BRI (Table 4). Compared to the first two cases, where it was at a risky level, BRI was low. This reduction in BRI was due to a drastic reduction in the

Table 4. Production of different commodities, income, resource requirements and environmental impact at the aggregate level when maximizing farm income in Haryana.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Food	Million tons	13.5	13.7	11.4	10.7	10.6	10.6	10.5
Rice	Million tons	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Wheat	Million tons	11.0	11.2	8.9	8.2	8.1	8.1	8.0
Oilseed	Million tons	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Chickpea	Million tons	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Cotton	Million bales*	1.53	1.53	1.53	1.53	1.53	1.53	1.53
Sugar (jaggery)	Million tons	0.90	0.9	0.90	0.90	0.90	0.90	0.90
Milk	Billion liters	6.1	5.4	5.0	4.7	4.6	4.6	4.2
Income**	Billion rupees	236.7	102.6	145.9	58.7	57.6	56.3	46.1
Land used	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Irrigation	Billion m^3	41.7	17.8	30.8	15.2	15.0	14.8	18.2
N fertilizer	Million tons	2.17	0.90	1.57	0.64	0.62	0.60	0.65
Employment	Million labour days	663	316	661	370	364	354	387
Capital	Billion rupees	162.0	70.4	116.9	55.9	54.8	53.3	56.4
N loss	Thousand tons	40.9	35.6	43.3	37.2	36.7	36.8	31.6
Biocide index	–	739	303	459	133	127	121	81

* Each bale of cotton = 170 kg.

** Objective function maximized.

Table 5. Area (% of agricultural land) under different land use types when farm income was maximized.

Land use type	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech + Water	Land +Tech + Water + Capital	Land +Tech + Water + Capital + Labour
Rice-rice-wheat	0.8	1.19	1.2	4.4	4.4	4.0
Rice-wheat	0.0	4.2	0.0	7.9	7.4	6.9
Basmati rice-wheat	0.0	4.1	0.0	0.0	0.0	0.0
Rice-mustard	8.3	1.3	11.7	3.1	3.5	4.7
Cotton-wheat	6.8	7.0	9.2	18.2	18.1	18.5
Maize-mustard	0.0	7.1	0.0	10.5	10.2	9.4
Maize-chickpea	0.3	0.0	0.4	3.6	3.7	3.4
Maize-potato-wheat	49.7	9.3	42.6	2.7	2.0	1.3
Sugarcane-wheat	2.8	2.5	3.6	4.0	4.0	3.9
Irrigated pearl millet-wheat	0.0	2.5	0.0	6.6	6.4	7.9
Rainfed pearl millet-wheat	18.0	3.1	18.0	4.4	4.6	1.6
Fallow-wheat	0.0	57.6	0.0	34.6	35.7	36.7
Fallow-chickpea	13.4	–	13.4	0.0	0.0	1.7
Fallow-mustard	0.0	–	0.0	0.0	0.0	0.0
Pearl millet-fallow	0.0	–	0.0	0.0	0.0	0.0

Table 6. Area (% of agricultural land) under different technology levels when farm income was maximized.

Technology level	Constraints					
	Land	Land +Water	Land +Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
1	0.0	60.3	31.4	44.6	45.9	48.8
2	0.0	0.0	0.0	44.9	43.2	40.9
3	0.0	0.0	51.2	7.4	7.7	7.2
4	0.0	0.0	13.1	2.3	2.3	2.2
5	100.0	39.7	4.3	0.9	0.9	0.9

area under potato-maize-wheat. The expansion of maize-mustard, rice-wheat, basmati rice-wheat and irrigated pearl millet-wheat compensated for this in the irrigated areas (Table 5). In the rainfed areas, the water limitation forced the model to recommend large-scale cultivation of the fallow-wheat system, the most remunerative rainfed system in this study. Two extreme technologies were selected: 60% of the area under the first level of technology and 40% under the fifth level (Table 6).

The addition of the technology adoption constraint to the constraint set as in the fourth case reduced food grain production further to 10.7 million t, very close to the current level of production. All other crop production levels remained at the 1996-97 level. Income declined to 58.7 billion rupees, along with a reduction in all other inputs used in production. Employment, however, increased to 370 million labour days (Table 4). The area under rice-mustard and maize-potato-wheat became almost negligible in this scenario (Table 5). The expansion of cotton-wheat, maize-mustard, rice-rice-wheat, rice-wheat and irrigated pearl millet-wheat could be observed in irrigated areas. In the rainfed areas, fallow-wheat was still the most favoured cropping system, followed by rainfed pearl millet-wheat. A shift toward the adoption of lower technology levels occurred consistent with the area under different landholdings in the state (Table 6).

The introduction of capital and labour as additional constraints as in the fifth and sixth cases had only a marginal effect on income, production of different commodities, resource requirements, land use types and technologies used (Tables 4, 5 and 6). This indicates that, at the aggregate state level, capital and labour constraints were not very critical to increasing income if other constraints such as water and technology adoption persisted.

Maximizing employment

Maximization of employment was another major focus of the study. The maximum employment potential in Haryana under the constraint of the land resource was calculated as 752 million labour days, almost double the current level. This was associated with 34.3 million t of food grain production and 6.2 billion litres of milk production (Table 7). To generate this level of employment, 100% of the agricultural land was used and 56.1 billion cubic metres of water would be needed. In addition to increased employment, this would result in an income of 88.4 billion rupees per annum. The scenario would at the same time result in a loss of 64.8 thousand tons of N through leaching and a slightly risky but acceptable level of BRI.

The increased employment was associated with the cultivation of the rice-rice-wheat system in 50.6% of the agricultural area. The dominant cropping systems on the remaining land were rainfed pearl millet-wheat, fallow-chickpea and rice-mustard (Table 8). Technology level 1 covered 31.4% of the area and 50.6% and 18.0% of the area were under levels 4 and 5, respectively (Table 9).

The introduction of water as a constraint, in addition to land, reduced employment opportunities to 558 million labour days (Table 7). Food grain production declined to the current level, along with other crops, except for maize, chickpea and sugarcane, which increased relative to the current level. This was due to an increased area under labour-intensive and water-use-efficient sugarcane-wheat and maize-chickpea systems at the expense of labour-intensive but water-demanding rice-based systems. Income also decreased considerably, along with a reduction in input use. Technologies 1, 3 and 5 were predominant (Table 9).

Table 7. Production of different commodities, income, resource requirements and environmental impact at the aggregate level when maximizing employment in Haryana.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Food	Million tons	34.3	10.5	17.5	10.5	10.5	10.5	10.5
Rice	Million tons	23.8	2.5	8.4	2.5	2.5	2.5	2.5
Wheat	Million tons	10.5	8.0	9.1	8.0	8.0	8.0	8.0
Oilseed	Million tons	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Chickpea	Million tons	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Cotton	Million bales*	1.53	1.53	1.53	1.53	1.53	1.53	1.53
Sugar (jaggery)	Million tons	0.90	0.90	0.90	2.41	1.88	1.42	0.90
Milk	Billion litres	6.23	5.41	5.53	5.30	3.81	3.95	4.20
Income	Billion rupees	88.4	68.6	114.4	53.1	53.7	53.2	46.1
Land used	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Irrigation	Billion m^3	56.1	17.8	37.8	16.3	15.8	15.3	18.2
N fertilizer	Million tons	1.42	0.89	1.45	0.67	0.61	0.60	0.65
Employment**	Million labour days	752	558	688	428	399	373	387
Capital	Billion rupees	111.2	82.0	108.1	62.2	56.4	53.9	56.4
N loss	Thousand tons	64.8	32.9	49.5	34.4	35.4	35.4	31.6
Biocide index	–	108	210	321	140	128	124	81

* Each bale of cotton = 170 kg.

** Objective function maximized.

When technology adoption and land were the only constraints, as in the third case, employment decreased from 752 to 688 million labour days, but that was accompanied by a drastic reduction in total food grain production to 17.5 million t, about half of that in the first case (Table 7). This was due to a reduction in the rice-rice-wheat area and a shift to maize-potato-wheat (Table 8), which resulted in increased income. The technology adoption constraint allows 70% of the area to be cultivated under the third level of technology (Chapter 5) and, at that level, the maize-potato-wheat system requires 392 labour days versus 389 for the rice-rice-wheat system; hence, the former *lut* was selected by the model (Table 9).

Adding the technology adoption constraint to the land and water constraints drastically reduced employment, yet it exceeded the current level (Table 7). More than double the production of sugarcane took place because of the increased area under the labour-intensive sugarcane-wheat system. Other land use changes also occurred and cotton-wheat gained prominence in the irrigated areas and pearl millet-wheat in the rainfed areas (Table 8).

Table 8. Area (% of agricultural land) under different land use types when employment was maximized.

Land use type	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech + Water	Land +Tech + Water + Capital	Land +Tech + Water + Capital + Labour
Rice-rice-wheat	50.6	5.0	16.7	2.7	2.9	1.6
Rice-wheat	0.0	1.2	0.0	12.0	12.3	11.8
Basmati rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-mustard	8.4	0.6	11.4	0.7	0.3	3.5
Cotton-wheat	6.6	7.3	9.0	20.4	20.7	19.9
Maize-mustard	0.0	11.0	0.0	12.8	15.2	11.2
Maize-chickpea	0.3	22.8	0.3	3.4	4.1	4.8
Maize-potato-wheat	0.0	0	28.3	0.0	0.0	0.4
Sugarcane-wheat	2.7	15.1	3.0	10.3	7.6	5.8
Irrigated pearl millet-wheat	0.0	0	0.0	1.4	1.3	3.4
Rainfed pearl millet-wheat	18.0	36.8	18.0	35.3	16.5	10.6
Fallow-wheat	0.0	0	0.0	1.1	19.0	26.8
Fallow-chickpea	13.4	0	13.4	0.0	0.0	0.0
Fallow-mustard	0.0	0	0.0	0.0	0.0	0.0
Pearl millet-fallow	0.0	0	0.0	0.0	0.0	0.0

Table 9. Area (% of agricultural land) under different technology levels when employment was maximized.

Technology level	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech + Water	Land +Tech + Water + Capital	Land +Tech + Water + Capital + Labour
1	31.4	36.8	31.4	39.8	44.1	47.3
2	0.0	0.0	0.0	47.6	47.0	43.1
3	0.0	34.9	51.2	9.1	7.4	6.9
4	50.6	0.1	13.1	2.5	1.2	1.9
5	18.0	28.2	4.3	1.1	0.3	0.8

Constraints on capital and labour availability reduced the sugarcane area and hence sugar production. Milk production was also significantly affected because of a considerable reduction in the pearl millet-wheat area (Tables 7 and 8), and hence in animal feed. There was a gradual shift toward the adoption of lower-level technologies, with 90% of the area cultivated under technologies 1 and 2 (Table 9).

Minimizing agricultural area

In this scenario, the agricultural area was minimized while targets of production were at least equal to their current levels. Hence, the model restriction of using all land imposed earlier was removed. This is important, considering increasing urbanization and industrialization of Haryana, because of the state's close proximity to the capital city of New Delhi. The outputs showed that only 36.9% of the agricultural land was needed to produce the current levels of production in the absence of constraints on technology adoption, water, capital and labour (Table 10). Interestingly, agricultural income in the state was also 60% higher than currently attained. However, this required 20%, 50% and 17% more irrigation, fertilizer and capital and there was a considerable loss in employment potential. The environmental impact in this scenario was more or less similar to the baseline of 1996-97 (Table 10).

Half of the agricultural land was allotted to the rice-wheat system, whereas the other dominant cropping systems were cotton-wheat, maize-mustard, pearl millet-wheat and sugarcane-wheat (Table 11). As expected, 100% of the area was cultivated under technology level 5 (Table 12).

The results of this scenario indicate that, if alternative sources of livelihood are available to a large number of Haryana's farmers and if irrigation and capital invest-

Table 10. Production of food (including rice and milk), income, resource requirements and environmental impact at the aggregate level when minimizing agricultural area in Haryana. Production of all crops was at their 1996-97 level in all cases and hence is not shown.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Food	Milliontons	14.3	10.5	10.5	10.5	10.5	10.5	10.5
Rice	Million tons	6.3	2.5	2.5	2.5	2.5	2.5	2.5
Milk	Billion litres	4.46	4.95	5.34	5.02	4.11	4.34	4.20
Income	Billion rupees	74.6	65.3	70.9	51.1	52.3	51.8	46.1
Land used*	%	36.9	76.3	60.2	83.3	85.3	86.4	100.0
Irrigation	Billion m^3	21.9	17.2	20.2	16.2	16.0	15.7	18.2
N fertilizer	Million tons	0.98	0.72	0.96	0.65	0.63	0.62	0.65
Employment	Million labour days	283	329	321	332	331	332	387
Capital	Billion rupees	65.8	59.6	63.3	51.5	50.7	50.6	56.4
N loss	Thousand tons	28.2	37.2	37.8	34.9	34.5	34.2	31.6
Biocide index	-	85	191	227	160	153	149	81

* Objective function minimized.

Table 11. Areas (% of agricultural land) under different land use types when agricultural area was minimized.

Land use type	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech + Water	Land +Tech + Water + Capital	Land +Tech + Water + Capital + Labour
Rice-rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-wheat	41.8	20.1	6.5	16.1	15.1	14.8
Basmati rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-mustard	2.2	12.3	15.8	6.1	6.5	6.3
Cotton-wheat	16.7	15.3	17.1	23.9	23.0	23.0
Maize-mustard	17.2	4.2	1.6	9.3	8.7	8.9
Maize-chickpea	4.9	3.2	4.0	3.4	3.4	3.4
Maize-potato-wheat	0.0	2.1	8.5	0.0	0.0	0.0
Sugarcane-wheat	5.8	4.9	5.5	4.2	4.6	4.5
Irrigated pearl millet-wheat	11.4	15.6	41.0	12.1	12.6	12.0
Rainfed pearl millet-wheat	0.0	0	0.0	0.0	0.0	0.0
Fallow-wheat	0.0	22.3	0.0	24.9	26.2	27.2
Fallow-chickpea	0.0	0	0.0	0.0	0.0	0.0
Fallow-mustard	0.0	0	0.0	0.0	0.0	0.0
Pearl millet-fallow	0.0	0	0.0	0.0	0.0	0.0

Table 12. Area (% of agricultural land) under different technology levels when agricultural area was minimized.

Technology level	Constraints					
	Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
1	0.0	44.4	0.0	26.2	33.7	35.0
2	0.0	10.2	0.0	56.9	52.5	52.1
3	0.0	5.6	71.1	10.7	8.7	8.1
4	0.0	2.8	21.8	4.3	3.5	3.3
5	100.0	36.8	7.2	1.9	1.5	1.5

ment in the remaining agricultural areas could be expanded, Haryana could meet its commitment of agricultural production with only 37% of its currently cultivated land.

Once the constraint of technology adoption was introduced, the required minimum agricultural area increased to 60.2%, whereas relative to the previous scenario, less irrigation, capital and fertilizer were used (Table 10). The scenario nevertheless resulted in relatively higher employment. Both N losses and biocide residue index, however, increased because of changes in land use and technologies. The land use pattern changed drastically with pearl millet-wheat occupying the major area (41.0%) instead of rice-wheat, followed by cotton-wheat and rice-mustard (Table 11). Since water was not yet a constraint, no rainfed crop was selected.

A major shift in technology adoption occurred, with 71% of the area under level 3 and 21.8% under level 4 (Table 12). Small farmers represent 60% of the landholdings and 20.4% of the area of the state and in the model they were restricted to using technologies 1 and 2. Since both these technologies were not selected by the model, it is apparent that, in this scenario, the area was minimized by keeping the land of most small and some medium farmers uncultivated at all times.

When land and availability of water were the only constraints, agricultural land use increased to 76% to produce the current production levels. All inputs, such as N fertilizer, capital and irrigation water, were very close to the current level, but income was about 40% higher. In the land use pattern, there was a clear shift toward the rice-wheat system on irrigated land. Other major cropping systems were irrigated pearl millet-wheat, cotton-wheat and rice-mustard (Table 11). In the rainfed areas, a shift toward fallow-wheat from pearl millet-wheat could be observed. The first and fifth levels of technologies predominanted in most regions.

The introduction of capital and labour as additional constraints increased the minimum agricultural land use requirement to 83-86%. Requirements of N fertilizer, capital and irrigation water decreased to the current levels or even slightly lower. Yet, income was still higher by 11-13% (Table 10). The environmental impact remained much higher. The land use pattern was similar in all three cases with the dominance of fallow-wheat, cotton-wheat and rice-wheat cropping patterns (Table 11). A shift toward the adoption of lower technology levels was observed with 87% of the area under levels 1 and 2 (Table 12).

Minimizing water use

The earlier scenario analyses revealed that restricted availability of water was the major constraint to increasing food production in Haryana. Therefore, in this scenario, a minimum water requirement was determined to produce current levels of food grains, oilseed, pulses, cotton and sugar. Results showed that, if the land resource was the only constraint, the current levels of production in Haryana could be attained with only 9.9 billion cubic metres of water, which is almost half the current water use. This scenario still generates higher milk production and income than the 1996-97 baseline, but drastically reduces employment opportunities in the agricultural sector. At the same time, resource requirements in terms of capital and N fertilizer also decreased. N loss was maintained at the same level, but the biocide residue index declined drastically because only 6.8% of the area was allocated to cotton-wheat and maize-potato-wheat, the two most biocide-consuming land use systems (Tables 13 and 14). Fallow-wheat occupied 60.6% of the arable area of the state. Other important cropping systems were rice-wheat, maize-mustard and pearl millet-wheat. The current technology level occupied 71.7% of the area and the remainder was cultivated under level 5

Table 13. Production of milk, income, resource requirements and environmental impact at the aggregate level when minimizing water use in Haryana. Production of all crops was at their 1996-97 level in all scenarios and hence is not shown.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech +Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Milk	Billion litres	4.9	4.3	4.9	5.0	4.3	4.4	4.2
Income	Billion rupees	58.5	52.3	55.0	50.1	51.8	51.6	46.1
Land used	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Irrigation*	Billion m^3	9.9	12.3	11.4	13.7	13.7	13.8	18.2
N fertilizer	Million tons	0.56	0.59	0.59	0.57	0.57	0.57	0.65
Employment	Million labour days	236	310	301	341	341	341	387
Capital	Billion rupees	46.0	47.7	47.7	50.3	50.4	50.4	56.4
N loss	Thousand tons	31.9	27.6	33.3	34.6	34.6	35.1	31.6
Biocide index	-	31	93	77	122	122	121	81

* Objective function minimized.

Table 14. Area (% of agricultural land) under different land use types when water use was minimized.

Land use type	Constraints					
	Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
Rice-rice-wheat	0.0	0.0	0.0	1.2	1.2	1.3
Rice-wheat	6.8	5.01	8.8	9.5	9.5	9.5
Basmati rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-mustard	2.4	6.55	3.1	6.5	6.5	6.4
Cotton-wheat	6.8	7.02	11.7	20.0	20.0	19.2
Maize-mustard	6.0	0.17	7.5	7.2	7.2	7.2
Maize-chickpea	2.3	0.0	3.0	3.6	3.6	3.5
Maize-potato-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane-wheat	2.7	2.45	3.4	3.8	3.8	3.9
Irrigated pearl millet-wheat	1.4	0.0	2.5	5.4	5.4	5.5
Rainfed pearl millet-wheat	11.1	18	10.3	7.1	7.1	7.1
Fallow-wheat	60.6	51.17	49.8	35.7	35.7	36.3
Fallow-chickpea	0.0	0.0	0.0	0.0	0.0	0.0
Fallow-mustard	0.0	9.68	0.0	0.0	0.0	0.0
Pearl millet-fallow	0.0	17.98	0.0	0.0	0.0	0.0

Table 15. Area (% of agricultural land) under different technology levels when water use was minimized.

Technology level	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech +Water	Land +Tech +Water + Capital	Land +Tech +Water + Capital + Labour
1	71.7	78.8	60.1	47.9	47.9	47.3
2	0.0	0	0.0	42.2	42.2	42.5
3	0.0	0	27.0	6.9	6.9	7.4
4	0.0	0	9.3	2.2	2.2	2.0
5	28.3	21.2	3.6	0.8	0.8	0.8

(Table 15). This indicates that, if much of the state continues to use low levels of technology, but water-saving cropping systems, food production and income of the state can be met with only 50% of the current use of water resources.

When other constraints were gradually added in this scenario, water use still remained below 75% of the current use, while maintaining the current level of production of different commodities and income (Table 13). This was attained by the predominance of fallow-wheat, cotton-wheat, rice-wheat, maize-mustard and pearl millet-wheat cropping systems at relatively lower levels of technologies (Tables 14 and 15). Although this sounds attractive, in this scenario, individual farmers, especially those with large landholdings and a wide resource base, are likely to suffer in their income and hence such land use may not be acceptable.

Minimizing biocide residue index

The use of biocides in agriculture is a major environmental concern. Biocide use in Haryana is higher than the national average. As the demand for food and fibre will increase in the future, biocide use is expected to also increase, unless some environmentally safer biocides are developed (change in technology) or land use is changed to minimize biocide use. The results of minimizing the biocide residue index (Table 16) showed that, if the land resource was the only constraint, current levels of production could be obtained with a much lower BRI (24) than the current level by changing land use. This is attained by putting more emphasis on lower levels of technologies and by reducing cropping intensity (Tables 17 and 18). Almost 50% of the land in this scenario was fallow during the *kharif* season and pearl millet, rice and cotton were the dominant crops. This scenario is characterized by a much lower resource requirement than the 1996-97 baseline. In this situation, 34.4% of the area was occupied by fallow-wheat and 23.7% by irrigated pearl millet-wheat (Table 17). The current level of technology (level 1) would predominate in 84.1% of the area (Table 18).

The introduction of technology adoption as a constraint increased BRI to 39 for the same level of production (Table 16) using the same land use systems. There was some

Table 16. Production of milk, income, resource requirements and environmental impact at the aggregate level when minimizing biocide residues in Haryana. Production of all crops was at their 1996-97 level in all scenarios and hence is not shown.

Item	Unit	Constraints						Current level (1996-97)
		Land	Land + Water	Land + Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour	
Milk	Billion litres	5.1	5.2	5.3	5.0	4.0	4.0	4.20
Income	Billion rupees	52.7	50.3	51.4	49.7	51.3	51.2	46.1
Land used	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Irrigation	Billion m^3	14.8	15.1	16.0	15.1	15.4	15.4	18.2
N fertilizer	Million tons	0.53	0.42	0.56	0.55	0.60	0.60	0.65
Employment	Million labour days	274	326	304	334	338	338	387
Capital	Billion rupees	45.7	47.8	47.6	49.4	50.6	50.4	56.4
N loss	Thousand tons	34.4	33.3	34.6	35.2	38.0	37.9	31.6
Biocide index*	-	24	82	39	106	106	106	81

* Objective function minimized.

Table 17. Area (% of agricultural land) under different land use types when biocide residue index was minimized.

Land use type	Constraints					
	Land	Land +Water	Land +Tech	Land +Tech +Water	Land +Tech + Water + Capital	Land +Tech + Water + Capital + Labour
Rice-rice-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Rice-wheat	2.9	2.5	3.0	11.0	16.7	16.4
Basmati rice-wheat	0.0	0	0.0	0.0	0.0	0.0
Rice-mustard	13.2	1.5	15.4	9.6	1.6	2.1
Cotton-wheat	7.0	14.1	8.6	23.1	19.8	19.7
Maize-mustard	0.9	0.2	0.3	6.0	10.4	10.4
Maize-chickpea	0.0	0.0	0.0	1.2	0.0	0.0
Maize-potato-wheat	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane-wheat	2.7	1.5	3.1	4.0	4.0	4.0
Irrigated pearl millet-wheat	23.7	0.0	27.8	7.6	8.4	8.3
Rainfed pearl millet-wheat	0.0	18.0	0.0	0.0	0.0	0.0
Fallow-wheat	34.4	50.7	26.7	29.6	18.6	19.7
Fallow-chickpea	15.3	0.0	15.3	7.8	15.3	15.3
Fallow-mustard	0.0	0.5	0.0	0.0	5.1	4.0
Pearl millet-fallow	0.0	11.0	0.0	0.0	0.0	0.0

Table 18. Area (% of agricultural land) under different technology levels when biocide residue index was minimized.

Technology level	Constraints					
	Land	Land + Water	Land +Tech	Land + Tech + Water	Land + Tech + Water + Capital	Land + Tech + Water + Capital + Labour
1	84.1	82.7	74.3	62.4	45.0	45.2
2	0.0	2.7	8.8	26.8	46.1	46.1
3	0.0	0.0	3.6	6.9	6.0	5.9
4	0.0	0.0	9.8	2.6	2.0	2.0
5	15.9	14.6	3.4	1.3	0.8	0.8

increase in area under technologies 2 to 4 (Table 18). When water and land were introduced as constraints, BRI increased to 82, concurrently with an increase in the cotton-wheat cropping system. BRI further increased to 106 when the availability of water, capital and labour were introduced as constraints (Table 16). Compared to the previous scenario, this increased the capital requirement but generated more employment. This increase was largely because of the cotton-wheat system, which was allotted 20-23% of the area, and to some extent because of rice-wheat (occupying 11-17% of the area).

Conclusions

- The results presented in this chapter are exploratory in nature, and time frames for implementing technically feasible solutions are not part of this analysis. The main purpose was to illustrate the windows of opportunity as a basis for discussions on future planning for food security.
- Haryana has considerable opportunities to increase food production and agricultural income compared with the current levels, provided additional water resources could be made available or water management improved. Water resource availability in the state could increase in the future, but this would be very small. At the same time, all available irrigation water could not be fully used because of its spatial and temporal distribution. Our results could, however, be slightly biased because of inaccuracies and inadequacies in the quantities of groundwater and canal water data.
- The current natural constraints of land and water limit maximum food production potential to 17 million t. In these calculations, the model assumes that all water and capital within a land unit can be shared. It implies that groundwater resources available within a farm can be transported to other farms without cost, irrespective of the distance involved. This does not look feasible, even with the current policy of an almost free water supply in the region. The same holds for capital.
- Capital was generally not a constraint in most analyses when availability of natural resources was considered. This indicates that additional capital investment in the state would not be very rewarding, unless the spatial and temporal availability of

water could be improved.

The model suggests that, to increase income, more rice should be produced in the irrigated areas and sugarcane when water becomes a constraint. It assumes that all products could be sold at a fixed price, an assumption that is not likely to hold in many cases. Model adaptations are needed to account for the impact of food supply on its prices. Gross income in the results often appears to be too high. Rates of return on capital investments appear to exceed 100% in many cases. This was largely because of the exclusion of fixed costs of land and livestock from the calculations.

Haryana has considerable potential to withdraw agricultural land from cultivation, without affecting basic food production and income at the aggregate level. This would require that the small farmers who cannot use alternative, efficient and capital-intensive technologies not cultivate their land and that their water and other resources be made available to other farmers who presumably could use these more efficiently. Alternatively, technologies that are affordable and can be applied on small farms should be developed. There is also a need for land consolidation to overcome the technology adoption constraint, which needs radical land reforms. Another option to reduce the area under cultivation without affecting production is that larger farmers sacrifice technology use and hence income. Such structural changes are not possible without a radical policy shift. There is an urgent need to explore off-farm employment opportunities for a large number of small farmers.

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9. Balancing food demand and supply

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Introduction

Farmers in Haryana, like anywhere else in India, are now under pressure to explore opportunities for increasing income from agricultural land. In recent times, the production of rice and wheat, the primary staple foods for the vast majority of the population and conventional crops in the region, has surpassed local demand. Combined with declining demand in other states, farmers are now having difficulty in getting a remunerative price for their produce. The government has been able to provide a minimum support price for both crops so far, but, because of increasing buffer stocks, such guaranteed prices may not remain feasible in the future. Therefore, unless farmers diversify to other crops and land uses, their agricultural income may further decline. Today, farmers in the state as well as planners of the region are very keen to know the best farming options available to them that can ensure maximum returns.

When planning for the future, the growing population, the increasing demand for food and the role of Haryana in ensuring food security for the country have to be kept in mind (see Chapter 2). Planning for the future therefore has to consider food demand, while increasing farmers' income, taking into account costs of environmental impact and protecting or enhancing employment opportunities in agriculture. In the previous chapter, the upper limit of production opportunities, income and employment generation and associated cropping patterns, technologies and environmental impacts were explored for a given set of constraints. These extreme values help in understanding the upper limit of attainment of specific objectives in the absence of restrictions. By progressively introducing selected constraints, we were able to understand the relative importance of various resources and constraints. The estimation of 'extreme points' and trade-off analyses provided meaningful insights into the feasible-solution space and information on how much of one objective function should be sacrificed to attain an incremental increase in another objective. In this chapter, we present results of two specific scenarios that explore land use changes and resources required for ensuring food security by increasing agricultural income while meeting food production targets of 2000 and 2010.

P.K. Aggarwal et al. *(eds), 2001. Land use analysis and planning for sustainable food security: with an illustration for the state of Hatyana, India. IARI-India, IRRI-Philippines and WUR-The Netherlands. pp, 137-151.*

Scenarios and developmental targets

The two scenarios are referred to as *Current improvement* and *Exploration 2010.* The current improved scenario refers to 2000, and is based on currently available resources and demand for different agricultural commodities. The future explorative scenario searches for the best option to maximize farmers’ income in 2010 on the basis of projected availability of land and water resources and on the basis of projected demand for food. Scenarios for a longer time horizon were not developed because of expected rapid transformations in the structure and function of agro-ecosystems in the coming years and the associated large uncertainties. The major emphasis in these scenarios was on determining of agricultural land use patterns in different regions, which will make it possible to maximize regional income while maintaining the basic goals of food production, employment and environmental protection. Although it is certain that the prices and returns of agricultural enterprises will be changing in time, for simplicity and for a lack of clear understanding of future trends, the relative change in costs and returns was assumed to remain the same as in 1996-97, the baseline year used in this study. For the same reasons, new technologies in the form of varieties, resource management and biocides that could become available in the future and possible modifications in soil quality and hence inputs/outputs have also not been considered.

These scenarios were operationalized by specifying a group of objective functions and specific constraints. Developmental targets demand for specific items such as food grains and milk, income and employment to realize a poverty-free and food-secure Haryana were incorporated into the model through specific restrictions by imposing constraint sets and lower and upper bounds of resources. The internal demand for direct consumption within Haryana is relatively low, in particular for food grains (Chapter 3). The state produces a large quantity of cereals, which is sent out of the region to ensure food security of other states of the country. For example, the demand for rice and wheat in Haryana for internal consumption is estimated to be, at a maximum, 0.28 and 2.8 million tons, respectively, by 2010, whereas current production of these crops in the state is already 2.5 and 8.0 million tons, respectively. Haryana, with less than 3% of the total cultivated area of the country, contributes around 6% to its total food grain production. To maintain future food availability India, the state has to continue to perform its lead role. Moreover, though Haryana has a substantial food surplus, some people still live below the poverty line. Therefore, the scenarios oscillate around increasing the state’s contribution to the national food basket and creating a poverty-free Haryana.

The food demand for the *Current improvement* and *Exploration 2010* scenarios was therefore recalculated on the basis of total demand of food for the country in different years (Chapter 3) and the current relative contribution of Haryana to India’s agricultural production. The latter was assumed to remain identical in the future. Table 1 summarizes the demand for different commodities in the two scenarios and the associated availability of resources and implied constraints. The demand for rice and wheat is thus projected to increase to 3.13 and 9.68 million tons by 2010, respectively. The demand for oilseeds, cotton, sugar and milk is also expected to show a substantial increase.

Table 1. Targets of different commodities in the *Current improvement* and *Exploration 2010* scenarios. Also shown are the assumptions about different resources and constraints.

Objective variable	Units	*Current improvement*	*Exploration 2010*
Food	Million tons	10.57	12.81
Rice	Million tons	2.57	3.13
Wheat	Million tons	8.00	9.68
Pulses	Million tons	0.26	0.35
Pearl millet	Million tons	0.71	0.83
Oilseeds	Million tons	1.08	1.41
Cotton	Million bales	1.68	2.19
Sugarcane (jaggery)	Million tons	0.99	1.29
Maize	Million tons	0.04	0.04
Milk	Million tons	4.57	6.30
Land	% area	100	100
Income	Billion rupees	> 46.1	> 46.1
Employment*	Million labour days	> 348	> 348
Technology adoption	Landholding	As current	As current
Irrigation	Billion m^3	< 18.5	< 21.5

* Employment target was set at 90% of the 1996-97 level of 387 million labour days.

It was assumed that

- The entire land area currently under agriculture would continue to remain within this sector and would be cultivated because the spatial distribution of future demand for urbanization, forestry and other land uses is not known now.
- Land degradation status would remain at the 1996-97-level (described in Chapter 4).
- There would not be any significant land consolidation or fragmentation and thus the proportions of landholding sizes and numbers would remain as in 1996-97.
- The technology adoption constraint for small and medium farmers, as defined in Chapter 7, would remain the same.
- Employment opportunities for labour in agriculture would be at least 90% of the current level (387 million labour days).
- Availability of irrigation water would increase to 21.5 billion cubic metres by 2010 from the current availability of 18.5 billion because of the augmented supply of water from the Ravi and Beas rivers according to the projected plan (Irrigation Department of Haryana, 1995). Since the spatial distribution of this increase was not specified, it was assumed that this additional water would become available in all districts.
- Annual and seasonal water availability (and not monthly) is a constraint in irrigated land units.
- Agricultural income of the state would not be lower than the 1996-97 level of 46.1 billion rupees.

- Capital availability would not be a constraint, considering that additional funds, if needed, could be mobilized for farming through credit institutions or from other sources.

Analysis procedure

The scenario analysis procedure is an iterative process in which a scenario is defined by a set of objective functions. When not optimized, an objective function is treated as a constraint with a target that is in agreement with policy priorities. We followed an iterative method for scenario generation (Changhe, 2000), starting with the selection of a set of objective functions that are adapted in accordance with the defined policy scenarios. In the next step, a priority ranking is assigned to each of the selected objective functions. The objective function with the highest priority is first optimized with specific targets for different developmental goals. The second objective function in the priority list is optimized after introducing the optimized value of the first objective function with an assumed deviation (10% in this study), plus (for a minimized objective) or minus (for a maximized objective) (Changhe, 2000). This procedure is continued till all objective functions are optimized. In this procedure, a small sacrifice by a higher priority objective function provides some space for improving lower priority objective functions. Some discrepancies between the set targets for each product and the optimized value could occur in this procedure because of this assumed deviation.

Maximization of income was considered to be the primary goal in both scenarios. The other objective functions in order of decreasing priority were maximization of food production, maximization of employment, minimization of water use and biocide residue index. In all cases, it was ensured that the production of various commodities was at least at the target level given in Table 1. In general, this approach resulted in consistent improvement in the value of different objective functions when optimized. The inclusion of environmental objectives, however, resulted in a modest reduction in food production.

Current improvement scenario

Income and capital

At the state level, the results showed that Haryana could achieve an income of 55 billion rupees, 15% higher than the 1996-97 level (Figure 1). Capital and other resource endowments of 1996-97 were sufficient to meet the targets of this scenario. However, it was also evident that the capital currently being used in agriculture cannot be reduced without negatively affecting agricultural production. Net return (income over capital use), as an index of the efficiency of on-farm investment, is more relevant from the farmer's point of view. This ratio was 82 in 1996-97, but could be improved to 99.3, indicating considerable scope for improving agricultural income of the state with proper land use management. In general, calculated net return and income in our analysis appear to be too high, largely because the fixed costs (cost of land and livestock) and other opportunity costs were not included in the calculation of net income.

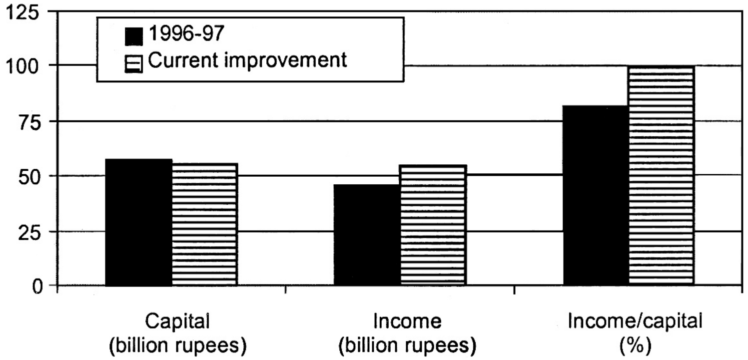

Figure 1. Capital used and income generated by agriculture in the 1996-97 baseline and generated in the *Current improvement* scenario.

Production

The results revealed that all the targets set for the various products, including milk (Table 1), were met, except for maize, for which production (2.07 million t) strongly exceeded the target (0.04 million t). The model selected cultivation of fallow-wheat and pearl millet-wheat in the rainfed areas for maximizing income of the whole state (Figures 2 and 3). Other rainfed systems, such as fallow-chickpea, fallow-mustard and pearl millet-fallow, were not selected because of their relatively lower income. Therefore, targets of chickpea and mustard were met by allocating their production to irrigated areas. In these areas, cotton-wheat, rice-wheat and maize-mustard were the other dominant land use types (Table 2; Figure 2). The model selected 18% of the area under maize, mainly because of its association with mustard, for which the production

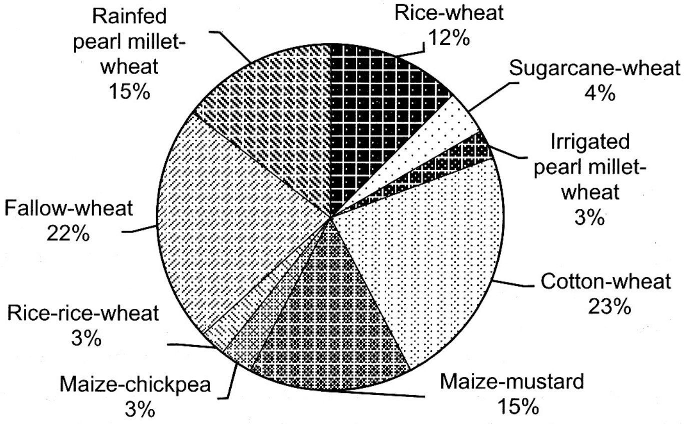

Figure 2. Recommended land use (agricultural area under different cropping systems) for maximizing income in the *Current improvement* scenario.

Table 2. Recommended technologies (% coverage of the area) for various cropping systems for maximizing income in Haryana under the *Current improvement scenario.*

Land use system	Tech. 1	Tech. 2	Tech. 3	Tech. 4	Tech. 5
Rice-rice-wheat	0.0	100.0	0.0	0.0	0.0
Rice-wheat	0.0	100.0	0.0	0.0	0.0
Basmati rice-wheat	0.0	0.0	0.0	0.0	0.0
Rice-mustard	0.0	100.0	0.0	0.0	0.0
Cotton-wheat	43.3	38.2	12.7	4.1	1.7
Maize-mustard	17.5	65.0	13.0	3.3	1.2
Maize-chickpea	0.0	8.6	61.3	20.3	9.8
Maize-potato-wheat	0.0	0.0	0.0	0.0	0.0
Sugarcane-wheat	0.0	69.4	19.1	8.2	3.4
Irrigated pearl millet-wheat	29.7	70.3	0.0	0.0	0.0
Rainfed pearl millet-wheat	100.0	0.0	0.0	0.0	0.0
Fallow-wheat	100.0	0.0	0.0	0.0	0.0
Fallow-chickpea	0.0	0.0	0.0	0.0	0.0
Fallow-mustard	0.0	0.0	0.0	0.0	0.0
Fallow-pearl millet	0.0	0.0	0.0	0.0	0.0

target was high. This crop was available in only two land use types: rice-mustard and maize-mustard. Since irrigation water was a constraint in many places, rice-mustard could not be grown. Hence, to meet the production targets of oilseeds, the maize-mustard cropping system was selected.

All rice-based land use types were grown at relatively low levels of technology (Table 2). The model allocated large areas in the state to wheat cultivation in the *rabi* season. Since the targets for chickpea and mustard also had to be met, a considerable proportion of these crops was selected at relatively higher technologies (Table 2). Chickpea was selected to a large extent only in Sonipat District of the state (Figure 3). Cotton was selected predominantly for cultivation in Hissar, Sirsa and Jind districts, although some small patches were selected elsewhere (Figure 3). A substantial area of sugarcane, cotton and maize was also selected at the higher use-efficient technologies 3, 4 and 5.

Employment

Changes in cropping pattern and shifts in technology might affect on-farm employment generation. Since the target in this scenario was set at retaining 90% of the current employment opportunities, labour input declined slightly (Figure 4) from 387 million to 372 million days, indicating that the increase in income was partly the result of increasing mechanization or of selection of land use systems requiring low labour. Indeed, the area under fallow was considerable in the *kharif* season (Figure 2) and the labour-intensive sugarcane-wheat system was partly cultivated with more mechanized, profitable and productive technologies (Table 2).

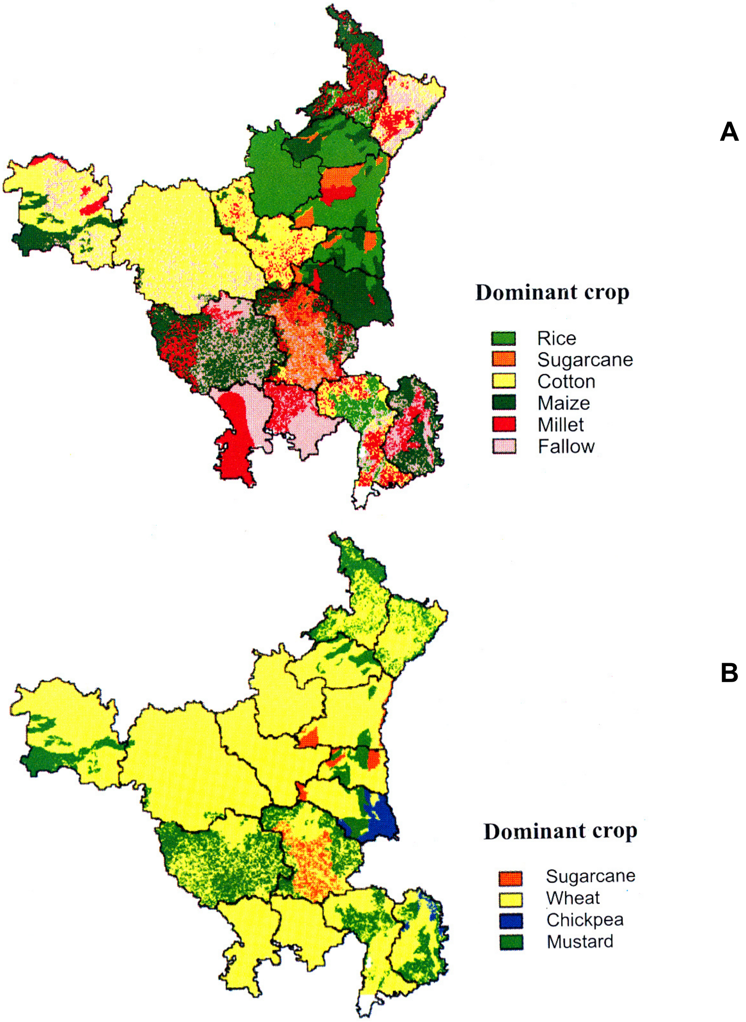

Figure 3. Selected land use (agricultural area under different cropping systems) in (A) *kharif* and (B) *rabi* seasons for maximizing income in the *Current improvement* scenario.

Water

Results of earlier analyses showed that in Haryana additional irrigation water is needed to increase production and income (Chapter 8). Yet, a certain quantity of irrigation water remains unused (Figure 5). This suggests that, overall, on an annual basis, inigation water is not a constraint in Haryana, but it is in the *kharif* season in all districts and in the *rabi* season in only a few districts. This pattern could also be related to the technology shift. In addition, the model lacks a cropping activity that can use surplus water in the summer season. Allocation of annually available water over the seasons is based on an arbitrary criterion. The description of this allocation probably needs further improvement.

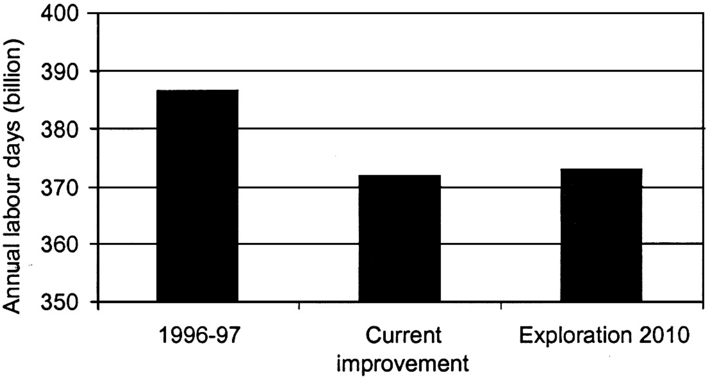

Figure 4. Employment opportunities (current baseline, 1996-97) and in the *Current improvement* and *Exploration 2010* scenarios for maximizing agricultural income in Haryana.

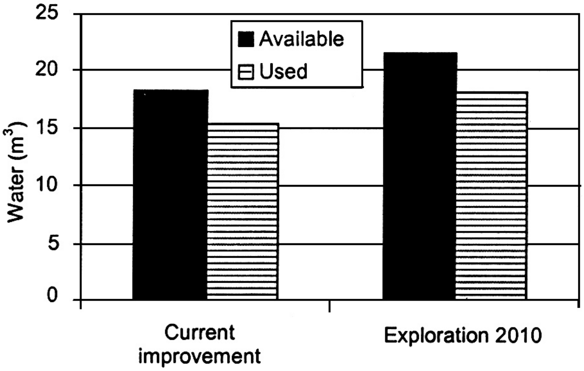

Figure 5. Use of available irrigation resources in the *Current improvement* and *Exploration 2010* scenarios for maximizing agricultural income.

Nitrogen fertilizer and nitrogen leaching

There was 7% less N fertilizer consumption in this scenario than in 1996-97. Again, this is associated with the area that remained fallow during the *kharif* season and with increased fertilizer use efficiency related to higher technology adoption in the *rabi* season.

Nitrate leaching was slightly higher for the *Current improvement* scenario than in the 1996-97 baseline (Figure 6). This indicates that increasing income from agriculture with current natural resource use has a small trade-off with N leaching. Fallow land increased considerably in this scenario. A significant part of the N mineralized in this land was lost below the rooting zone, resulting in overall increased N leaching in the state.

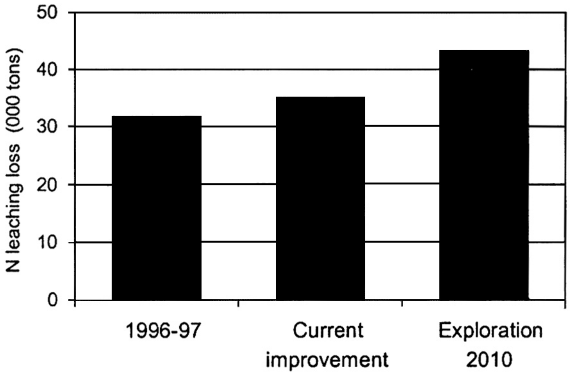

Figure 6. Estimated nitrate-leaching loss in Haryana in 1996-97 and in the *Current improvement* and *Exploration 2010* scenarios for maximizing agricultural income.

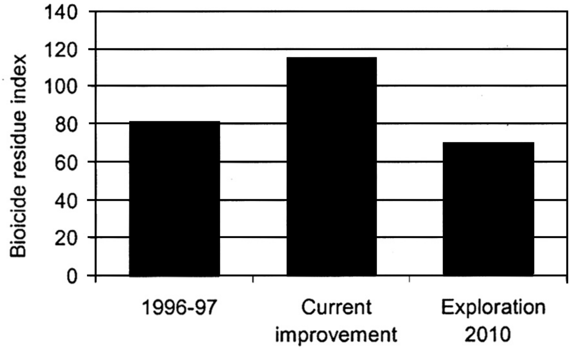

Figure 7. Estimated biocide residue index in Haryana in 1996-97 and in the *Current improvement* and *Exploration 2010* scenarios for maximizing agricultural income.

Biocide residues

Biocide residue index increased to 115 in the *Current improvement* scenario compared with 81 in 1996-97 (Figure 7). Values less than 100 are most desirable. The increase was largely caused by cotton cultivation; nevertheless, the increased value was still within the acceptable limits (< 200, Chapter 6). However, in Hissar and Sirsa districts, where most cotton was cultivated (Figure 3), the index was in the risky category. Safer biocides are therefore urgently needed.

Exploration 2010

The results indicated that it is not feasible to meet the targets of food production, income and employment with the projected resource availability in the state. Several iterations with the model showed that a small relaxation in the target of any commodity was needed to examine the feasible options and their trade-offs. Considering this, the target of pulses was relaxed in the model to a 20% lower value (Table 1).

To meet the increased targets of production and income of 2010, a 9% increase in capital investment in agriculture compared with the 1996-97 level would be necessary. If this additional investment could be made, it could generate much higher aggregated returns in net income (Figure 8) by increasing the efficiency of crop- and livestock-based enterprises. These returns were higher than the 1996-97 baseline as well as the *Current improvement* scenario.

Production

All production targets except pulses (which was relaxed by 20% in the model, see above) were met in this scenario. Increased income was caused by higher efficiency of production, as indicated by the greater adoption of higher technology levels relative to the *Current improvement* scenario (Figure 9). Technologies 3, 4 and 5 were applied on more than 50% of the land in the present scenario compared with only 10% of the area in the *Current improvement* scenario. Thus, much less land was needed to produce the targeted level of commodities.

The model selected 38% of the land in fallow during the *kharif* season to maximize income (Figure 10). This is much higher than the proportion of fallow land in the *Current improvement* scenario. The entire fallow land was in the rainfed districts (Figure 11). The increase in area under fallow is mainly because of the operation of the irrigation constraint, which restricts the area under agricultural activities. The model

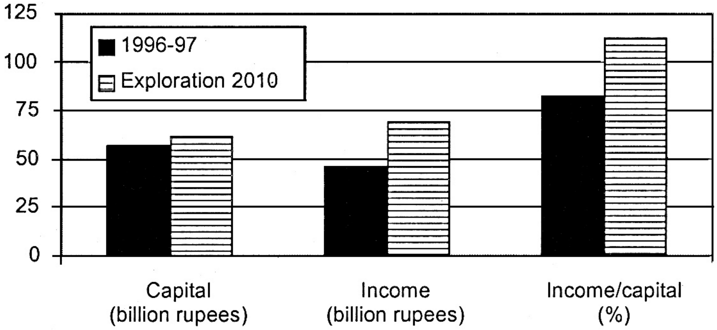

Figure 8. Estimated capital requirement and income generation from agriculture in Haryana in the 1996-97 baseline and in the *Exploration 2010* scenario.

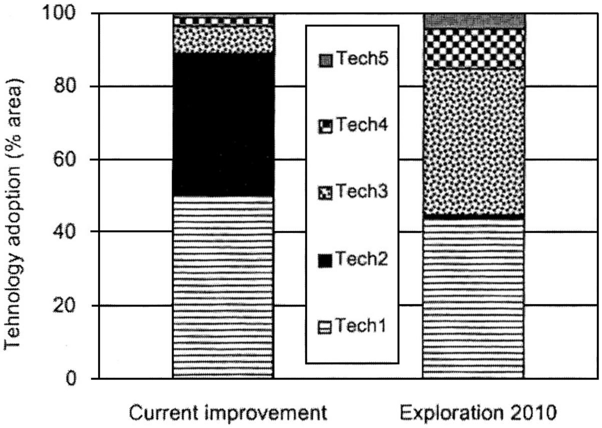

Figure 9. Comparison of adoption of different technologies in the *Current improvement* and *Exploration 2010* scenarios.

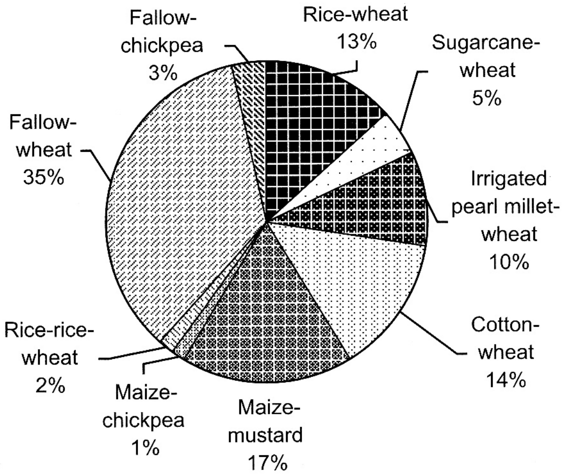

Figure 10. Selected land use (agricultural area under different cropping systems) for maximizing income in the *Exploration 2010* scenario.

allocates water within a land unit to one part of the unit where it is used to produce maximum income through the most efficient cropping system. The remaining un-irrigated area is then allocated to the best option available, which happens to be fallow-wheat in the model.

Pearl millet, selected for rainfed areas in the *Current improvement* scenario, was now allocated to the irrigated land, although the total area under this crop decreased (Table 3). The area under cotton decreased in this scenario relative to the previous one from 23% to 14%, whereas in both situations the areas under sugarcane, rice and maize were similar (Figures 3 and 10). There was a slight increase in area of mustard and chickpea and the region of dominant cultivation also changed (Figures 4 and 11). Maize, which was concentrated in Sonipat District in the Current improvement scenario, was now more common in Jind and Kaithal districts. The entire districts of MohinderGarh and Rewari were selected for fallow during the *kharif* season, whereas, in the preceding scenario, parts of these districts were cultivated with pearl millet. In both scenarios, cotton was selected for cultivation mainly in the districts of Hissar, Sirsa and Jind.

Table 3 shows that all cropping systems are cultivated at higher technology levels in this scenario than in the *Current improvement* scenario. In rainfed regions, only one level of technology was considered in the model. All rice was cultivated at technologies 3, 4 and 5. The rice-rice-wheat cropping system, characterized by the highest water requirement and the highest food production, was mainly cultivated using efficient technologies 4 and 5. Since water was a constraint, water use efficiency was the most important criterion for selecting the production activities to achieve the twin targets of production and income. Similarly, a large part of the sugarcane-wheat and cotton-wheat were also grown at the higher technologies.

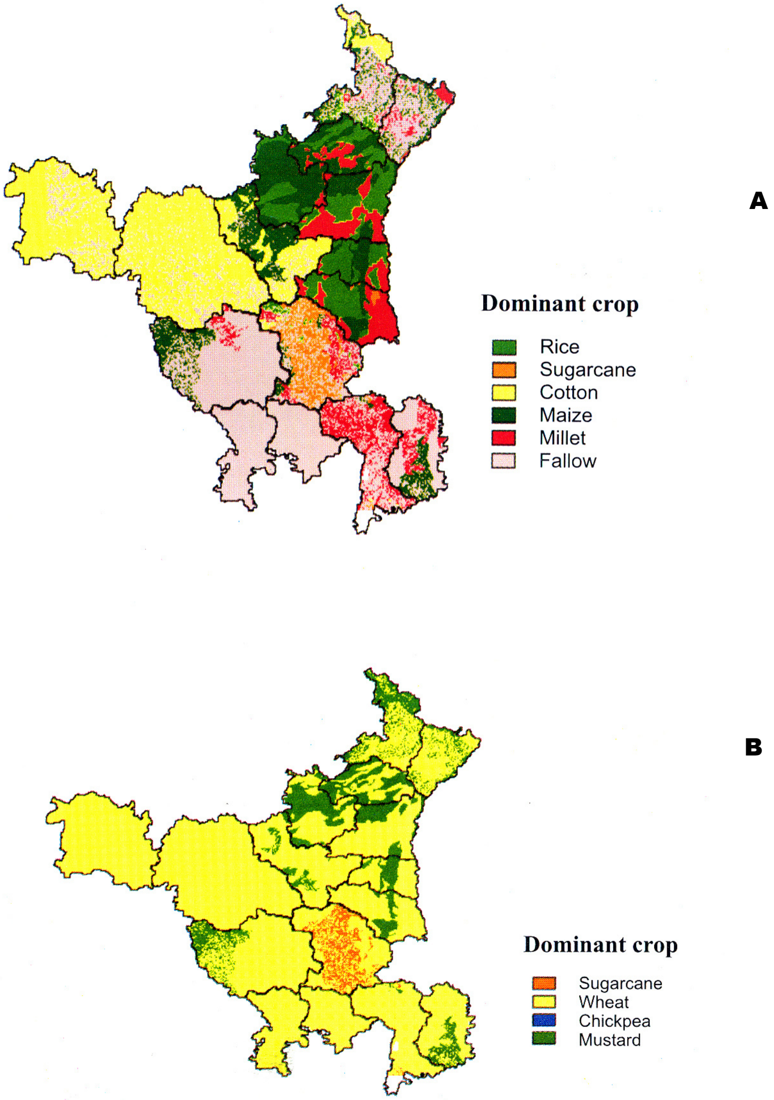

Figure 11. Selected land use (agricultural area under different cropping systems) in (A) *kharif* and (B) *rabi* seasons for maximizing income in the *Exploration 2010* scenario.

Employment

Employment opportunities in this scenario, focusing on maximizing income with increased targets for specific commodities, were one million labour days higher than in the *Current improvement* scenario. This was nevertheless much lower than the 1996-97

Table 3. Selected technologies for various cropping systems for maximizing income in Haryana under the *Exploration 2010* scenario.

	Tech. 1	Tech. 2	Tech. 3	Tech. 4	Tech. 5
Rice-wheat	0.0	0.0	91.7	7.9	0.4
Rice-rice-wheat	0.0	0.0	16.8	25.2	58.0
Rice-mustard	0.0	0.0	100.0	0.0	0.0
Cotton-wheat	2.9	0.0	27.4	49.5	20.3
Maize-mustard	12.9	0.3	86.7	0.1	0.0
Maize-chickpea	0.0	0.0	66.6	31.2	2.2
Sugarcane-wheat	0.0	0.0	39.9	51.5	8.6
Irrigated pearl millet-wheat	28.8	10.8	60.4	0.0	0.0
Fallow-wheat	100.0	0.0	0.0	0.0	0.0
Fallow-chickpea	100.0	0.0	0.0	0.0	0.0

level (Figure 4). The adoption of higher technologies that are more mechanized and the increased fallow area during the *kharif* season were the main causes of this result.

Water

Although water availability increased to 2 1.5 billion cubic metres, its use was still not complete (Figure 5). Similar to the *Current improvement* scenario and the results presented in Chapter 8, use was 85% of the available resources. This was largely because the resources were not available at the right place and/or at the right time. This could also be because primary data on spatial and temporal distribution of water were not available. The increased cover of efficient technologies was also a reason for savings in water use.

Fertilizer

To meet the increased targets of production, fertilizer use increased by 0.17 million t in this scenario relative to 1996-97. The increase in fertilizer use was limited by selecting more efficient technologies. The savings in fertilizer use as a result of the increased fallow area were only modest.

N leaching

The increase in fallow area combined with the increased amount of fertilizer use led to greater N leaching (Figure 6) than in the 1996-97 scenario or in the *Current improvement* scenario. This was 5.2% of the applied N, compared with 4.8% in 1996-97 and 5.8% in the *Current improvement* scenario.

Biocide index

The index was reduced to safe and acceptable limits because of the smaller area under cotton, the largest consumer of biocides (Figure 7). In cotton-dominant Hissar and Sirsa districts, the index was at risky levels.

Conclusions

- This analysis shows that considerable opportunities exist for increasing income from agriculture with the current and projected availability of natural resources in Haryana. In the short term, incomes can be maximized through crop diversification. The model suggested increased maize-mustard cultivation. This was largely the result of the mustard target, which was linked in this analysis to either rice or maize. Rice, having high water requirements, was not selected because its production target was low and because water availability in most districts was a constraint. Since there was no other cropping system with mustard, maize was selected. In practice, income could also be maximized with any other crop in the *kharif* season that is similar to maize in net returns and resource requirements.
- In 2010, all production targets could not be met with the projected availability of resources. However, only a small relaxation in target was needed in any one commodity. This indicates that, with available technologies and resources, the limits to increased food production and income are being reached in Haryana.
- The increased targets of 2010 could be met only by the greater adoption of efficient higher technology levels on a large proportion of land. This would require large-scale availability of machinery for land levelling, tillage and precise placement of seeds and fertilizers at the appropriate depths. The model assumed that such machinery would be available for rent from the market. Agencies willing to make capital investments, needed for the purchase of these implements, would have to be found. Moreover, additional capital would be needed for investment in other farm operations. Greater availability of rural credit would facilitate this.
- Technologies such as conservation tillage have now become available that can reduce the cost of cultivation and increase profits. These were not considered in this study. Similarly, future land reforms such as land consolidation and contract or cooperative farming were not considered. Such options could change the results significantly, because the model now restricts the adoption of higher technologies on small farms. Any land reform that increases the size of operational landholdings or any technology that can increase resource use efficiency on small farms can result in much higher income and food production.
- Both scenarios, exploring options for 2000 and 2010, indicated that an increase in fallow land during *kharif* is a worthwhile option for an overall increase in income of the state. This is encouraging from the point of view that apparently options are available to withdraw a fraction of the land from agriculture without compromising on income or food production. Of course, the model suggested that *rabi* crops be grown on all available land, but it should be feasible to explore options for finding pockets of land that can be spared.
- Increasing income had a trade-off with employment opportunities, which decreased by 4% in both scenarios. Unless off-farm opportunities for employment could be found for these people, this could cause a problem. Alternatively, we would need to examine more labour-intensive and yet profitable technologies.
- To maximize income from agriculture in the future, rational spatial and temporal distribution of groundwater and surface water is much needed. This will concur-

rently increase water use efficiency. A major problem in our analysis is that the data on distribution of irrigation water were available only at the district scale. This forced us to make assumptions on its distribution over space and time. Greater efforts are needed to better characterize the availability of water resources.

- The model did not indicate any serious problem of environmental degradation in terms of N losses or biocide residues at the aggregate scale with the proposed strategies for maximizing income. However, that may become a problem in selected land units. For example, cotton in both scenarios was concentrated in Hissar and Sirsa districts. In these regions, biocide residues were at a risky level. Safer biocides are needed to allow intensive and localized cultivation of crops such as cotton.
- Limitations in the analysis, for example, data quality at the desired scale, consideration of only a limited number of technologies and production techniques, lack of consideration of socioeconomic resources and of the goals of individual households, sharing of resources, including water and capital within a land unit, and absence of linkage of the model to the market, restrict full use of the decision support system. Nevertheless, the framework presented here can be used to generate information at the regional scale on options for agricultural development and on environmental impact. In close consultation with stakeholders, more focused queries and goals of development need to be identified, while improvements are necessary in the projection of future resources and databases for the region and subregions.

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10. Synthesis, conclusions and future studies

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Introduction

Rapid economic expansion and population growth in many Asian countries are increasing demand on land and associated natural resources for agriculture, housing, infrastructure, recreation and industry. The quest for an improved quality of life for humans has challenged the agricultural sector to increase productivity, create more diverse and better quality products and reduce environmental effects. Research and development strategies are needed to support decision making of policymakers to realize the potential of the multiple functions of agriculture and land, considering the potential conflicts in land use objectives among various interest groups (or stakeholders). A recent policy-oriented analytical framework of FAO on the multifunctional character of agriculture and land use builds on the concepts of sustainable agriculture and rural development. It identifies four key functions of agricultural activities and land use: food security and the environmental, economic and social function. The framework emphasizes conservation of land, water, plant and animal genetic resources and environmentally sound and technically appropriate, economically viable and socially acceptable agro-technologies. The big challenge for agricultural research and development is thus to contribute to solutions that best match the multiple development objectives of rural societies (e.g., increased income and employment, improved natural resource quality, food security) with the multiple functions of agricultural land use and production systems.

The concern about the sustainable development of land has led to the development of new concepts in land use planning (FAO, 1995) and eco-regional initiatives (Bouma *et al.,* 1995). A main objective of the latter is the development of a methodology that integrates biophysical and socioeconomic information to enable the design of sustainable land use systems, aimed at increasing food security. Such a methodology should be applicable at various hierarchical levels. The eco-regional approach provides a platform for discussions among scientists of different disciplinary backgrounds and nationalities and among scientists and policymakers and other stakeholders (Rabbinge, 1995).

Haryana State in northwestern India provides a typical example of many Asian regions, characterized at present by conflicts among land use objectives. Notwithstanding recent surpluses of rice and wheat production in the state, there is a continued

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need to increase land productivity, diversification, employment opportunities and agricultural income, and to arrest and preferably reverse the deterioration of agricultural land, a process that gains importance in intensive agricultural regions. There is increasing competition for agricultural land from urbanization, industrial development and recreation. Haryana is thus an appropriate example of the challenge to develop production systems that lead to increased future food security and to solutions that can increase farmers' income.

In this book, elements have been reported of a methodology developed for exploratory land use analysis and applied for generating options for policy and technical changes for food security. The main objective of this research was to develop a decision support system (DSS) that could assist policymakers in examining the consequences of their action or lack of action on food security of the region as a whole, characterized by food production, income, employment and environmental impact assessment. The methodology and its results have been described in detail in the preceding chapters. In this chapter, we review the participatory nature of the decision support system, discuss the strengths and weaknesses of the different elements of the methodology, examine the feasibility of its implementation and finally summarize the major conclusions and opportunities for future work.

Participatory land use planning

There is increasing awareness among researchers and among other stakeholders in the research process that ensuring the impact of research requires participatory approaches (Hoefsloot and Van den Berg, 1998). Too often, such perceptions of the scientists of the needs of stakeholders were inadequate and hence research remained confined to 'laboratories'. Greater efforts are therefore being made all over the world now to involve stakeholders in research and its use right from the beginning.

The development of a DSS for sustainable food security also needed an effort in which stakeholders could define priorities in their information needs so that scientists could better direct their research efforts toward the generation of the desired information. Anyone or rather everyone could be a stakeholder in such an all-encompassing exercise: farmers, deciding what crops to grow; banks and other money-lending agencies, providing credit for specific land use activities; traders, who would like to know the supply of specific commodities; environmental agencies, which would like to monitor the impact of agricultural activities on the environment; and administrative and technical managers at the village, district, state and national levels and politicians. The primary stakeholders for such a regional study were considered to be agricultural and land use officials of the state government, with whom periodic meetings were organized to identify, discuss and quantify possible policy directions.

While it is most desirable to include the entire hierarchy of stakeholders in the planning process, in particular farmers, the ultimate decision makers on land use, that appeared not to be feasible in this study which is subnational in scope, considering that the state consisted of 4.4 million hectares of land area and 1.3 million landholdings. Even a stratified sampling would have required enormous efforts. Interests of farmers' groups were taken into account indirectly, however, by considering the area under different landholdings and their aggregated capital and other resource endowments. Objectives that need to be minimized or maximized were identified through discussions with the various stakeholders and a review of policy documents. The whole process of model development was shared with the stakeholders, who made several suggestions for its improvement. Encouraged by this participatory method, the state government even designated a senior official of its agricultural department as *nodal officer* for the project. This officer ensured that the data available with different departments were made available to the research team. Periodic meetings were organized either at Chandigarh, the state capital, or at IARI, New Delhi, to review progress and plan future courses of action. But for the cooperation of the Department of Agriculture, Haryana, this study would not have been completed.

In the entire process, however, there was no significant direct contact with the farmers – the ultimate decision makers on land use of a region. Greater impact of such explorative studies can only be guaranteed through more explicit consideration of the entire hierarchy of stakeholders to allow simultaneous optimization of their goals and aspirations and integrate these in the ongoing policy process (De Ridder *et al.,* 2000).

The methodology development also involved integration of scientific information from many disciplines. In the study, scientists were involved with disciplinary backgrounds in crop ecology, plant protection, plant physiology, soil sciences, agronomy, remote sensing and geographic information systems (GIS), meteorology, statistics, hydrology and economics. These scientists brought with them the knowledge base of the region and the strengths and constraints of their disciplines. Development of such an inter-disciplinary knowledge base required intensive communication and mutual understanding among the scientists. Thus, in exploring options for future land use, not only scientists and stakeholders have to cooperate but also scientists of different disciplines.

Elements of the methodology used in the DSS

Land use studies can be explorative, defining the envelope of development options, with a focus on ‘what-if' types of questions. The range of options has been referred to as a ‘window of opportunities’ or ‘space of possible solutions’ (Van Latesteijn, 1999). Alternatively, they can be predictive and focus on policies to realize a desired change. These studies therefore emphasize the current situation in terms of the (socio-) economic environment and land use pattern, and consider these as the main constraints to modification.

The study on Haryana was largely explorative, focusing on the opportunities for increasing food production in a sustainable manner. In some scenarios, these exploratory studies were modified to mimic the predictive studies by incorporating current land use patterns, availability of resources and demand for various products now or in the near future.

Options for future land use are explored using knowledge on the biophysical processes underlying crop and livestock production processes, societal objectives of food, income, employment and environmental protection, and exogenous variables affecting the system under study. Multiple goal linear programming (MGLP) has earlier also been used as a tool to integrate these types of information and to generate land use scenarios (De Wit *et al.,* 1988; Van Keulen, 1990). A scenario approach serves to investigate the consequences of combinations of exogenous conditions (such as population growth and demand for agricultural produce) and to evaluate the preferences for objectives (Van Ittersum *et al.,* 1998). Figure 1 summarizes the main elements of the methodology used in the present analysis.

Resource characterization

The biophysical characteristics of land units determine their suitability for agricultural production and are used to decide which crops can be grown in which cropping systems, and how many livestock of a specified type can be supported. Suitability is related to soil and climate characteristics, which determine production and inputs needed for a particular crop, cropping system and livestock. For instance, a specific crop can be grown on many land units, but will produce differentially using different quantities of inputs depending upon the biophysical features of the unit. To obtain realistic estimates of land use options available to stakeholders, it is important that the spatial and temporal variability in the availability of natural and other production resources be quantified satisfactorily at the desired scale. For both explorative and predictive studies, reliable estimates/projections of the availability of current and future resources in different land units are also necessary.

Haryana was chosen as the study area because of the conflicts in various objectives in the state, as well as the extensive database available for the state. Yet, some critical data could not be obtained, which could affect the choice of land use options. For example, detailed data on water resources were not available, although water availability is a key constraint in the region. We had information on only the extent of groundwater available per district per year and the area irrigated from different sources. This

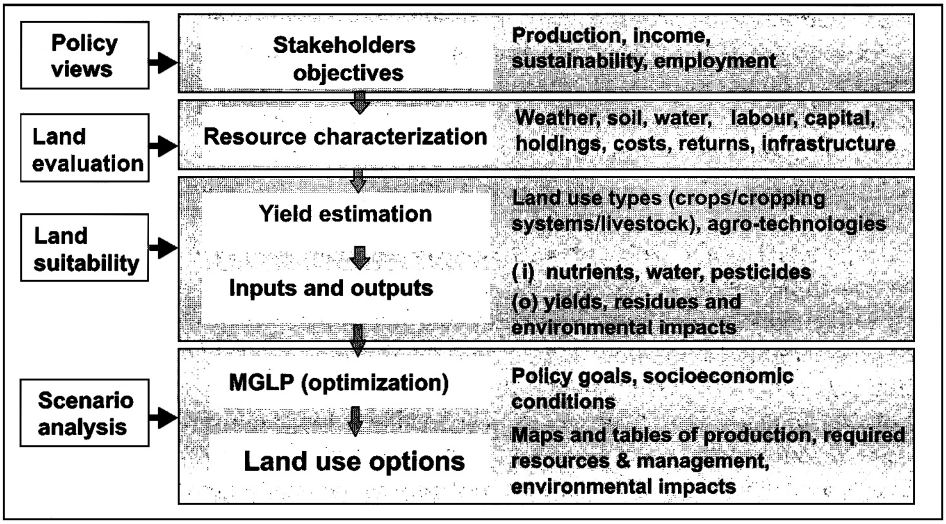

Figure 1. Main elements of the methodology followed in this book.

information was used to estimate total water availability for irrigation (surface water + groundwater) per annum/season/month per land unit. Although this was greatly facilitated by the GIS- and remote sensing-based estimates of irrigated/rainfed areas, more direct quantification of the spatial and temporal distribution of irrigation spread and volume would be very useful for developing implementable strategies for future land use. The situation was similar for capital availability. In the absence of any direct estimates, we had to recalculate the capital resources available for farming based on the current production levels of different crops and livestock in all districts of Haryana, and the associated costs.

We have assumed that all land being cultivated now will remain available for farming even in the future. This may be restricted, however, because of the rapidly increasing urbanization and industrialization of the state. The National Capital Region, which is being carved out of Haryana and other neighbouring states around New Delhi, will take considerable agricultural area out of cultivation, particularly around major cities. Moreover, the present area under forest cover in Haryana is almost negligible. This area needs to be expanded urgently to meet the targets set by the National Forest Policy.

Production activities

Production activities in a linear programming (LP) model represent the cultivation of a crop in a cropping system and/or keeping a particular livestock unit, using a well-defined production technology and in a particular physical environment (land unit). Production activities are characterized by relevant inputs and outputs. In explorative land use studies, a distinction is often made among current, improved and alternative production activities (Van Keulen *et al.,* 2000). Current production activities are technologies as currently practised, irrespective of the question whether inputs are used efficiently andor whether the resource base is maintained. Improved activities are defined as current activities that are improved with respect to one or a few inputs/technologies. Alternative production activities are usually not practised widely at present.

The use of LP in our methodology results in static end-pictures. Many current activities may not be sustainable from an ecological and agricultural point of view because they negatively affect resource quality over time. This time dimension cannot be dealt with in LP.

Although it is desirable to incorporate as many combinations of crops, livestock and production technologies as possible, we have to keep in mind the increasing complexity of the model with every addition and our limited capability to comprehend the ensuing results at that scale. The possible number of combinations of cropping systems and livestock and the degree of suitability of land units are enormous and choices have to be made. For example, we considered only 15 land use types (*luts*) that are currently practised in some parts of the state. Alternate crops such as sunflower, forage crops, pigeonpea, mungbean, vegetables, fruits and flowers were not considered, although they may have considerable potential in the region. Indeed, rice was not always grown in the state at such a scale as now. The introduction of irrigation and modem varieties and a guaranteed purchase of paddy at a remunerative price substantially changed the cropping pattern. Similarly, we have considered only five levels of technologies with one production technique in each case. Conservation tillage and bed planting are gaining momentum in northwestern India (R.K. Gupta, Rice-Wheat Consortium, CIMMYT, personal communication), but these have not been considered. Similarly, we have not considered other techniques such as organic cropping and integrated pest management (IPM), largely to restrict the model size and because increasing food production was taken as the major production orientation for food security. It was our (probably biased) perception that organic technologies will not be practical on a large scale in view of the limited organic matter available in the state. Since the MGLP could not handle a very large matrix, a compromise was needed by restricting the number of land units, of land use types or of technologies. This guided our decision process and what is currently most realistic and plausible, considering that the recent past and the present were evaluated (Van Keulen *et al.,* 2000; De Ridder *et al.,* 2000; Van Ittersum *et al.,* 1998).

Improved and alternative technologies, in terms of high input use and potential production with higher use efficiencies, were also included in our study. Several crops can also be considered as representing a crop type. For example, potato, with its short duration and capital- and chemical-intensive cultivation technology, can be considered representative for many vegetables. Similarly, chickpea represents all types of legume crops. Simulation models were used as a frame of reference (Van Ittersum and Rabbinge, 1997). Considering a broader range of orientations would have created a wider window of opportunities. Our case study appears to take an intermediate position, which permits exploration of only a limited number of land use options. Nevertheless, the results provide sufficient clues to possible generic combinations of *luts* and technologies.

Technical coefficients

The MGLP model requires reliable quantification of the inputs and outputs for different technologies of land use types. Traditionally, such information is obtained from primary field surveys. These data, however, have limitations. They are not specific to the biophysical characteristics of the region, they are based on current activities in a specific year and they cannot be extrapolated to the whole region. Information on aspects such as environmental impact of agro-technologies is not available in such surveys. Current technologies, as practised in a region, generally do not represent the ‘potential’ situation, that is, the production possibilities as dictated by factors that cannot or can hardly be affected by land users, such as radiation and temperature. The technical coefficients of these technologies are difficult to quantify and, in traditional farm surveys, such information is not generally available.

For alternative production techniques that are not currently practised in a region, applying crop growth simulation models can generate technical coefficients. Such models are now available for major crops. We have therefore used the target yield approach, in which technologies and inputs/outputs are calculated for predefined yield levels. To estimate yield potential, we have used several crop growth simulation models originating from different sources and having different structures. Only limited validation was performed for these models in the region. Care was taken, however, to ensure that the simulated potential yields did reflect, in general terms, the measured yield trends in the state. Greater efforts are needed to calibrate and validate crop models to provide technical coefficients at the farm and regional scale.

A technical coefficient generator (TCG) has been developed based on current knowledge of production ecology to generate biophysical input/output tables needed for optimization. This procedure derives economic yields and environmental impacts for current land use types from basic soil and weather characteristics and inputs used. The TCG is linked to the spatial and temporal availability of natural resources. It can therefore be applied to develop a user-friendly generic farm advisory DSS to provide recommendations to a variety of stakeholders on optimal management practices, especially related to water and nutrients, and comparative costs and benefits of various production activities in different regions. Such a DSS is currently being developed at the Indian Agricultural Research Institute.

Although simple in approach and easy to use, this TCG approach does not allow upscaling of critical daily events to seasonal and annual results. This semiempirical approach also has limitations in extending current knowledge to determine input/output relationships for alternative but possible production activities in the future. For that purpose, simple yet robust simulation models are needed.

MGLP

MGLP-type models at the regional level provide a picture of the envelope of land use possibilities, largely determined by biophysical factors. The main determinants are the availability and quality of the natural resources: soil, climate and water, the genetic properties of the crops and animals used in the agricultural production process, and the available technologies. Our results show that, if land were the only constraint, the human carrying capacity' of Haryana would be several times higher than the current level because of the high potential of the state to produce food and the associated potential to generate income and employment with limited environmental impact. For example, the absolute maximum food production potential of the state was estimated at 39.1 million t (10.5 million t was harvested in 1996-97) while keeping the production of other commodities such as cotton and sugarcane at their current level. This biophysical potential may generally not be economically viable and hence has been defined by some as 'paradise', and attempts to realize it would be futile (De Zeeuw and Van der Meer, 1992). However, these results do provide a yardstick against which current achievements can be measured, thus indicating the scope for improvements as the basis for policy formulation and implementation and the extremes of goal achievements, if socioeconomic constraints would (could) be removed (Rabbinge *et al.,* 1994; Van Ittersum *et al.,* 1998).

When the availability of water resources was also considered, attainable levels of

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[1] In this study, human carrying capacity is defined following the definition of Kessler (1994); 'the maximum level of exploitation of renewable resources, imposing limits on a specific type of land use that can be sustained without causing irreversible land degradation within a given area'. As such, it is a measure of (agro-)ecological sustainability.

food production, income and employment potential in the state were very realistic in view of current achievements, indicating that future progress in agriculture in the state is intimately linked to the improvement in water availability and its management. Options are available to increase food production and income at the state level with the current availability of natural resources as was shown in Chapters 8 and 9. Model results also suggest that additional capital investment in Haryana's agriculture might not be rewarding unless water availability is increased.

Feasibility of implementation

Can the results of such exploratory studies ever be implemented in a region, particularly in a region such as Haryana with an area of 4.4 million hectares and 1.3 million landholdings? The ultimate decision as to how land is used rests with the land users – the farmers. Their choice of land use is guided by the basic needs of food for the household, their social responsibilities, the opportunity costs of the land, the availability of off-farm opportunities, temporal requirements/availability of capital, credit and labour, the availability of capital goods such as machinery, seeds, fertilizer, irrigation and biocides, accessibility to markets and expected product prices. Society can, however, guide their decisions on land use by policy measures, for example, by changing the costs of various inputs and outputs through price instruments such as subsidies and levies; through land reforms and rural development, such as by developing roads, increasing/decreasing access to markets and irrigation facilities; and by introducing new technologies (Van Keulen *et al.,* 1998). Developments in other sectors of society that affect farmers' opportunities for interaction with the rest of the world and the political system may also considerably influence farmers' decisions on agricultural land use.

The decision support system presented in the preceding chapters basically captures most of these elements. The illustrations in Chapters 8 and 9, although not considering all aspects because of a lack of data, provided explicit objectives of information needs and quality data at the desired scale and provided valuable outputs. The DSS is not meant to handle the issues of an individual farmer, but rather of a region consisting of a group of farmers. We have illustrated the framework for the whole of Haryana, but the results can be analysed at the smallest biophysical entity – the land unit, which in our analysis varied in size from 18 to 98,000 ha. Though the size of the landholdings and their differential resource base were also considered, the model assumes that the resources available within the land unit are freely accessible anywhere within the unit, irrespective of the farmer. In reality, that is not the case because most resources are individually owned. For example, in the model, the capital base of individual households can be shared among the whole community of farmers in a land unit. This is not an easy task in a democratic set-up. In the model, it is also assumed that groundwater can be physically accessed anywhere in the land unit, irrespective of its physical source within the land unit. In large land units, this may not be feasible. Hence, the opportunities for implementation of this DSS at the individual farmer's level are limited (Van de Ven, 1996). There is therefore an urgent need to incorporate aspects related to household modelling within this approach (Sissoko, 1998).

The DSS, however, provides valuable information to other stakeholders, such as district and state officials responsible for formulating and implementing policy aimed at achieving the overall goals of agricultural development in the state. We must remember that the DSS provides an exploratory land use analysis and that more specific information on targets, constraints and refined databases is needed before its results can provide information of immediate use. Some of the limitations of the DSS, even at this level, such as the absence of linkage with the market, consumption of agricultural products and the time dimension, are important constraints to the full exploitation of the DSS for sustainable food security planning. There will be a large capital requirement to finance the equipment needed for implementing capital-intensive technologies, such as technologies 4 and 5 in this study. This also needs to be considered in future analyses.

At the same time, we must evaluate how policy decisions are made today and whether the impact of policy is considered for the complete chain of stakeholders. In other words, do current policy decisions follow a bottom-up approach or a top-down approach and are they scale-neutral? Experience suggests that most policies in any sector have some bias, even if not explicitly or implicitly intended. Let us examine, for example, the impact of the Green Revolution that brought food security to South Asia in the 1960s. The technology was particularly successful in regions such as Punjab State in India, which were well endowed and capable of absorbing the high-yielding technology. Within a region as well, large farmers, having more capital and other resources, benefitted more from the government policy of subsidies and remunerative prices than the small farmers (Conway and Barbier, 1990). And yet, the technology ensured overall food security for several densely populated regions of the world. Hence, the Green Revolution may not have been a panacea for all problems, but it has definitely contributed appreciably to solving some of the most pressing problems (Evans, 1998; Pinstrup-Anderson and Hazell, 1985). Considering this, the decision support system is a step forward, as it allows examining the impact of policies, not only on the region as a whole but also on different types of farms and subregions considering their resource endowments (Kruseman, 2000). It considers not only food production but also other aspects of food security such as income, employment and environmental impact.

Another major objection that can be raised with respect to the proposed methodology is the lack of validation. As a rule, optimization results cannot be validated (WRR, 1992). It would be desirable, however, to develop a DSS for smaller spatial entities, such as a village, where its recommendations could be evaluated vis-à-vis the current practices before large-scale implementation would be attempted. That could also increase confidence in this approach.

Future studies

Description of production activities (technologies)

Analysis of the possibilities for regional development as a tool for identifying the scope for improvement and attainment of various objectives strongly hinges on an accurate quantitative description of agricultural production technologies. Our methodology needs to include a wide spectrum of alternative production activities that may become feasible in the future. For such alternative production techniques, available simulation models for major crops can adequately generate technical coefficients. Well-validated simulation models are not (yet) available for most perennial crops or for mixed cropping systems, common in many farming systems with low external inputs. Similarly, tools are needed to better quantify livestock, fishery, poultry and piggery activities in the analysis. This lack of quantitative tools for generating accurate technical coefficients of alternative production technologies seriously hampers their inclusion in land use analysis.

Spatial analysis

This DSS methodology operates at the regional level and resource availability and quality are defined at that level, for example, the total area of land of a certain quality, the total quantity of irrigation water and the total labour force. However, the spatial distribution of these resources is of major importance for the way in which they are being, and can be, used. This holds for both physical characteristics (i.e., the spatial distribution of the water resources determines to what extent they can be used for various purposes) and socioeconomic characteristics (i.e., the distance to markets, in absolute terms or in terms of transport possibilities, determines to what extent a certain commodity is economically attractive). The larger the distance, the higher the transportation costs, and hence the more difficult the marketing of a commodity. For some commodities, such as fresh milk or vegetables, distance may even be a prohibitive constraint.

First attempts to introduce the spatial dimension in models for land use analysis have been made, but only partially. Especially for the effective targeting of policy measures, this lack of spatial differentiation is a serious limitation.

Linkage with the market

A major limitation of the current methodology is its static nature. It does not consider the impact that over- or underproduction could have on the prices of a commodity and hence on the returns of the production enterprise. Consequently, it shows very high incomes proportional with increased production in most situations.

Assessing environmental impact

Quantifying the sustainability of the food production system was a major goal of the DSS. The model quantifies the amount of water used and hence its possible effects on groundwater levels, NO_3-leaching losses and biocide residue indices as indicators of the sustainability of different land use systems. However, the impact of production systems when practised continuously for several years on sustainability, including changes in water table depth, is not yet quantified. Modelling approaches should be developed to quantify such effects at the regional scale. Similarly, costs of environmental impacts have not been quantified at all.

Integrating regional analysis and farm household analysis

The ultimate decision makers on land use are farm households, and the possibilities to affect land use therefore depend on the criteria used by the farm households in these decisions and their response to policy measures. The regional land use analysis can illustrate the (bio)physical potentials of natural resources, but is not intended to identify the (major) socioeconomic constraints to modifying land use at the farm household level. For that purpose, the regional analysis has to be integrated with farm household analysis that incorporates farmers' behaviour. Again, developments in this direction have started (Sissoko, 1998), but a much more systematic analysis is necessary, one that yields a methodology in which results of regional models can be used to identify boundary conditions and/or objectives for farm household models (FHMs). Results from FHMs, such as production andor price elasticities, in turn, should provide the revised scenario settings for subsequent regional analysis.

Such integration is also hampered by the typical methodology applied in socioeconomic analysis, which is based on identifying of so-called farm types distinguished by economic characteristics. Regional analysis on the basis of upscaling of farm household results typically suffers from aggregation bias because non-linear relations play a major role in the process. Such biases could be minimized when, similar to the biophysical data, which have a long tradition in being geo-referenced, socioeconomic information would also be presented, incorporating its spatial dimension (Mohamed, 1999).

Uncertainty analysis

The scope for agricultural development is determined, in addition to the long-term possibilities and constraints, by the risks associated with uncertainty. This uncertainty plays a role in both the biophysical factors (weather cannot be predicted and the more erratic the weather pattern in a region, the larger the uncertainty) and economic factors (in most situations, producers are price-takers that have no influence on the market price of their commodities). In addition, in subsistence farming systems, which have only weak links with the market economy, food security is a major consideration, and that will lead to risk-averse behaviour, which may effectively constrain the possibilities for increased production at higher risks. In explorative land use analyses, this uncertainty should therefore be incorporated.

Interaction with stakeholders

In developing tools for land use analysis, the biggest challenge is probably their implementation in the 'practice' of land use planning and policy analysis. That requires close cooperation with the various stakeholders, in which it is important that the models be designed in such a way that answers are generated to questions relevant to the stakeholders. Moreover, the stakeholders need to develop confidence in the tools being applied. No generally accepted and proven 'package' of procedures is available to stimulate, maintain and institutionalize that process. At the same time, it is also important that stakeholders more objectively and explicitly specify their needs. Often, stakeholders appear more concerned with the management and policy decisions of today, so that future planning does not get proper attention.

In conclusion, we now have a decision support system that is appropriate for exploring opportunities for a sustainable increase in food security in a region. It can also be used to explore options to increase the efficiency of resource use, considering the current availability of natural and capital resources. The strength of the methodology is the link between biophysical and socioeconomic characteristics in analysing possibilities for and constraints to different crop and livestock production systems. This allows us to examine the various interrelationships and to explore options that are 'real' and feasible at least at the regional level. The inclusion of capabilities to consider feedback of market conditions on production and income, environmental costs and the time dimension for sustainability quantification would make this DSS a valuable tool in the future to evaluate the relationships of food production, income, employment and environment with regional (agricultural) policies.

Uncertainties associated with this bio-economic framework and their possible effect on policy formulation and implementation can be considered a limitation. Although efforts are definitely needed to improve precision (and these are being made), we must at the same time realize that our current decision-making processes are also characterized by several limitations: the lack of consideration of impact on all stakeholders, inadequate understanding and lack of appropriate data. In most current agri-policy decisions, biophysical characterization and suitability of a technology to land characteristics are not considered. And yet, policy decisions are made. In that respect, this framework is a step forward. The decision support system can assist planners in rapidly evaluating ex ante the consequences of their proposed policy actions on agricultural and food security aspects of different regions. With current emphasis on sustainable ecoregional development and the free market economy, efficiency in decision making and in comprehending the impact of global changes on regions becomes increasingly important. Raising food production per se may not be the key question in the future; rather, economic, social and environmental costs associated with different levels and modes of production are increasingly becoming important elements in the decision-making process. Explicit consideration of these elements and their possible trade-offs requires a knowledge base of several disciplines of agricultural research, as well as continuous interaction with stakeholders. The decision support system presented here is a powerful tool that can accelerate knowledge integration and its use for agricultural development and agri-wealth creation. There is a need to strengthen research programs involving biologists, social scientists, economists and stakeholders to alleviate the limitations of the current methodologies. A nested modelling approach, using iterative bottom-up and top-down communication between farms and the region, would be most desirable. Simultaneously, user-friendly interface programs should be developed to facilitate the direct use of the DSS by the various stakeholders (cf. Laborte *et al.,* 2000).

For Haryana, the DSS was able to identify opportunities for increasing food production in the near future, considering different constraints and the possible effects on income, employment and environmental quality indicators. The carrying capacity of Haryana with its current and projected availability and quality of resources is considerably higher than the current population density. Brown and Kane (1994) reported that India would need to import food on a large scale in the coming years. Considering the potential of small states such as Haryana, where yield gaps are smaller (Aggarwal, 2000), such projections of imports of food appear doubtful at least. Realizing these potentials, however, would require some decisions to optimize resource use. The distribution of water, capital and infrastructure in space and time does not support optimal land use. Improvement of resource management, especially water management, is needed. However, to fully solve the conflicts among all objectives, other supporting policy measures would also be needed. When the DSS has been expanded to overcome its current limitations, and data at the desired scale become available, the stakeholders' needs for an instrument to rapidly explore the effects of policy on food security in a changing world economic environment could be satisfied. Analyses, such as performed in this report for Haryana, need to be continuously updated as more and more accurate data become available, insights into interactions between biology and economics increase and newer tools become available (cf. Struif Bontkes, 1999). Among other uses, this DSS could also be used to define extrapolation domains of research recommendations for impact assessment of climate change and for yield gap analysis.

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