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Options to Enhance the Impact of AKST on Development and Sustainability Goals

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Key Messages

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1. Many of the challenges facing agriculture over the next 50 years will be able to be resolved by smarter and more targeted application of existing AKST. But new science and innovation will be needed to respond to both intractable and changing challenges. These challenges include climate change, land degradation, availability of water, energy use, changing patterns of pests and diseases as well as addressing the needs of the poor, filling the yield gap, access to AKST, pro-poor international cooperation and entrepreneurialism within the "localization" pathway.

2. Smarter and more targeted application of existing best practice AKST will be critical to achieving development and sustainability goals. It is essential to build on the competences and developments in a wide range of sectors to have the maximum impact. The greatest scope for improvements exists in small-scale diversified production systems.

3. The challenges are complex, so AKST must be integrated with place-based and context relevant factors to address the multiple functions of agriculture. A demand-led approach to AKST needs to integrate the expertise from a range of stakeholders, including farmers, to develop solutions that simultaneously increase productivity, protect natural resources including those on which agriculture is based, and minimize agriculture's negative impact on the environment. New knowledge and technology from sectors such as tourism, communication, energy, and health care, can enhance the capacity of agriculture to contribute to the development and sustainability goals. Given their diverse needs and resources, farmers will need a choice of options to respond to the challenges, and to address the increasing complexity of stresses under which they operate. There are opportunities to enhance local and indigenous self-sufficiency where communities can engage in the development and deployment of appropriate AKST.

4. Advances in AKST, such as biotechnology, nanotechnology, remote sensing, precision agriculture, information communication technologies, and better understanding and use of agroecological processes and synergies have the potential to transform our approaches in addressing development and sustainability goals, but will need to be inclusive of a wide variety of approaches in order to meet sustainability and development goals. The widespread application of these breakthroughs will depend on resolving concerns of access, affordability, relevance, biosafety, and the policies (investment and incentive systems) adopted by individual countries. There will be new genotypes of crops, livestock, fish, and trees to facilitate adaptation to a wider range of habitats and biotic and abiotic conditions. This will bring new yield levels, enhance nutritional quality of food, produce non-traditional products, and complement new production systems. New approaches for crop management and farming systems will develop alongside breakthroughs in science and technology. Both current and new technologies will play a crucial role in response to the challenges of hunger, micronutrient deficiencies, productivity, and environmental protection, including optimal soil and water quality, carbon sequestration, and biodiversity. Ecological approaches to food production also have the potential to address inequities created by current industrial agriculture.

5. Transgenic approaches may continue to make significant contributions in the long term, but substantial increases in public confidence in safety assessments must be addressed. Conflicts over the free use of genetic resources must be resolved, and the complex legal environment in which transgenes are central elements of contention needs further consideration.

6. AKST can play a proactive role in responding to the challenge of climate change and mitigating and adapting to climate-related production risks. Climate change influences and is influenced by agricultural systems. The negative impacts of climate variability and projected climate change will predominately occur in low-income countries. AKST can be harnessed to mitigate GHG emissions from agriculture and to increase carbon sinks and enhance adaptation of agricultural systems to climate change impacts. Development of new AKST could reduce the reliance of agriculture and the food chain on fossil fuels for agrochemicals, machinery, transport, and distribution. Emerging research on energy efficiency and alternative energy sources for agriculture will have multiple benefits for sustainability.

7. Reconfiguration of agricultural systems, including integration of ecological concepts, and new AKST are needed to address emerging disease threats. The number of emerging plant, animal, and human diseases will increase in future. Multiple drivers, such as climate change, intensification of crop and livestock systems, and expansion of international trade will accelerate the emergence process. The increase in infectious diseases (HIV/AIDS, malaria, etc.) as well as other emerging ones will challenge sustainable development and economic growth, and it will ultimately affect both high and low-income countries.

8. Improving water use in agriculture to adapt to water scarcity, provide global food security, maintain ecosystems and provide sustainable livelihoods for the rural poor is possible through a series of integrated approaches. Opportunities exist through AKST to increase water productivity by reducing unproductive losses of water at field and basin scales, and through breeding and soil and crop management. The poor can be targeted for increased benefit from the available water through systems that are designed to support the multiple livelihood uses of water, and demand led governance arrangements that secure equitable access to water. Economic water scarcity can be alleviated through target water resources development that includes socioeconomic options ranging from large to small scale, for communities and individuals. Allocation policies can be developed with stakeholders to take into account whole basin water needs. Integration of food production with other ecosystem services in multifunctional systems helps to achieve multiple goals, for example, integrated rice/

aquaculture systems or integrated crop/livestock systems. While the greatest potential increases in yields and water productivity are in rainfed areas in developing countries, where many of the world's poorest rural people live, equally important is improved management of large dams and irrigation systems to maintain aquatic ecosystems.

9. The potential benefits and risks of bioenergy are strongly dependent on particular local circumstances. Research is needed on better understanding these effects and improving technologies. Expansion of biofuel production from agricultural crops (1st generation) may in certain cases promote incomes and job creation, but negative effects on poverty (e.g., rising food prices, marginalization of small-scale farmers) and the environment (e.g., water depletion, deforestation) may outweigh these benefits and thus need to be carefully assessed. Small-scale biofuels and bio-oils could offer livelihood opportunities, especially in remote regions and countries where high transport costs impede agricultural trade and energy imports. There is also considerable potential for expanding the use of digesters (e.g., from livestock manure), gasifiers and direct combustion devices to generate electricity, especially in off-grid areas and in cogeneration mode on site of biomass wastes generating industries (e.g., rice, sugar and paper mills). The next generation of liquid biofuels (cellulosic ethanol and biomass-to-liquids technologies) holds promise to mitigate many of the concerns about 1st generation biofuels but it is not clear when these technologies may become commercially available. Moreover, considerable capital costs, large economies of scale, a high degree of technological sophistication and intellectual property rights issues make it unlikely that these technologies will be adopted widely in many developing countries in the next decades. Research and investments are needed to accelerate the development of these technologies and explore their potential and risks in developing countries.

6.1 Improving Productivity and Sustainability of Crop Systems

6.1.1 Small-scale, diversified farming systems

Considerable potential exists to improve livelihoods and reduce the environmental impacts of farming by applying existing AKST in smarter ways to optimize cropping and livestock systems, especially in developing countries.

Small-scale diversified farming is responsible for the lion's share of agriculture globally. While productivity increases may be achieved faster in high input, large scale, specialized farming systems, greatest scope for improving livelihood and equity exist in small-scale, diversified production systems in developing countries. This small-scale farming sector is highly dynamic, and has been responding readily to changes in natural and socioeconomic circumstances through shifts in their production portfolio, and specifically to increased demand by increasing aggregate farm output (Toumlin and Guèye, 2003).

Small-scale farmers maximize return on land, make efficient decisions, innovate continuously and cause less damage to the environment than large farms (Ashley and Maxwell, 2001). Yet they have lower labor productivity and are less efficient in procuring inputs and in marketing, especially in the face of new requirements regarding produce quality. Land productivity of small-scale farms was found to be considerably higher than in large ones in a comparison across six low-income countries (IFAD, 2001).

AKST investments in small-scale, diversified farming have the potential to address poverty and equity (especially if emphasis is put on income-generation, value-adding and participation in value chains), improve nutrition (both in terms of quantity and quality through a diversified production portfolio) and conserve agrobiodiversity. In small-scale farming, AKST can build on rich local knowledge. Understanding the agroecology of these systems will be key to optimizing them. The challenges will be to: (1) to come up with innovations that are both economically viable and ecologically sustainable (that conserve the natural resource base of agricultural and non-agricultural ecosystems); (2) develop affordable approaches that integrate local, farmer-based innovation systems with formal research; (3) respond to social changes such as the feminization of agriculture and the reduction of the agricultural work force in general by pandemics and the exodus of the young with the profound implications for decision making and labor availability. Small-scale farming is increasingly becoming a part-time activity, as households diversify into off-farm activities (Ashley and Maxwell, 2001) and AKST will be more efficient, if this is taken into account when developing technologies and strategies for this target group.

6.1.1.1 Research options for improved productivity

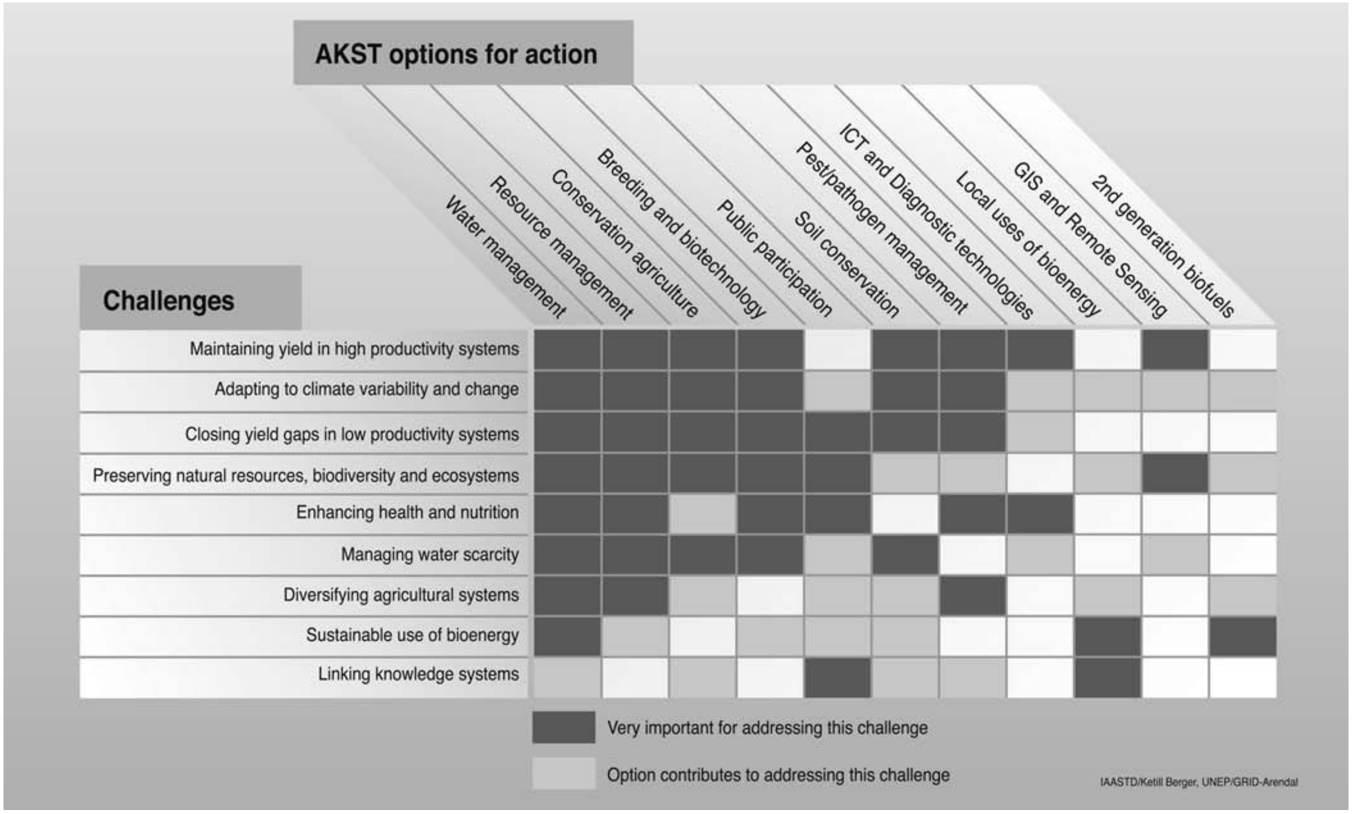
To solve the complex, interlinked problems of small farmers in diverse circumstances, researchers will have to make each time a conscious effort to develop a range of options. There will be hardly any "one-size-fits-all" solutions (Franzel et al., 2004; Stoop and Hart, 2006). It is questionable if AKST will have the capacity to respond to the multiple needs of small-scale diversified farming systems (Table 6-1, 6-2).

AKST options that combine short-term productivity benefits for farmers with long-term preservation of the resource base for agriculture (Douthwaite et al., 2002; Welches and Cherrett, 2002) are likely to be most successful. In small-scale, diversified farming systems, suitable technologies are typically highly site-specific (Stoop and Hart, 2006) and systems improvements need to be developed locally, in response to diverse contexts.

Integrated, multifactor innovations. In the past, a distinction was made between stepwise improvements of individual elements of farming systems and "new farming systems design". Stepwise improvement has had more impact (Mettrick, 1993), as it can easily build on local knowledge. Recently, successful innovations of a more complex nature were developed, often by farming communities or with strong involvement of farmers. Examples include success cases of Integrated Pest Management (see 6.4.3) as well alternative ways of land management such as the herbicide-based no-till systems of South America (Ekboir, 2003), the mechanized chop-and-mulch system in Brazil (Denich et al., 2004) or the Quesungual slash-and-mulch systems in Honduras (FAO, 2005).

In the future, research addressing single problems will probably become less relevant, as the respective opportuni-

Table 6-1. **Key Relationships between Future Challenges and Agricultural Knowledge, Science and Tecnology (AKST) Options for Action**



ties for simple, one-factor improvements have been widely exploited already. It will be more promising to develop innovations that address several factors simultaneously (as in the above examples) and which will therefore be more context and site specific and more information-intensive.

This will require a change of emphasis in research for farming system optimization. Research needs to develop decision support tools that assist extension workers and farmers in optimizing specific farm enterprises. Such tools already exist for farm economics, site-specific nutrient management, crop protection and land use planning. Integrative approaches such as RISE (Response Inducing Sustainability Evaluation) (Häni et al., 2003), which combine economic, social and ecological aspects, aim at assessing and improving sustainability at the farm level.

Two-thirds of the rural poor make their living in less favored areas (IFAD, 2001). They will continue to depend on agriculture. Returns on investment in AKST may be limited in these areas due to their inherent disadvantages (remoteness, low-fertility soils, climatic risks) and the highly diverse systems (Maxwell et al., 2001). On the other hand, the impact of innovations on poverty, equity and environmental health may be substantial. Recent examples show that improvements are possible in less favored areas, both for simple technological changes (e.g., more productive crop varieties) as well as for more complex innovations (e.g., the mucuna cover crop system or the slash-and-mulch system in Honduras).

Sustainable alternatives to shifting cultivation. Shifting cultivation was the most widespread form of land use in the tropics and subtropics, but over the past decades, a transition occurred to managed fallows or continuous cropping with crop rotation in densely populated areas. Alternatives to slash-and-burn clearing have been developed, which better conserve the organic matter accumulated during the fallow periods. Managed fallows and sound rotations may enhance soil fertility regeneration and even produce additional benefits. This allows for extending cropping periods and reducing fallow periods without compromising sustainability. The resulting "offshoots" of shifting cultivation raise a number of issues to be addressed by AKST. Firstly, it will be important to understand the transition process, its drivers and the newly emerging problems in order to assist farmers. Secondly, for targeted up-scaling of local experiences, it will be crucial to examine the potentials and limitations of different offshoots of shifting cultivation (Franzel et al., 2004).

In less favored areas, low external input agriculture is the rule, as in these circumstances the use of mineral fertilizers and pesticides is risky and only profitable in selected cases (e.g., in high value crops). Most of the successful innovations developed for these areas built strongly on local knowledge.

Due to the site specificity of these innovations, transfer to other unfavorable environments has worked only to a very limited extent (Stoop et al., 2002). The challenge for

Table 6-2. **AKST options for addressing main challenges with related AKST gaps and needs.**

AKST potential to address challenge	AKST gaps and needs: Technology and knowledge	AKST gaps and needs: Capacity building, policies, and investments	Regional applicability
Preserving and maintaining natural resources and ecosystems			
Minimize the negative impacts of agriculture expansion on ecosystem services (6.3.1.1, 6.1.1.1).	Trade-offs analysis to assess dynamic relations between the provision of ecosystem and economic services in conflicting areas. Develop biotechnologies to reduce impacts	Training of researchers, technicians, land administrators and policy makers for the application of trade-offs analytical tools, and adoption of improved crop plants.	LAC (B)
Design of multifunctional agricultural landscapes that preserve and strength a sustainable flow of ecosystem services (6.7.5.2).	Configure systems to resemble structural and functional attributes of natural ecosystems	Enhance local capacities to develop land use strategies and policies to maximize the supply of essential ecosystem services.	LAC, SSA, tropical Asia (B)
Enhance the geographical spread of multifunctional agricultural systems and landscapes (6.7.5.2.1).	Typify the ecological service supplier as a new category of rural producer.	Implementation of public recognition and payment systems for ecological service suppliers that provide demonstrable services to society.	All regions
Creation of more conservation management areas (6.3.1.1)	Research designed to optimize productivity of the small/subsistence farmer. Incentives for in situ conservation	Promote transboundary initiatives and legislation	All regions
Sustainable management of fisheries and aquaculture (6.5)	Improved knowledge of contributions of capture and cultured fisheries to food and nutrition, food security and livelihoods	Promote alternative strategy for meeting the increasing demands for fish products Promote improved fish technology	All regions
Environmental management of dams to reduce impact on aquatic ecosystems (6.6.3)	Environmentally sound management of dams		All regions
Basin water management (6.6.3.2)	Basin management tools Benefit sharing tools for negotiation	Policies for effective water allocation	All regions
Improving water management			
Improve water productivity by reducing evaporative losses (6.6.3.1)	Biotechnologies including genetics and physiology B,C		Semiarid areas (A)
Restore existing irrigation systems (6.6.3.1)	Environmentally sound management of irrigation systems	Investment in irrigation	S and SE Asia, Central Asia, China (A); SSA (B)
Increase sustainable use of groundwater (6.6.3.2)	Hydrologic process understanding for sustainable use of groundwater		S. Asia, China (A) SSA (B)
Precision irrigation, deficit irrigation (6.6.3.1)	Technologies for use of low quality water in precision irrigation	Policies for secure access to water and for effective water allocation	NAE, MENA (A) S&SEAsia, SSA (B)
Rain water harvesting, supplemental and small scale irrigation for rainfed agriculture (6.6.3)	Affordable small scale technologies for rain water harvesting and water management	Investment in water management for rain-fed systems	S.Asia, SSA (A)
Integrated soil water and soil fertility management (6.4.2.1)			S. Asia, SSA (A)

continued

Table 6-2. **continued**

AKST potential to address challenge	AKST gaps and needs: Technology and knowledge	AKST gaps and needs: Capacity building, policies, and investments	Regional applicability
Multiple water use systems, domestic and productive uses, crops/livestock/ fisheries (6.4.2.2)	Institutional and design requirements for MUS systems	Policy that promotes sector integration	All regions
Basin water management (6.4.2.2)	Basin management tools Benefit sharing tools for negotiation	Policies for effective water allocation	All regions
Linking knowledge systems			
Promote local uses of biodiversity (6.1.2; 6.8.1.2)	Mobilize and promote indigenous technologies and innovation systems, and resolve intellectual property issues.	Education, training and dissemination, extension; international coordination of IPR systems.	All regions
Enhance participatory approaches for natural resource management (6.7.5.1)	Merge farmer-based and region-specific innovation systems with formal research Improved collaborative NRM for rare species (CITES) Formal and indigenous mapping tools for monitoring of fragmented biodiversity	Gender mainstreaming Scientific and digital divide Education, training and extension, equity, transboundary initiatives and collaborations	All regions
Increase participatory research that merges indigenous and Western science (farmer field schools, seed fairs) (6.6.1; 6.7.5.1)	Develop affordable technologies that integrate local, farmer-based innovation systems with formal research	Promotion of grassroot extension, transboundary collaborations	All regions
Promote underutilized crops (6.6.1)	Develop approaches that integrate local knowledge systems with formal research	IPR, biopiracy, information and dissemination	All regions
Enhancing health and nutrition			
Detection, surveillance, and response to emerging diseases (6.7.3) Better surveillance of zoonotic diseases Early disease warning systems Integrated vector and pest management Environmental management of dams to reduce vector-borne disease	Improve understanding of disease transmission dynamics More rapid and accurate diagnostic tools Improved vaccines Develop faster genomic-based methods for diagnostics and surveillance	Public health infrastructure and health care systems Better integration of human and veterinary health	SSA, S. and SE Asia (B)
Biofortification of crop germplasm (6.2; 6.7.1; 6.7.2)	Cost effective and efficient screening methods for breeding and introducing multi-gene traits Incorporate multiple nutrient traits	Public sector financing and work force Biosafety protocol Public sector investment	SSA, S. and SE Asia (A, B)
Multiple water use systems, domestic and productive uses, crops/livestock/ fisheries (6.6.3)	Institutional and design requirements for MUS systems, such as Rice+Fish program; rice livestock programs	Policy that promotes sector integration; Enhance incentives for breeders	All regions
Closing yield gaps in low productivity systems			
Improve practices for root health management (6.1.3)	Genomics-based diagnostic tools for understanding root disease dynamics	Bolster S&T capacity in pest management	All regions
Conventional Breeding/rDNA assisted (6.3.1.1; 6.8.1.1)	Incorprate traits that confer stable performance like weed competitiveness, resistance to pest & diseases & tolerance to abiotic stresses	IPTGR Plant Variety Protection Public sector investment	All regions (A, B)
Transgenics (GM) (6.3)	Develop biosafety testing methodologies. Incorporate genes conferring stable performance	Biosafety protocol Public sector investment	All regions (A, B)
Improve the performance of livestock in pastoral and semi-pastoral subsistence communities. (6.2)	Enhance nutrient cycling	Improve access to grazing and water-endowed areas for nomadic and semi-nomadic communities	SSA (A, B)

Table 6-2. **continued**

AKST potential to address challenge	AKST gaps and needs: Technology and knowledge	AKST gaps and needs: Capacity building, policies, and investments	Regional applicability
Rain water harvesting, supplemental and small scale irrigation for rainfed systems (6.8.1.2)	Affordable small scale technologies for rain water harvesting and water management	Investment in water management for rainfed systems	SAsia, SSA (A)
Integrate soil water and soil fertility management (6.6.2.2; 6.6.3.3)	Enhance crop residue return to bolster soil organic matter levels, seed treatment of fertilizer with improved rainwater capture		SAsia, SSA (A)
Multiple water use systems, domestic and productive uses, crops/livestock/ fisheries (6.6.3.2)	Institutional and design requirements for MUS systems	Policy that promotes sector integration	All regions
Maintaining yields in high productivity systems			
Conventional Breeding/rDNA assisted (6.3.1.1)	Develop varieties with higher yield potential	IPTGR; Plant Variety Protection Reinvest in plant breeding professionals	All regions
Transgenics (GM) (6.3.1.2)	Incorporate yield enhancing traits Appropriateness to small holder systems	Biosafety protocol; Public sector investment IPR issues to resolve	All regions
Soil nutrient management to reduce pollution (6.6.2.1)	Wider adoption of precision agriculture technologies	Regulations and law enforcement in developing countries	All regions
Improve performance in intensive livestock systems (6.2)	Application of production methods and techniques to optimize the use of inputs.		All regions with livestock systems
Enhance livestock productivity through use of biotechnology, genomics and transgenics for breeding (6.3.2)	Enhance capacities for gene identification and mapping, gene cloning, DNA sequencing, gene expression.		All regions
Restore existing irrigation systems (6.6.3.1)	Environmentally sound management of irrigation systems	Investment in irrigation	SE Asia, S. Asia, Central Asia, China (A); SSA (B)
Increase sustainable use of groundwater (6.6.3.2)	Hydrologic process understanding for sustainable use of groundwater		S. Asia, China (A) SSA (B)
Improve sustainability of protected cultivation (6.1.1.1)	Low-cost multifunctional films Ecologically sound management for greenhouses	Internalize externalities	NAE, Mediterranean (A) LAC, SSA (B)
Precision irrigation, deficit irrigation (6.6.3.1)	Technologies for use of low quality water in precision irrigation	Policies for secure access to water and for effective water allocation	NAE, MENA (A) S. and SE Asia, SSA (B)
Adaptation to and mitigation of climate change			
Broader adoption of soil conserving practices to reduced projected increase in soil erosion with climate change (6.8.1.1)	Prioritization of soil erosion 'hotspots'	Enhance land tenure security Strengthen conservation allotment policies.	All regions, esp. in mountainous develop. countries
Conventional breeding and biotechnology to enhance abiotic stress tolerance (6.3.1.1; 6.2; 6.8.1.1) Genetic and agronomic improvement of underutilized crops (6.8.1.1)	Change crop types; agroecosystem zone matching; Identify genes needed for GM	Biosafety protocol Public sector investment	All regions

Table 6-2. **continued**

AKST potential to address challenge	AKST gaps and needs: Technology and knowledge	AKST gaps and needs: Capacity building, policies, and investments	Regional applicability
Increase water productivity to bridge dry spells (6.8.1.2) Small-scale development of drip irrigation, treadle pumps (6.6.3.3)	Broader promotion of supplemental irrigation, soil nutrient management, improved crop establishment practices.	Policies for secure access to water Investment in risk reduction strategies	SSA, S. Asia, MENA (A)
Storage: rain water harvesting, small scale, large scale (6.6.3; 6.8.1.2)	Environmentally sound construction and management of large dams Decision support for scale of storage that is environmentally and socially sound	Enhance land tenure security Water rights and access	SSA, S. Asia (A)
Reduce agricultural GHG emissions (6.8.1.1)	Aerobic rice production (CH_4 and N_2O) Site specific nutrient management (N_2O) Animal feed improvement (CH_4 and N_2O) Expand land-based C sequestration potential	Transitional costs associated with land management changes Capacity building for outreach and extension	All regions
Sustainable use of bioenergy			
Production and use bioenergy to promote rural development (6.8.2)	Promote R&D for small-scale biodiesel and unrefined bio-oils for local use to improve energy access in local communities	Capacity building, promote access to finance	SSA, S. and SE Asia, LAC
	Promote R&D to reduce costs and improve operational stability of biogas (digesters), producer gas systems and co-generation applications	Develop demonstration projects, product standards and disseminate knowledge	All regions
Improvements in the environmental and economic sustainability of liquid biofuels for transport (6.8.2.1)	Promote R&D for 2nd generation biofuels focusing on reducing costs to make them competitive. Conduct research on environmental effects of different production pathways.	Facilitate the involvement of small-scale farmers in 2nd generation biofuels/feedstock production and low-income countries, e.g., by developing smallholder schemes, improving access to information and dealing with IPR	High-income regions (B) Low-income regions (C)

Key: A = AKST exists, B = AKST emerging, C = AKST gaps

Source: Authors' elaboration.

AKST will be to find ways for combining local knowledge with innovations developed in similar other contexts to generate locally adapted new options. The question development agents will have to address is, under which circumstances they may scale up innovations *per se* and when they should focus on scaling-up innovation *processes* (Franzel et al., 2004). In the scaling-up process, it will be crucial that research and extension act in a careful, empirical and critical way (Tripp, 2006). If wide dissemination of innovations that were successful in a certain context is attempted, this may create exaggerated expectations and hence frustration, if these innovations are not adapted in many other contexts. This happened for example with alley cropping (Carter, 1995; Akyeampong and Hitimana, 1996; Swinkels and Franzel, 2000; Radersma et al., 2004) or the system of rice intensification (SRI) developed in Madagascar (Stoop et al., 2002). Agricultural research and extension still largely works with technologies that rely strongly on external inputs, even in less favored areas (Stoop, 2002).

Potential for innovation in low external input agriculture is highest if research focuses on understanding and building on local concepts of farming such as the exploitation of within-farm variation, or intercropping. However, if research and extension work with technologies that rely strongly on external inputs, farmers will seldom adopt the results (Stoop, 2002). A further challenge is the dissemination, as farmer-to-farmer diffusion is less important than commonly assumed for such innovations (Tripp, 2006).

Low External Input Sustainable Agriculture (LEISA) comprises organic farming. Organic farming and conventional (non-labeled) LEISA can mutually benefit from each other. Organic farming with its stringent rules on external input use has to be even more innovative to solve production problems, sometimes opening up new avenues. Organic farming has the additional opportunity of deriving benefits from close links between producers and consumers. The challenge, however, is to exploit this potential.

New low external input technologies have the potential to improve productivity while conserving the natural resource base, but there is no evidence that they are specifically pro-poor (Tripp, 2006). An important concern in low external input farming is soil nutrient depletion. Across

Africa, nutrient depletion is widespread, with average annual rates of 22 kg N, 2.5 kg P and 15 kg K per ha of arable land (Stoorvogel and Smaling, 1990). Low external input technologies aiming at soil fertility improvement can seldom reduce these rates (Onduru et al., 2006).

Protected cultivation systems. Protected cultivation of high value crops has expanded rapidly in the past decades (Castilla et al., 2004), especially in the Mediterranean basin (Box 6-1). At present, however, greenhouse production with limited climate control is ecologically unsustainable as it produces plastic waste and contaminates water due to intensive use of pesticides and fertilizers. Demand for innovation thus exists with regard to reducing environmental impact, as well as enhancing productivity, product quality and diversity.

Scope exists to develop affordable plastic films that improve radiation transmission quantitatively and qualitatively. Multilayer, long-life, thermal polyethylene films can combine desirable characteristics of various materials such as anti-drop and anti-dust effects. Photoselective films have the potential to influence disease and insect pest behavior by blocking certain bands of the solar radiation spectrum (Papadakis et al., 2000) or to limit solar heating without reducing light transmission (Verlodt and Vershaeren, 2000). Protected cultivation has its own, specific pest and disease populations as well as specific challenges related climate and substrate. Plant breeding for these specific conditions has the potential to reduce significantly the amount of pollutants released, while improving productivity. Grafting vegetables to resistant rootstocks is a promising option to control soil-borne pathogens (Oda, 1999; Bletsos, 2005; Edelstein and Ben-Hur, 2006) and may help to address salt and low temperature stress (Edelstein, 2004), but needs further research to improve rootstocks. Pest and disease control with the use of antagonists has developed quickly in protected cultures in Northern Europe and Spain (Van Lenteren, 2000, 2003). There are many site and crop specific possibilities for further development of non-chemical pest control for protected cultivation.

Production in low-cost greenhouses has the potential to increase productivity and income generation, to improve water use efficiency and reduce pollution of the environment. Variability in climatic and socioeconomic conditions will require the development of location-specific solutions.

Box 6-1. Advantages of the Mediterranean glasshouse system.

The Mediterranean greenhouse agrosystem represents greenhouse production in mild winter climate areas and is characterized by low technological and energy inputs. Strong dependence of the greenhouse microclimate on external conditions (La Malfa and Leonardi, 2001) limits yield potential, product quality, and the timing of production. It keeps production costs low as compared to the Northern European greenhouse industry. The latter is based on sophisticated structures, with high technological inputs that require important investments, and produces higher yields at higher costs (Castilla et al., 2004).

Post-harvest loss. Although reduction of post-harvest losses has been an important focus of AKST and development programs in the past, in many cases the technical innovations faced sociocultural or socioeconomic problems such as low profit margins, additional workload or incompatibility with the existing production or post-production system (Bell, 1999). The divergence between technical recommendations and the realities of rural life translated in many cases into low adoption rates.

In specific cases, large shares of food produced are lost after harvest. Yet, the rationale for improvements in the post-harvest systems has been shifting from loss prevention (Kader, 2005) to opening new markets opportunities (Hellin and Higman, 2005). Making markets work for the poor (Ferrand et al., 2004) is emerging as the new rationale of development, reflecting a shift away from governmental operation of post-harvest tasks to enabling frameworks for private sector initiatives in this field (Bell et al., 1999).

Ecological agricultural systems, which are low external input systems that rely on natural and renewable processes, have the potential to improve environmental and social sustainability while maintaining or increasing levels of food production. There is now increasing evidence of the productive potential of ecological agriculture (Pretty, 1999; Pretty, 2003; Pretty et al., 2006; Badgley et al., 2007; Magdoff, 2007).

Some contemporary studies also show the potential of ecological agriculture to promote environmental services such as biodiversity enhancement, carbon sequestration, soil and water protection, and landscape preservation (Culliney and Pimentel, 1986; Altieri, 1987; Altieri, 1999; Altieri, 2002; Albrecht and Kandji, 2003).

There is now substantial scientific evidence to show that designing and managing agricultural systems based on the characteristics of the original ecosystem is not a threat to food security. A survey of more than 200 projects from Latin America, Africa, and Asia, all of which addressed the issue of sustainable land use, found a general increase in food production and agricultural sustainability (Pretty et al., 2003). Likewise, low external input crop systems, when properly managed, have demonstrated the potential to increase agricultural yield with less impact on the environment (Bunch, 1999; Tiffen and Bunch, 2002; Rasul and Thapa, 2004; Pimentel et al., 2005; Badgley et al., 2007; Scialabba, 2007). A recent investigation comparing organic with conventional farming experiences from different parts of the world indicates that sustainable agriculture can produce enough food for the present global population and, eventually an even larger population, without increasing the area spared for agriculture (Pretty et al., 2003; Badgley et al., 2007).

In spite of the advantages of ecological agriculture in combining poverty reduction, environmental enhancement and food production, few studies address the issues of how to assess the tradeoffs (Scoones, 1998). Tradeoff analysis to assess dynamic relations between the provision of ecosystem and economic services can help to harmonize land use options and prevent potential conflict regarding the access to essential ecosystem services (Viglizzo and Frank, 2006).

Methods are focused on the identification of tradeoffs and critical thresholds between the value of economic and ecological services in response to different typologies of human intervention.

In the same way, the concept of ecological agriculture needs a better understanding of the relationship among the multiple dimensions of rural development, i.e., agricultural productivity, environmental services, and livelihood. Such questions are still open for further elaboration and pose a challenge to AKST (Buck et al., 2004; Jackson et al., 2007).

6.1.1.2 Land use options for enhancing productivity

Productivity of farming systems can be enhanced by more intensive use of space or time. Intercropping (including relay intercropping and agroforestry) is a traditional form of such intensification, widespread in food production in low-income countries, especially in less favored areas. Growing several crops or intercrops in sequence within a year offers the possibility to intensify land use in time. This intensification was made possible by changes in the crops and varieties grown (day-length-neutral or short-season varieties; varieties tolerant to adverse climatic conditions at the beginning or the end of the growing season) or in land management (no-till farming, direct seeding, etc.). On the other hand, farmers quickly change to simpler cropping systems, if economic prospects are promising (Abdoellah et al., 2006).

The development of new elements (crops or crop varieties, pest and land management options), which farmers then integrate according to a multitude of criteria into their farm systems will continue to enhance productivity. Similarly, agroforestry initiatives will be most successful, where research concentrates on developing a range of options with farmers (Franzel et al., 2004).

Intercropping has the potential to increase return to land by investing (usually) more labor. The challenge for AKST will be to strike a balance between (1) understanding the interactions in highly complex intercropping and agroforestry systems (including learning from and with farmers) and (2) developing options that farmers may add to their systems. Adding new elements may offer potential for farmers to participate in value chains and enhance income generation while ensuring subsistence. There exists considerable potential for AKST to develop germplasm of agroforestry species with commercial value (Franzel et al., 2004).

AKST has contributed substantially to intensification in time, especially in high potential areas. However, double or triple cropping in rice or rice-wheat production created new challenges on the most fertile soils (Timsina and Connor, 2001). In spite of such drawbacks, there is promise for further intensifying land use in time by optimizing rotation management and developing novel varieties that can cope with adverse conditions.

Mixed farming. In many low-income countries, integration of crop and livestock has advanced substantially for the past few decades. In densely populated areas, mixed farming systems have evolved, where virtually all agricultural by-products are transformed by animals (Toumlin and Guèye, 2003). With the demand for livestock products expected to surge in most low-income countries, potential for income generation exists. A major challenge for AKST will be to understand the tradeoffs between residue use for livestock or soil fertility and to optimize nutrient cycling in mixed systems.

Improve sustainability through multifunctional agriculture and ecosystem services. Ecosystem services are the conditions and processes through which natural ecosystems sustain and fulfill human life (Daily, 1997) and can be classified in four utilitarian functional groups: (1) provisioning (e.g., food, freshwater), (2) regulating (e.g., climate and disturb regulation), (3) cultural (e.g., recreation, aesthetic) and (4) supporting (e.g., soil formation, nutrient cycling) (MA, 2005). Given that many ecosystem services are literally irreplaceable, estimations of socioeconomic benefits and costs of agriculture should incorporate the value of ecosystem services (Costanza et al., 1997). Because of the rapid expansion of agriculture on natural lands (woodlands, grasslands) and the trend to use more external inputs (Hails, 2002; Tilman et al., 2002), the negative impact of agriculture on ecosystem services supply will require increasing attention (Rounsevell et al., 2005).

The construction of multifunctional agroecosystems can preserve and strengthen a sustainable flow of ecosystem services (Vereijken, 2002). They are best modeled after the structural and functional attributes of natural ecosystems (Costanza et al., 1997). Multifunctional agroecosystems will provide food and fiber, control disturbances (e.g., flood prevention), supply freshwater (filtration and storage), protect soil (erosion control), cycle nutrients, treat inorganic and organic wastes, pollinate plants (through insects, birds and bats), control pests and diseases, provide habitat (refugium and nursery), provide aesthetic and recreational opportunities (camping, fishing, etc.) and culture (artistic and spiritual). The evaluation of ecosystem services is an evolving discipline that currently has methodological shortcomings. However, methods are improving and site-specific valuation will be possible in the coming years. The application of tradeoff analysis to support the design of multifunctional rural landscapes will demand expertise on multicriteria analysis and participatory approaches.

Frequently recommended measures (Wayne, 1987; Viglizzo and Roberto, 1998) for addressing multifunctional needs include (1) diversification of farming activities in time and space rotational schemes, (2) the incorporation of agroforestry options, (3) conservation/rehabilitation of habitat for wildlife, (4) conservation/management of local water resources, (5) the enforcement of natural nutrient flows and cycles (exploiting biological fixation and bio-fertilizers), (6) the incorporation of perennial crop species, (7) the well-balanced use of external inputs (fertilizers and pesticides), (8) the application of conservation tillage, (9) biological control of pests and diseases, (10) integrated management of pests, (11) conservation and utilization of wild and underutilized species, (12) small-scale aquaculture, (13) rainfall water harvesting.

6.1.2 Achieving sustainable pest and disease management

Agricultural pests (insect herbivores, pathogens, and weeds) will continue to reduce productivity, cause post-harvest losses and threaten the economic viability of agricultural livelihoods. New pest invasions, and the exacerbation of existing pest problems, are likely to increase with future climate change. Warmer winters will lead to an expansion of insect and pathogen over wintering ranges (Garrett et al., 2006); this process is already under way for some plant pathogens (Rosenzweig et al., 2001; Baker et al., 2004). Within existing over winter ranges, elevation of pest damage following warm winters is expected to intensify with climate change (Gan, 2004; Gutierrez et al., 2006; Yamamura et al., 2006). Increased temperatures are also likely to facilitate range expansion of highly damaging weeds, which are currently limited by cool temperatures, such as species of *Cyperus* (Terry, 2001) and *Striga* (Vasey et al., 2005).

Several current AKST strategies for managing agricultural pests could become less effective in the face of climate change, thus potentially reducing the flexibility for future pest management in the areas of host genetic resistance, biological control, cultural practices, and pesticide use (Patterson, 1999; Strand, 2000; Stacey, 2003; Bailey, 2004; Ziska and George, 2004; Garrett et al., 2006). For example, loss of durable host resistance can be triggered by deactivation of resistance genes with high temperatures, and by host exposure to a greater number of infection cycles, such as would occur with longer growing seasons under climate change (Strand, 2000; Garrett et al., 2006). Recent evidence from CO_2-enrichment studies indicates that weeds can be significantly more responsive to elevated CO_2 than crops, and that weeds allocate more growth to root and rhizome than to shoot (Ziska et al., 2004). This shift in biomass allocation strategies could dilute the future effectiveness of post-emergence herbicides (Ziska and George, 2004; Ziska and Goins, 2006). Elevated CO_2 is also projected to favor the activity of *Striga* and other parasitic plant species (Phoenix and Press, 2005), which currently cause high yield losses in African cereal systems.

In addition to range expansion from climate change, the future increase in the trans-global movement of people and traded goods is likely to accelerate the introduction of invasive alien species (IAS) into agroecosystems, forests, and aquatic bodies. The economic burden of IAS is US$300 billion per year, including secondary environmental hazards associated with their control, and loss of ecosystem services resulting from displacement of endemic species (Pimentel et al., 2000; GISP, 2004; McNeely, 2006). The costs associated with invasive species damage, in terms of agricultural GDP, can be double or triple in low-income compared with high-income countries (Perrings, 2005).

6.1.2.1 Diversification for pest resistance

To enhance the effectiveness of agroecosystem genetic diversity for pest management, some options include shifting the focus of breeding towards the development of multi- rather than single-gene resistance mechanisms. Other options include pyramiding of resistance genes where multiple minor or major genes are stacked, expanding the use of varietal mixtures, and reducing selection pressure through diversification of agroecosystems.

Multigene resistance, achieved through the deployment of several minor genes with additive effects rather than a single major gene, could become an important strategy where highly virulent races of common plant diseases emerge, as in the case of the Ug99 race of wheat stem rust for which major gene resistance has become ineffective (CIMMYT, 2005). Integration of genomic tools, such as marker-assisted selection (MAS) to identify gene(s) of interest, will be an important element of future resistance breeding. Future breeding efforts will need to include greater farmer involvement for successful uptake and dissemination, e.g., farmer-assisted breeding programs where farmers work with research and extension to develop locally acceptable new varieties (Gyawali et al., 2007; Joshi et al., 2007). Better development of seed networks will be needed to improve local access to quality seed.

Gene pyramiding (or "stacking") has the potential to become a future strategy for broadening the range of pests controlled by single transgenic lines. For example, expressing two different insect toxins simultaneously in a single plant may slow or halt the evolution of insects that are resistant, because resistance to two different toxins would have to evolve simultaneously (Gould, 1998; Bates et al., 2005). Though the probability of this is low, it still occurs in a small number of generations (Gould, 1998); the long-term effectiveness of this technology is presently not clear. The use of gene pyramiding also runs the risk of selecting for primary or secondary pest populations with resistance to multiple genes when pyramiding resistance genes to target a primary pest or pathogen (Manyangarirwa et al., 2006). Gene flow from stacked plants can accelerate any undesirable effects of gene flow from single trait transgenic plants. This could result in faster evolution of weeds or plants with negative effects on biodiversity or human health, depending on the traits (as reviewed by Heinemann, 2007). Finally, mixtures of transgenes increase the complexity of predicting unintended effects relevant to food safety and potential environmental effects (Kuiper et al., 2001; Heinemann, 2007).

Varietal mixtures, in which several varieties of the same species are grown together, is a well-established practice, particularly in small-scale risk-adverse production systems (Smithson and Lenne, 1996). While this practice generally does not maximize pest control, it can be more sustainable than many allopathic methods as it does not place high selection pressure on pests, and it provides yield stability in the face of both biotic and abiotic stresses. For example, varietal mixtures could play an important role in enhancing the durability of resistance for white-fly transmitted viruses on cassava (Thresh and Cooper, 2005). Research on varietal mixtures has been largely neglected; more research is needed to identify appropriate mixtures in terms of both pest resistance and agronomic characteristics, and to backcross sources of pest and disease resistance into local and introduced germplasm (Smithson and Lenne, 1996).

In addition to varietal mixtures, future AKST could enhance the use of cropping system diversification for pest control through supporting and expanding, where appropriate and feasible, practices such as intercropping, mixed cropping, retention of beneficial noncrop plants, crop rotation, and improved fallow, and to understand the mechanisms of pest control achieved by these practices. The underlying principal of using biodiversity for pest control is to reduce the concentration of the primary host and to create conditions that increase natural enemy populations (Altieri, 2002). The process of designing systems to achieve multiple functions is knowledge intensive and often location specific. An important challenge for AKST will be to better elucidate underlying pest suppression mechanisms in diverse systems, such as through understanding how pest community genetics influence functional diversity (Clements et al., 2004). An equally important task will be to preserve local and traditional knowledge in diverse agroecosystems.

6.1.2.2 Tools for detection, prediction, and tracking

AKST can contribute to development through the enhancement of capacity to predict and track the emergence of new pest threats. Some recent advances are discussed below.

Advances in remote sensing. Applications include linking remote sensing, pest predictive models, and GIS (Strand, 2000; Carruthers, 2003), and coupling wind dispersal and crop models to track wind-dispersed spores and insects (Kuparinen, 2006; Pan et al., 2006). Recent advances in remote sensing have increased the utility of this technology for detecting crop damage from abiotic and biotic causal factors, thus remote sensing has good prospect for future integration with GIS and pest models. The spread of these technologies to low-income countries will likely to continue to be impeded by high equipment costs and lack of training. The further development and dissemination of low-cost thermocyclers for PCR (polymerase chain reaction) techniques could help to address this need. In general, a lack of training and poor facilities throughout most of the developing countries hinders the ability to keep up with, let alone address, new pest threats.

Advances in molecular-based tools. Emerging tools such as diagnostic arrays will help to better identify the emergence of new pest problems, and to differentiate pathovars, biovars, and races and monitor their movement in the landscape (Garrett et al., 2006). Using molecular methods for pathogen identification has excellent potential in high-income countries.

Advances in modeling pest dynamics. Recent progress in developing new mathematical approaches for modeling uncertainties and nonlinear thresholds, and for integrating pest and climate models, are providing insights into potential pest-host dynamics under climate change (Bourgeois et al., 2004; Garrett et al., 2006). Increased computational power is likely to facilitate advances in modeling techniques for understanding the effects of climate change on pests. However, the predictive capacity of these models could continue, as it currently is, to be hampered by scale limitations of data generated by growth chamber and field plot experiments, inadequate information concerning pest geographical range, and poor understanding of how temperature and CO_2 interactions affect pest-host dynamics (Hoover and Newman, 2004; Scherm, 2004; Chakaborty, 2005; Zvereva and Kozlov, 2006). Greater focus on addressing these limitations is needed. Improved modeling capacity is needed for understanding how extreme climate events trigger pest and disease outbreaks (Fuhrer, 2003). Modeling pests of tropical agriculture will likely have the greatest impact on helping AKST to address food security challenges, as these regions will be most negatively affected by climate change. This will require a substantial investment in training, education, and capacity development.

Prevention of invasive alien species. The invasive alien species issue is complex in that an introduced organism can be a noxious invasive in one context yet a desirable addition (at least initially) in another (McNeely, 2006). International assistance programs (development projects, food aid for disaster relief, and military assistance) are an important means through which IAS are introduced into terrestrial and freshwater systems, as in the case of fast growing agroforestry trees, aquaculture species, and weed seed-contaminated grain shipments (Murphy and Cheesman, 2006). Addressing this problem will require much more detailed information on the extent of the problem, as well as greater understanding of vectors and pathways. Raising awareness in the international aid community, such as through toolkits developed by the Global Invasive Species Program (GISP, 2004) are an important first step, as are prerelease risk assessments for species planned for deliberate release (Murphy and Cheesman, 2006).

More rigorous risk assessment methods are needed to determine the pest potential of accidentally introduced organisms and those intentionally introduced, such as for food and timber production, biological control, or soil stabilization. Elements needed to build risk assessment capacity include broad access to scientific literature about introduced species, access to advanced modeling software and processing time, improved expertise for determining risks related to invasive characteristics, and development of public awareness campaigns to prevent introduction (GISP, 2004).

Early detection of invasive alien species. The capacity to survey for introduction of nonnative species of concern could be enhanced. Where resources for conducting surveys are limited, surveys can prioritize towards species known to be invasive and that have a high likelihood of introduction at high risk entry points, or areas with high value biodiversity (GISP, 2004). Develop contingency planning for economically important IAS.

Management of invasive alien species. Current mechanical, chemical and biological control methods are likely to continue to be important in the future. In the case of biological control, the use of plant pathogens as natural enemies is emerging as an alternative or complement to classical biological control using arthropods, and it is being piloted in tropical Asia for controlling the highly damaging weed, *Mikania micrantha* (Ellison et al., 2005). Additionally, new and emerging genomic tools could aid IAS management, particularly for preventing the conversion of crops into weeds (Al-Ahmad et al., 2006).

Basic quantitative data on the impacts and scale of the IAS problem is still lacking in many developing countries (Ellison et al., 2005). Gaining greater knowledge of the extent of the problem will require better cross-sectoral linkages, such as between institutions that serve agriculture, natural resource management, and environmental protection.

Risk assessment for entry, establishment, and spread is a newly developing area for IAS (GISP, 2004). For example, Australia recently instituted a weed risk assessment system based on a questionnaire scoring method to determine the weed inducing potential of introduced organisms. Risk assessment is only one tool of many, and will likely have limited utility given that the number of potentially invasive species far outstrips the ability to assess the risk of each one, and high-income countries are better equipped to conduct risk assessments than low-income ones. Full eradication is generally quite difficult to achieve, and requires a significant commitment of resources. Therefore prioritization of IAS management by potential impacts, such as to those that alter fundamental ecosystem processes, and to value of habitats is an important starting point.

6.1.3 Plant root health

The ability to address yield stagnation and declining factor productivity in long-term cropping systems will depend on efforts to better manage root pests and diseases primarily caused by plant-parasitic nematodes and plant-pathogenic fungi (Luc et al., 2005; McDonald and Nicol, 2005). Soil-borne pests and diseases are often difficult to control because symptoms can be hard to diagnose and management options are limited, such as with plant-parasitic nematodes. Nematodes prevent good root system establishment and function, and their damage can diminish crop tolerance to abiotic stress such as seasonal dry spells and heat waves, and competitiveness to weeds (Abawi and Chen, 1998; Nicol and Ortiz-Monasterio, 2004). With future temperature increase, crops that are grown near their upper thermal limit in areas with high nematode pressure, such as in some cereal systems of South and Central Asia (Padgham et al., 2004; McDonald and Nicol, 2005), could become increasingly susceptible to yield loss from nematodes. Approaches for managing soil-borne pests and diseases are changing due to increasing pressure (commercial and environmental) for farmers to move away from conventional broad-spectrum soil fumigants, and greater recognition of the potential to achieve biological root disease suppression through practices that improve overall soil health.

6.1.3.1 Low input options

Soil solarization, heating the surface 5-10 cm of soil by applying a tightly sealed plastic cover, can be a highly effective means of improving root health through killing or immobilizing soilborne pests, enhancing subsequent crop root colonization by plant-growth promoting bacteria, and increasing plant-available nitrogen (Chen et al., 1991). Biofumigation of soils is achieved by the generation of isothiocynate compounds, which are secondary metabolites released from the degradation of fresh *Brassica* residues in soil. They have a similar mode of action as metamsodium, a common synthetic replacement of methyl bromide, and have been used to control a range of soilborne fungal pathogens including *Rhizoctonia, Sclerotinia,* and *Verticillium* (Matthiessen and Kirkegaard, 2006). For many plant parasitic nematodes, significant control is often achieved when solarization is combined with biofumigation (Guerrero et al., 2006).

Soil solarization is an environmentally sustainable alternative to soil fumigation, though its application is limited to high value crops in hot sunny environments (Stapleton et al., 2000), Soil solarization of nursery seedbeds is an important but underutilized application of this technology, particularly for transplanted crops in the developing world, where farmers contend with high densities of soilborne pests and have few if any control measures. Solarization of rice seedbed soil, which is commonly infested with plant parasitic nematodes, can improve rice productivity in underperforming rice-wheat rotation areas of South Asia (Banu et al., 2005; Duxbury and Lauren, 2006). This technique has potential for broader application, such as in transplanted vegetable crops in resource-poor settings. Biofumigation using isothiocynate-producing *Brassicas* has reasonably good potential for replacing synthetic soil fumigants, especially when combined with solarization. Commercial use of biofumigation is occurring on a limited scale. However, there are significant hurdles to the broad-scale adoption of *Brassica* green manures for biofumigation related to its highly variable biological activity under field conditions compared with *in vitro* tests, and to the logistical considerations involved with fitting *Brassicas* into different cropping systems and growing environments (Matthiessen and Kirkegaard, 2006). The repeated use of chemical replacements for methyl bromide and biofumigation can lead to a shift in soil microbial communities. This shift can result in enhanced microbial biodegradation of the control agent, diminishing its effectiveness (Matthiessen and Kirkegaard, 2006).

6.1.3.2 Research needs and options

Biological control. Future nematode biocontrol could be made more effective through shifting the focus from controlling the parasite in soil to one of targeting parasite life stages in the host. This could be accomplished through the use of biological enhancement of seeds and transplants with arbuscular mycorrhiza, endophytic bacteria and fungi, and plant-health promoting rhizobacteria, combined with improved delivery systems using liquid and solid-state fermentation (Sikora and Fernandez, 2005; Sikora et al., 2005). Better biocontrol potential for both nematodes and fungi could also be achieved through linking biocontrol research with molecular biology to understand how colonization by beneficial mutualists affects gene signaling pathways related to induced systemic resistance in the host (Pieterse et al., 2001).

Disease suppression. Understanding the link between cultural practices that enhance soil health (crop rotation, conservation tillage, etc.) and the phenomena of soil disease suppressiveness would aid in developing alternative approaches to chemical soil fumigation, and could enhance appreciation of local and traditional approaches to managing soilborne diseases. Soil health indicators are needed that are specifically associated with soilborne disease suppression (van Bruggen and Termorshuizen, 2003; Janvier et al., 2007). Given the complex nature of soils, this would necessitate using a holistic, systems approach to develop indicators that could be tested across different soil types and cropping systems. Advances in genomics and molecular biology could aid in developing such indicators. Advances in the application of polymerase chain reaction (PCR)-based molecular methods of soil DNA may enable greater understanding of functional diversity, and relationships between soil microbial communities and root disease suppression linked to soil properties and changes in crop management practices (Alabouvette et al., 2004).

The loss of broad-spectrum biocides, namely methyl bromide, has created opportunities for investigating new directions in managing root diseases. Synthetic substitutes, such as chloropicrin and metam sodium, are generally less effective than methyl bromide, can cause increased germination of nutsedge and others weeds (Martin, 2003), and pose substantial health risks to farm workers and adjacent communities (MMWR, 2004).

Biocontrol of soilborne pests and pathogens will likely continue to succeed on the experimental level, and yet still have only limited impact on field-based commercial applications of biocontrol until impediments to scaling up biocontrol are addressed. These include the exceedingly high costs of registration, and lack of private sector investment (Fravel, 2005). The recent success in scaling up nematode biocontrol using a nonpathogenic strain of *Fusarium oxysporum* to control the highly destructive *Radopholus similis*, causal agent of banana toppling disease (Sikora and Pokasangree, 2004), illustrate how the alignment of multiple factors—a very effective biocontrol agent, a highly visible disease problem with significant economic impact, and substantial private-sector investment—was necessary to allow for development of a potential commercial product.

Long-term and stable organic production systems generally have less severe root disease problems than conventionally managed systems; however, the specific mechanisms that lead to soilborne disease suppression remain poorly understood (van Bruggen and Termorshuizen, 2003). Given that soilborne pests and disease play a role in the productivity dip associated with the transition from conventional to organic production, greater attention towards developing indicators of root disease suppression would help to better address development and sustainability goals.

6.1.4 Value chains, market development

Although reduction of post-harvest losses has been an important focus of AKST and development programs in the past, in many cases the technical innovations faced sociocultural or socioeconomic problems such as low profit margins, additional workload or incompatibility with the existing production or postproduction system (Bell et al., 1999). The divergence between technical recommendations and the realities of rural life translated in many cases into low adoption rates.

In specific cases, large shares of food produced are lost after harvest. Yet, the rationale for improvements in the postharvest systems has been shifting from loss prevention (Kader, 2005) to opening new markets opportunities (Hellin and Higman, 2005). Making markets work for the poor (Ferrand et al., 2004) is emerging as the new rationale of development, reflecting a shift away from governmental operation of postharvest tasks to enabling frameworks for private sector initiatives in this field (Bell et al., 1999).

Research and capacity development needs. Increasing attention is being placed on value and market-chain analysis, upgrading and innovation. Processing, transport and marketing of agricultural products are increasingly seen as a vertical integration process from producers to retailers, to reduce transaction costs and improve food quality and safety (Chowdhuri et al., 2005).

In *market-chain analysis,* some of the challenges include improving small-scale farmer competitiveness and farmers' organizations (Biénabe and Sautier, 2005); institutional capacity building (especially access to information) (Kydd, 2002); and the reinforcement of links and trust among actors in the market chain (Best et al., 2005).

Demand driven production asks for improved market literacy of producers as a prerequisite for access to supermarkets, a challenge especially for small-scale farmers (Reardon et al, 2004; Hellin et al., 2005). Building trust among the stakeholders in the market chain is a crucial component of vertical integration (Best et al., 2005; Chowdhury et al., 2005; Giuliani, 2007). It enhances transparency of the market chain and exchange of information. Typically, actors in the market chains are at first skeptical about information sharing; when they realize that all can benefit from more transparency along the market chain they more readily provide information. Maximizing added value at farm or village level is a promising option for small-scale farmers; rural agroenterprises and household level processing can increase income generation (Best et al., 2005; Giuliani, 2007).

The creation of community-based organizations or farmers groups can result in economies of scale. Collectively, small-scale farmers are able to pool their resources and market as a group, hence reducing transaction costs (Keizer et al., 2007). It can improve their access to resources such as inputs, credit, training, transport and information, increase bargaining power (Bosc et al., 2002) and facilitate certification and labeling.

Better market access is often a key concern of small-scale farmers (Bernet et al., 2005). Promising market options directly linked to rural poor small-scale producers and processors include fair-trade channels, private-public partnership, and the creation of local niche markets (eco-labeling, certification of geographical indications of origin, tourism-oriented sales outlets, etc.). Crops neglected so far by formal research and extension hold promise for upgrading value chains (Hellin and Highman, 2005; Gruère et al., 2006; Giuliani, 2007) in which small-scale farmers have a comparative advantage.

Value-chain analysis investigates the complexity of the actors involved and how they affect the production-to-consumption process. It incorporates production activities (cultivation, manufacturing and processing), non-production activities (design, finance, marketing and retailing), and governance (Bedford et al., 2001). The analysis of livelihoods of small-scale producers, processors and traders and their current and potential relation to markets is a starting point in ensuring that markets benefit the poor. Analyzing the market chain and the requirements and potentials of all its actors allows for identifying interventions along the chain likely to provide benefits to low-income households (Giuliani, 2007).

Investments in value chain research have the potential to improve equity by opening up income opportunities for small-scale farmers. The challenge will be to make small-scale farmers competitive and to identify opportunities and develop value chains which build on their potential (labor availability, high flexibility). Increasing requirements of the market regarding food quality, safety and traceability will limit small-scale farmer participation in certain value chains. Further, access to market may be limited by inadequate infrastructure, such road systems and refrigerated transport and storage.

Successes in value chain development have been achieved through an extensive consultation processes (Bernet et al., 2005) that generate group innovations based on well-led and well-structured participatory processes. These processes stimulate interest, trust and collaboration among members of the chain. The costs and benefits of such approaches will have to be carefully assessed to determine where investment is justified; e.g., investments for upgrading the market chain could be high compared with potential benefits for niche products with limited market volume.

6.2 Improve Productivity and Sustainability of Livestock Systems

On-farm options

Mixed systems. Mixed crop-livestock systems can contributes to sustainable farming (Steinfeld et al., 1997). Improving the performance of mixed crop-livestock production systems and promoting livestock production, particularly on small-scale farms can be attained by providing access to affordable inputs for small-scale livestock keepers. Along with inputs, adequate knowledge and technologies for on-farm nutrient cycling, on-farm production of feed and fodder, and the use of crop residues and crop by-products, can also provide benefits to small-scale producers.

Intensifying the livestock component in these systems increases the availability of farmyard manure, leading to increased fodder production and increased crop yields. More research is needed on the storage and application of farmyard manure, the conservation of cultivated fodder and crop residues, and the use of crop by-products as animal feed.

Livestock keeping can improve health and nutrition in many small households and generate additional income and employment (ILRI, 2006), even when households have limited resources such as land, labor and capital (PPLPI, 2001; Bachmann, 2004). Output per farm may be small, but the combined effect of many small-scale enterprises can be large, e.g., small-scale dairy in India (Kurup, 2000), piggery in Vietnam (FAO, 2006) and backyard poultry in Africa (Guye, 2000).

Extensive systems. There is little scope for extensive livestock production systems to further extend the area presently being grazed without environmentally unsustainable deforestation (Steinfeld et al., 2006). In some areas even pasture land is decreasing as it is converted into cropland, often resulting in land use conflicts (ECAPAPA, 2005). Where pasture areas with open access remain more or less stable, productivity of land and ultimately of livestock is threatened due to overstocking and overgrazing.

Livestock productivity can be increased through the improvement of pasture and rangeland resources and better animal health. Better animal health may require improved access to veterinary services, such as the establishment of systems of community based animal health workers (Leonard et al., 2003). Feeding conserved fodder and feeds (primarily crop by-products) may help overcome seasonal shortages, while planting fodder trees, more systematic rotational grazing and fencing may improve grazing areas. Tree planting may gain further importance when linked to carbon trade programs. Fencing, on the other hand, may not be socially or culturally acceptable, in particular in areas with communal grazing land (IFAD, 2002). Land use strategies that include participatory approaches are more effective at avoiding conflicts (ECAPAPA, 2005).

Biological complexity and diversity are necessary for survival in traditional pastoral communities (Ellis and Swift, 1988). Long term conservative strategies often work best in traditional systems. The introduction of new breeding techniques (e.g., sexing of sperm straw) might cause a rapid increase in the number of cattle, but may also lead to the disappearance of local breeds and a reduction in the genetic diversity of rustic breeds of cattle, which are well adapted to extreme environments.

The overall potential of pastoral grazing systems is high (Hesse and MacGregor, 2006); the primary issue is the environmental sustainability of these systems (Steinfeld et al., 2006). Hence options to improve productivity must focus more on the application of management than the technology (ILRI, 2006).

Intensive systems. Increasingly, intensive livestock production trade is associated with a fear of contamination of air and water resources (de Haan et al., 1997; FAO, 2006). Future systems will need to consider human health aspects as well as the whole livestock food value chain (fodder and animal feed production, processing and marketing of products, etc). Since cross-regional functions such as assembly, transport, processing and distribution can cause other externalities, they must be assessed as part of an integrated system. Intensive systems are prone to disease and animals can spread zoonotic diseases like tuberculosis or bird flu that can affect humans (LEAD, 2000).

Improvements in intensive livestock production systems include locating units away from highly populated areas, and using management practices and technologies that minimize water, soil and air contamination.

6.3 Breeding Options for Improved Environmental and Social Sustainability

6.3.1 Crop breeding

Climate change coupled with population growth will produce unprecedented stress on food security. Abiotic stresses such as drought and salinity may reduce yields worldwide by up to 50% (Jauhar, 2006). Increasing demand cannot always be met by increasing the land devoted to agriculture (Kumar, 2006), however, it may be possible to improve plant productivity. Traits that are the focus of abiotic stress resistance include optimized adaptation of temperature-dependent enzymes (to higher or lower temperatures), altering day-length regulation of flower and fruit development, optimization of photosynthesis including circumventing inherent limitations in C_3 and C_4 pathways in plants (Wenzel, 2006).

6.3.1.1 Options for conventional plant breeding

The following options apply to plant breeding to help meet world demand for nutrition and higher yields in low external input production systems and lower resource demands in high external input production systems. However useful these innovations might be, biotechnology *per se* cannot achieve development and sustainability goals. Therefore, it is critical for policy makers to holistically consider biotechnology impacts beyond productivity goals, and address wider societal issues of capacity building, social equity and local infrastructure.

Modern, conventional and participatory plant breeding approaches play a significant role in the development of new crop varieties (Dingkuhn et al., 2006). The exodus of a specialist workforce in plant breeding (Baenziger et al., 2006), especially from the public sector, is a worrisome trend for maintaining and increasing global capacity for crop improvement. Critical to improved plant breeding is ensuring the continuity of specialist knowledge in plant breeding. Approaches that encourage research in the field and continuity of career structure for specialists are key to the continuation of conventional plant breeding knowledge.

There is a need for new varieties of crops with high productivity in current and emerging marginal and unfavorable (e.g., water stressed) environments; resource limited farming systems; intensive land and resource use systems; areas of high weed pressure (Dingkuhn et al., 2006); and bioenergy. Ensuring access to locally produced high-quality seeds and to opportunities for farmer-to-farmer exchanges will improve productivity, decrease poverty and hunger, encourage retention of local knowledge, safeguard local intellectual property, and further exploit the biological diversity of crop wild relatives.

Plant breeding is facilitating the creation of new genotypes with higher yield potentials in a greater range of environments (Dingkuhn et al., 2006; Hajjar and Hodgkin, 2007) mainly through recruiting genes from within the gene pool of interbreeding plants and also through biotechnology assisted hybridization and tissue regeneration (Wenzel, 2006).

Crop biodiversity is maintained both through *ex situ* and *in situ* conservation in the genomes of plants from which crops were derived, and in the genomes of crop relatives (Brush and Meng, 1998). The value of traits sourced from wild relatives has been estimated at US$340 million to the US economy every year (Hajjar and Hodgkin, 2007). Traits such as pest and disease resistance are usually determined by single genes. Wild relatives have so far contributed modestly as a source of genes for introduction of multigene traits, such as abiotic stress tolerances, but there is considerable diversity still to be tapped (Hajjar and Hodgkin, 2007).

In developing countries, public plant breeding institutions are common but their continued existence is threatened by globalization and privatization (Maredia, 2001; Thomas, 2005). Plant breeding activities differ between countries; public investment in genetic improvement may benefit from research units that include local farming communities (Brush and Meng, 1998). Moreover, differences in intellectual property protection philosophies could endanger *in situ* conservation as a resource for breeding. For example, patent protection and forms of plant variety protection place a greater value on the role of breeders than that of local communities that maintain gene pools through *in situ* conservation (Srinivasan, 2003).

Options for strengthening conservation in order to preserve plant genetic diversity include:

- Integrating material on the importance of biodiversity into curricula at all educational levels;
- Channeling more resources into public awareness at CGIAR and NGO system level;
- Facilitating national programs to conduct discussions with farmers about the long-term consequences of losing agrobiodiversity;
- Studying and facilitating the scaling up of indigenous agroecosystems that feature a high degree of agrobiodiversity awareness;
- Involving farmers in a fully participatory manner in research focused on agrobiodiversity conservation;
- Undertaking surveys of farmers and genebanks to establish which communities want their landraces back, and to find out if the landrace is still maintained in a genebank;
- Developing sustainable reintroduction campaigns;
- Developing a system whereby genebanks regenerate landraces and maintained them in farmers' fields: a hybrid *in situ* and *ex situ* conservation system;
- Involving farmers in the characterization of landraces to increase exposure and possible utilization of the material at farm level;
- Promoting the development of registration facilities that recognize a given landrace as the indigenous property of a particular area or village to enhance the importance of the landrace as an entity that is a part of local heritage;
- Developing and promoting viable and sustainable multistakeholder incentive schemes for communities who maintain local material in their agroecosystem.

Provided that steps are taken to maintain local ownership and control of crop varieties, plant breeding remains a viable option for meeting development and sustainability goals. It will be important to find a balance between exclusive access secured through intellectual property (IP) mechanisms and the need for local farmers and researchers to develop locally adapted varieties (Srinivasan, 2003; Cohen, 2005). An initial approach could include facilitating NGOs to help develop the capacity of local small-scale farmers, and providing farmer organizations with advisers to guide their investments in local plant improvement.

6.3.1.2 Optimize the pace and productivity of plant breeding

Biotechnology and associated nanotechnologies provide tools that contribute toward the achievement of development and sustainability goals. Biotechnology has been described as the manipulation of living organisms to produce goods and services useful to human beings (Eicher et al., 2006; Zepeda, 2006). In this inclusive sense, biotechnology includes traditional and local knowledge (TK) and the contributions to cropping practices, selection and breeding made by individuals and societies for millennia (Adi, 2006); it would also include the application of genomic techniques and marker-assisted breeding or selection (MAB or MAS). Modern biotechnology includes what arises from the use of in vitro modified genes. Most obvious in this category is genetic engineering, to create genetically modified/engineered organisms (GMOs/GEOs) through transgenic technology by insertion or deletion of genes.

Combining plants with different and desirable traits can be slow because the genes for the traits are located in many different places in the genome and may segregate separately during breeding. Breeding augmented by molecular screening may yield rapid advances in existing varieties. This process, however, is limited by breeding barriers or viability in the case of cell fusion approaches, and there may be a limit to the range of traits available within species to existing commercial varieties and wild relatives. In any case, breeding is still the most promising approach to introducing quantitative trait loci (Wenzel, 2006). Emerging genomics approaches are showing promise for alleviating both limitations.

Genomics. Whole genome analysis coupled with molecular techniques can accelerate the breeding process. Further development of approaches such as using molecular markers through MAS will accelerate identification of individuals with the desired combinations of genes, because they can be rapidly identified among hundreds of progeny as well as improve backcross efficiencies (Baenziger et al., 2006; Reece and Haribabu, 2007). The range of contributions that MAS can make to plant breeding are being explored and are not exhausted (e.g., Kumar, 2006; Wenzel, 2006). It thus seems reasonable that MAS has the potential to contribute to development and sustainability goals in the long term, provided that researchers consistently benefit from funding and open access to markers. MAS is not expected to make a significant improvement to the rate of creating plants with new polygenic traits, but with future associated changes in genomics this expectation could change (Baenziger et al., 2006; Reece and Haribabu, 2007).

Regardless of how new varieties are created, care needs to be taken when they are released because they could become invasive or problem weeds, or the genes behind their desired agronomic traits may introgress into wild plants threatening local biodiversity (Campbell et al., 2006; Mercer et al., 2007).

MAS has other social implications because it favors centralized and large scale agricultural systems and thus may conflict with the needs and resources of poor farmers (Reece and Haribabu, 2007). However, breeding coupled to MAS for crop improvement is expected to be easily integrated into most regulatory frameworks and meet little or no market resistance, because it does not involve producing transgenic plants (Reece and Haribabu, 2007). Varieties that are developed in this fashion can be covered by many existing IP rights instruments (e.g., Baenziger et al., 2006; Heinemann, 2007) and would be relatively easy for farmers to experiment with under "farmers' privilege" provided that suitable *sui generis* systems are in place (Sechley and Schroeder, 2002; Leidwein, 2006). The critical limitation of MAS is its ultimate dependence on plant breeding specialists to capture the value of new varieties; unfortunately, current and projected numbers of these specialists is inadequate (Reece and Haribabu, 2007).

Transgenic (GM) plants. Recombinant DNA techniques allow rapid introduction of new traits determined by genes that are either outside the normal gene pool of the species or for which the large number of genes and their controls would be very difficult to combine through breeding. An emphasis on extending tolerance to both biotic (e.g., pests) and abiotic (e.g., water stress) traits using transgenes is relevant to future needs.

Assessment of transgenic (GM) crops is heavily influenced by perspective. For example, the number of years that GM crops have been in commercial production (approximately 10 years), amount of land under cultivation (estimated in 2007 at over 100 million ha) and the number of countries with some GM agriculture (estimated in 2007 at 22) (James, 2007) can be interpreted as evidence of their popularity. Another interpretation of this same data is that the highly concentrated cultivation of GM crops in a few countries (nearly three-fourths in only the US and Argentina, with 90% in the four countries including Brazil and Canada), the small number of tested traits (at this writing, mainly herbicide and pest tolerance) and the shorter-term experience with commercial GM cultivation outside of the US (as little as a year in Slovakia) (James, 2007), indicate limited uptake and confidence in the stability of transgenic traits (Nguyen and Jehle, 2007).

Whereas there is evidence of direct financial benefits for farmers in some agriculture systems, yield claims, adaptability to other ecosystems and other environmental benefits, such as reduced alternative forms of weed and pest control chemicals, are contested (Pretty, 2001; Villar et al., 2007), leaving large uncertainties as to whether this approach will make lasting productivity gains. The more we learn about what genes control important traits, the more genomics also teaches us about the influence of the environment and genetic context on controlling genes (Kroymann and Mitchell-Olds, 2005; MacMillan et al., 2006) and the complexity of achieving consistent, sustainable genetic improvements. Due to a combination of difficult to understand gene by environment interactions and experience to date with creating transgenic plants, some plant scientists are indicating that the rate at which transgenic plants will contribute to a sustained increase in future global food yields is exaggerated (Sinclair et al., 2004).

Adapting any type of plant (whether transgenic or conventionally bred) to new environments also has the potential to convert them into weeds or other threats to food and materials production (Lavergne and Molofsky, 2007; Heinemann, 2007). This problem is particularly relevant to transgenes because (1) they tend to be tightly linked packages in genomes, making for efficient transmission by breeding (unlike many traits that require combinations of chromosomes to be inherited simultaneously), and (2) the types of traits of most relevance to meeting development and sustainability goals in the future are based on genes that adapt plants to new environments (e.g., drought and salt tolerance). Through gene flow, wild relatives and other crops may become more tolerant to a broader climatic range and thus further threaten sustainable production (Mercer et al., 2007). An added complication is that these new weeds may further undermine conservation efforts. The emergence of a new agricultural or environmental weed species can occur on a decade (or longer) scale. For example, it can take hundreds of years for long-lived tree species to achieve populations large enough to reveal their invasive qualities (Wolfenbarger and Phifer, 2000). These realities increase uncertainty in long term safety predictions.

Transgene flow also creates potential liabilities (Smyth et al., 2002). The liability is realized when the flow results in traditional, economic or environmental damage (Kershen, 2004; Heinemann, 2007). Traditional damage is harm to human health or property. Economic damage could occur if a conventional or organic farmer lost certification and therefore revenue because of adventitious presence. Environmental damage could result from, for example, harm to wildlife.

There are a limited number of properly designed and independently peer-reviewed studies on human health (Domingo, 2000; Pryme and Lembcke, 2003). Among the studies that have been published, some have provided evidence for potential undesirable effects (Pryme and Lembcke, 2003; Pusztai et al., 2003). Taken together, these observations create concern about the adequacy of testing methodologies for commercial GM plants fueling public skepticism and the possibility of lawsuits. A class-action lawsuit was filed by USA consumers because they may have inadvertently consumed food not approved for human consumption (a GM variety of maize called Starlink) because of gene flow or another failure of segregation. The lawsuit ended with a settlement against the seed producer Aventis. This suggests that consumers may have grounds for compensation, at least in the USA, even if their health is not affected by the transgenic crop (Kershen, 2004).

Farmers, consumers and competitors may be the source of claims against, or the targets of claims from, seed producers (Kershen, 2004; Center for Food Safety, 2005; Eicher et al., 2006). For example, when non-GM corn varieties from Pioneer Hi-Bred were found in Switzerland to contain novel Bt genes, the crops had to be destroyed, and compensation paid to farmers (Smyth et al., 2002).

Even if liability issues could be ignored, the industry will remain motivated to track transgenes and their users because the genes are protected as IP. Transgene flow can create crops with mixed traits because of "stacking" (two transgenes from different owners in the same genome) or mixed crops (from seed mediated gene flow or volunteers), resulting in potential IP conflicts. IP protection includes particular genes and plant varieties as well as techniques for creating transgenic plants and product ideas, such as the use of Bt-sourced Cry toxins as plant-expressed insecticides. Broad IP claims are creating what some experts call "patent thickets"; the danger of thickets is that no single owner can possess all the elements in any particular transgenic plant (Thomas, 2005).

Release of insect resistant GM potatoes in South Africa illustrates the complexity that IP and liability create for transgenic crops. The potato has elements that are claimed by two different companies. One of the IP owners has been unwilling to license the IP to South Africa for fear of liability should the potatoes cross into neighboring countries (Eicher et al., 2006).

The harms associated with transgene flow might be addressed by a combination of physical and biological strategies for containment (for a comprehensive list, see NRC, 2004). However, no single method and possibly no combination of methods would be wholly adequate for preventing all flow even though for some genes and some environments, flow might be restricted to acceptable levels (Heinemann, 2007). Future strategies for containment involving sterilization (i.e., genetic use restriction technologies, GURTs) remain highly controversial because of their potential to cause both unanticipated environmental harm and threaten economic or food security in some agroeconomic systems (Shand, 2002; Heinemann, 2007).

For transgenic approaches to continue to make significant contributions in the long term, a substantial increase in public confidence in safety assessments will be needed (Eicher et al., 2006; Herrero et al., 2007; Marvier et al., 2007); conflicts over the free-use of genetic resources must be resolved; and the complex legal environment in which transgenes are central elements of contention will need further consideration.

Epigenetic modification of traits. Epigenes are defined as units of inheritance that are not strictly based on the order of nucleotides in a molecule of DNA (Strohman, 1997; Heinemann and Roughan, 2000; Gilbert, 2002; Ashe and Whitelaw, 2007; Bird, 2007). A growing number of traits are based on epigenetic inheritance, although at present most of these are associated with disease, such as Mad Cow Disease and certain forms of cancer.

In the future, it may be possible to introduce traits based on epigenes. For example, double-stranded RNA (dsRNA) is the basis of at least two commercial transgenic plants and is proposed for use in more (Ogita et al., 2003; Prins, 2003). Small dsRNA molecules appear to be the basis for the trait in "flavr savr" tomatoes—even though at the time of development the epigenetic nature of the modification was probably not known or fully understood (Sanders and Hiatt, 2005)—and the basis for viral resistance in papaya (Tennant et al., 2001). In these cases, the epigene is dependent upon a corresponding change at the DNA level, but in time it will be possible to use the epigenetic qualities of dsRNA to infectiously alter traits without also altering the DNA content of the recipient genome using rDNA techniques. Such promise has already been demonstrated using nematodes where feeding, or soaking the worm in a liquid bath of dsRNA, was sufficient for systemic genetic modification of the worm and the stable transmission of the epigene for at least two generations (Fire et al., 1998; Cogoni and Macino, 2000). The effects of dsRNA also can be transmitted throughout a conventional plant that has been grafted with a limb modified to produce dsRNA (Palauqui et al., 1997; Vaucheret et al., 2001; Yoo et al., 2004).

RNA-based techniques will accelerate research designed to identify which genes contribute to complex traits and when and where in the organisms those genes are expressed ("turned on"). Generally, dsRNA causes transient, long-term, sometimes heritable gene silencing (turns genes "off"). While silencing that occurs by the general pathways controlled by dsRNA molecules are targeted to sequence matches between the dsRNA and the silenced genes, there are often effects on nontarget genes as well. The number of genes simultaneously silenced by a single dsRNA (including the targets) can number in the hundreds (Jackson et al., 2003; Jackson and Linsley, 2004; Jackson et al., 2006), and a variety of dsRNAs with no sequence similarity can silence the same genes (Semizarov et al., 2003).

Once established, the effects of dsRNA may persist in some kinds of organisms, being transmitted to offspring. The instigating event is the initial combination of genetic elements with similar DNA sequences, but the silencing effect may persist even in hybrids that retain a single copy of the gene.

Furthermore, not all genes that are silenced remain so, nor are all plants grafted with tissues from silenced plants capable of acquiring the silenced phenotype. The science of infectious gene silencing is still young, leaving gaps in understanding how the molecules are transmitted and maintained, and in how the phenotype is regulated or reversed. If this or other epigenetic strategies for genetic modification are in time adopted, they must benefit from fundamentally new kinds of safety assessments in both their environmental and human health context. Importantly, these assessments should be conducted by competent researchers that are independent of the developing industry.

6.3.2 Livestock breeding options

Technologies such as artificial insemination and embryo transfer, which are routine in industrialized countries have been successfully transferred and introduced in other parts of the world (Wieser et al., 2000). However, breeding technologies are not exploited to the extent possible because animals are not adapted to local conditions, logistical problems and poor support for breeding services and information management (Ahuja et al., 2000). There is scope to further develop conventional breeding technologies, in particular through North-South cooperation. To be effective at meeting development goals breeding policies, programs and plans need to be location specific (Kurup, 2003; Chacko and Schneider, 2005).

Thus far the impact of genomics in livestock agriculture is limited to the use of transgenic animals such as chickens and cattle to produce pharmaceutical or therapeutic proteins in eggs and milk (Gluck, 2000). Genomics for diagnostics and animal vaccine development, and in feed production and formulation (Machuka, 2004) may further boost the livestock industry, although the competition from alternative sources will probably be strong (Twyman et al., 2003; Chen, 2005; Ma et al., 2005). Moreover, all these new technologies create safety risks and may not always increase sustainable production. Hence, applications should be thoroughly evaluated to ensure that they do not also undermine development and sustainability goals.

There are currently no transgenic food animals in commercial production and none likely in the short term (van Eenennaam, 2006). Over the next 10-50 years there is some potential for development and introduction of transgenic animals or birds with disease resistance, increased or higher nutritional value meat or milk production, or as biofactories for pharmaceuticals (Machuka, 2004). The science and technology is available, but the barriers include regulatory requirements, market forces and IP, safety concerns and consumer acceptance, i.e., the same range of issues as described for crops (Powell, 2003; van Eenennaam, 2006; van Eenennaam and Olin, 2006).

Responding to the increased demand for livestock products without additional threats to the environment is a major challenge for agriculture and for AKST. One option for satisfying the additional demand for animal protein is to use meat from monogastric animals (pigs and poultry) and eggs. Feed conversion rates and growth for monogastric animals are better than for ruminants, which is one reason why the increasing demand for meat tends to be met with chicken and pork. This development may be positive with regard to the direct pressure on (grazing) land caused by ruminants, but has resulted in the establishment of large pig and poultry production units which are often placed in peri-urban areas. Large volumes of animal feed are produced elsewhere and transported, while disposal of waste from these large units has become an environmental issue (FAO, 2006). Although these large livestock farms may generate some employment opportunities, the capital required excludes most small-scale farmers. One approach to increase the total efficiency and sustainability of the intensive livestock production system is area-wide integration, i.e., the integration of production with cropping activities. The main objective is to link these specialized activities on a regional scale to limit their environmental damage and enhance social benefits (LEAD, 2000).

Recent outbreaks of diseases, including some that threaten human as well animal health, highlight the need to scrutinize large livestock units and their sustainability in wider terms with regard to environment and health (Steinfeld et al., 2006).

For small-scale farmers in rural areas, local markets will remain the primary outlets for their products. These local markets may also provide opportunities for processed products. However, processing of meat and livestock products into high value niche produces for distant markets might be economically attractive. Some associated risks include the required investment in marketing for a successful enterprise may decrease the "additional" product value. In addition, rural processors may not be able to meet the quality standards to compete for distant urban or export markets (ILRI, 2006).

Further extension of grazing land to produce meat from ruminants is not a sustainable way to meet the growing demand for meat and livestock products (Steinfeld et al., 2006). Therefore, pastoralists and rangelands livestock keepers will only benefit from an increased demand for livestock products if they are able to improve their present production systems by efficient use of existing resources, i.e., breed improvement (Köhler-Rollefson, 2003) improvement of animal health and disease control (Ramdas and Ghotge, 2005), of grazing regime and pasture management, including the planting of fodder trees, and if possible supplementary feeding during times of limited grazing. Where there is potential for mixed farming, policies need to facilitate the transition of grazing systems into mixed farming systems in the semiarid and subhumid tropics through integrating crops and livestock (Steinfeld et al., 1997).

6.4 Improve Forestry and Agroforestry Systems as Providers of Multifunctionality

6.4.1 On-farm options

The ecological benefits of low-input agroforestry systems are more compatible with small-scale tropical/subtropical farming systems than for large farms. However, the coincidence of land degradation and poverty is also greatest in the tropics and subtropics and there is therefore considerable relevance of agroforestry for the attainment of development and sustainability goals. Disseminating and implementing a range of agroforestry practices, tailored to particular social and environmental conditions, on a wide scale will require large-scale investment in NARS, NARES, NGOs and CBOs, with support from ICRAF and regional agroforestry centers. Rehabilitation of degraded land and improving soil fertility can be accomplished by promoting a range of ecological/environmental services such as: (1) erosion control, (2) nutrient cycling, (3) protection of biodiversity in farming systems, (4) carbon sequestration, (5) promoting natural enemies of pests, weeds and diseases, (6) improving water availability, and (7) the restoration of agroecological function.

Agroforestry practices can also improve soil fertility in the future, which is crucial for achieving food security, human welfare and preserving the environment for smallholder farms (Sanchez, 2002; Oelberman et al., 2004; Schroth et al., 2004, Jiambo, 2006; Rasul and Thapa, 2006). An integrated soil fertility management approach that combines agroforestry technologies—especially improved fallows of leguminous species and biomass transfer—with locally available and reactive phosphate rock (e.g., Minjingu of northern Tanzania) can increase crop yields severalfold (Jama et al., 2006).

Tree crops can be established within a land use mosaic to protect watersheds and reduce runoff of water and erosion restoring ecological processes as the above- and below-ground niches are filled by organisms that help to perform helpful functions such as cycle nutrients and water (Anderson and Sinclair, 1993), enrich organic matter, and sequester carbon. (Collins and Qualset, 1999; McNeely and Scherr, 2003; Schroth et al., 2004). Many of these niches can be filled by species producing useful and marketable food and nonfood products, increasing total productivity and economic value (Leakey, 2001ab; Leakey and Tchoundjeu, 2001). A healthier agroecosystem should require fewer purchased chemical inputs, while the diversity alleviates risks for small-scale farmers. On large mechanized farming systems the larger-scale ecological functions associated with a land use mosaic can be beneficial.

As the science and practice of agroforestry are complex and comprise a range of disciplines, communities and institutions, strengthening strategic partnerships and alliances (farmers, national and international research organizations, government agencies, development organizations, NGOs, ICRAF, CIFOR, The Forest Dialogue, etc.) is crucial in order to foster the role of agroforestry in tackling future challenges. Local participation could be mobilized by incorporating traditional knowledge and innovations, as well as ensuring the scaling up and long-term sustainability of agroforestry.

Rights to land and trees tend to shape women's incentives and authority to adopt agroforestry technologies more than other crop varieties because of the relatively long time horizon between investment and returns (Gladwin et al., 2002). Agroforestry systems have high potential to help AKST achieve gender equity in property rights. This is especially true in customary African land tenure systems where planting or clearing trees is a means of establishing claims, on the trees, but also on the underlying land (Gari, 2002; Villarreal et al., 2006).

Reducing land degradation through agroforestry. Land degradation is caused by deforestation, erosion and salinization of drylands, agricultural expansion and abandonment, and urban expansion (Nelson, 2005). Data on the extent of land degradation are extremely limited and paradigms of desertification are changing (Herrmann and Hutchinson, 2005). Approximately 10% of the drylands are considered degraded, with the majority of these areas in Asia and Africa.

In all regions more threatened by deforestation, like the humid tropics, Latin America, Southeast Asia, and Central Africa, deforestation is primarily the result of a combination of commercial wood extraction, permanent cultivation, livestock development, and the extension of overland transport infrastructure (Zhang et al., 2002; Vosti et al., 2003; Nelson, 2005). Decreasing current rates of deforestation could be achieved by promoting alternatives that contribute to forest conservation. Methods may include improving forest management through multiple-use policies in natural forests and plantations of economic (cash) trees within forests (Wenhua, 2004) off-farm employment (Mulley and Unruh, 2004); and implementing an industrial development model, based on high-value added products.

Sustainable timber management implies ensuring forests continue to produce timber in long-term, while maintaining the full complement of environmental services and non-timber products of the forest. Although sustainable timber management sometimes provides reasonable rates of return, additional incentives are often needed as conventional timber harvesting is generally more profitable (Pearce and Mourato, 2004). Effective use of AKST supported by sustainable policy and legal systems and sufficient capacity is needed; the Chinese government's forest management plan implemented in 1998 offers a working example (Wenhua, 2004). However, local authorities are often inefficient in monitoring and enforcing environmental laws in large regions, as in Brazilian Amazonia where the construction of highways and the promotion of agriculture and cattle ranching facilitated the spread of deforestation. Off-farm employment can contribute significantly to forest conservation in the tropics, e.g., the tea industry in western Uganda (Mulley and Unruh, 2004).

6.4.2 Market mechanisms and incentives for agroforestry

Agroforestry is a method by which income can be generated by producing tree products for marketing as well as domestic use. There are many wild tree species that produce traditionally important food and nonfood products (e.g., Abbiw, 1990). These species can be domesticated to improve their quality and yield and to improve the uniformity of marketed products (Leakey et al, 2005) and enhance farmers' livelihoods (Schreckenberg et al., 2002; Degrande et al., 2006). Domestication can thus be used as an incentive for more sustainable food production, diversification of the rural economy, and to create employment opportunities in product processing and trade. The domestication of these species previously only harvested as extractive resources, creates a new suite of cash crops for smallholder farmers (Leakey et al., 2005). Depending on the market size, some of these new cash crops may enhance the national economies, but at present the greatest benefit may come from local level trade for fruits, nuts, vegetables and other food and medicinal products for humans and animals, including wood for construction, and fuel.

This commercialization is crucial to the success of domestication, but should be done in ways that benefit local people and does not destroy their tradition and culture (Leakey et al., 2005). Many indigenous fruits, nuts and vegetables are highly nutritious (Leakey, 1999b). The consumption of some traditional foods can help to boost immune systems, making these foods beneficial against diseases, including HIV/AIDS (Barany et al., 2003; Villarreal et al., 2006). These new nonconventional crops may play a vital role in the future for conserving local and traditional knowledge systems and culture, as they have a high local knowledge base which is being promoted through participatory domestication processes (Leakey et al., 2003; World Agroforestry Centre, 2005; Garrity, 2006; Tchoundjeu et al., 2006). Together these strategies are supportive of food sovereignty and create an approach to biodiscovery that supports the rights of farmers and local communities specified in the Convention on Biological Diversity.

A participatory approach to the domestication of indigenous trees is appropriate technology for rural communities worldwide (Tchoundjeu et al., 2006), especially in the tropics and subtropics, with perhaps special emphasis on Africa (Leakey, 2001ab), where the Green Revolution has been least successful. In each area a priority setting exercise is recommended to identify the species with the greatest potential (Franzel et al., 1996). Domestication should be implemented in parallel with the development of postharvest and value-adding technologies and the identification of appropriate market opportunities and supply chains. With poverty, malnutrition and hunger still a major global problem for about half the world population, there is a need to develop and implement a range of domestication programs for locally-selected species, modeled on that developed by ICRAF and partners in Cameroon/Nigeria (Tchoundjeu et al., 2006), on a wide scale. There will also be a need for considerable investment in capacity development in the appropriate horticultural techniques (e.g., vegetative propagation and genetic selection of trees) at the community level, in NARS, NARES, NGOs and CBOs, with support from ICRAF and regional agroforestry centers.

Agroforestry can be seen as a multifunctional package for agriculture, complemented by appropriate social sciences, rural development programs and capacity development. Better land husbandry can rehabilitate degraded land. For many poor farmers this means the mitigation of soil nutrient depletion by biological nitrogen fixation and the simultaneous restoration of the agroecosystem using low-input, easily-adopted practices, such as the diversification of the farming system with tree crops that initiate an agroecological succession and produce marketable products.

Over the last 25 years agroforestry research has provided some strong indications on how to go forward by replanting watersheds, integrating trees back into the farming systems to increase total productivity, protecting riparian strips, contour planting, matching tree crops to vulnerable landscapes, soil amelioration and water harvesting. There are many tree species indigenous to different ecological zones, that have potential to play these important roles, and some of these are currently the subject of domestication programs. In this way, the ecological services traditionally obtained by long periods of unproductive fallow are provided by productive agroforests yielding a wide range of food and nonfood products. This approach also supports the multifunctionality of agriculture as these species and products are central to food sovereignty, nutritional security and to maintenance of tradition and culture. Additionally, women are often involved in the marketing and processing of these products. Consequently this approach, which brings together AST with traditional and local knowledge, provides an integrated package which could go a long way towards meeting development and sustainability goals. The challenge for the development of future AKST is to develop this "Localization" package (Chapter 3.2.4; 3.4) on a scale that will have the needed impacts.

This integrated package is appropriate for large-scale development programs, ideally involving private sector partners (building on existing models—e.g., Panik, 1998; Mitschein and Miranda, 1998; Attipoe et al., 2006). Localization is the grassroots pathway to rural development, which has been somewhat neglected in recent decades dominated by Globalization. Programs like that proposed would help to redress the balance between Globalization and Localization, so that both pathways can play their optimal role. This should increase benefit flows to poor countries, and to marginalized people. There would be a need for considerable investment in capacity development in the appropriate horticultural and agroforestry techniques (e.g., vegetative propagation, nursery development, domestication and genetic selection of trees) at the community level, in NARS, NARES, NGOs and CBOs, with support from ICRAF and regional agroforestry centers.

By providing options for producing nutritious food and managing labor, generating income, agroforestry technologies may play a vital role in the coming years in helping reduce hunger and promote food security (Thrupp, 1998; Cromwell, 1999; Albrecht and Kandji, 2003; Schroth et al., 2004; Oelberman et al., 2004; Reyes et al., 2005; Jiambo, 2006; Rasul and Thapa, 2006; Toledo and Burlingame, 2006).

Recent developments to domesticate traditionally important indigenous trees are offering new opportunities to enhance farmer livelihoods in ways which traditionally provided household needs (especially foods) as extractive resources from natural forests and woodlands (Leakey et. al., 2005; Schreckenberg et al., 2002). These new non-conventional crops may play a vital role in the future for conserving local and traditional knowledge systems, as they have a high local knowledge base which is being promoted through participatory domestication processes (Leakey et al., 2003; World Agroforestry Centre, 2005; Garrity, 2006)

6.5 Sustainable Management of Fishery and Aquaculture Systems

Globally, fisheries products are the most widely traded foods, with net exports in 2002 providing US$17.4 billion in foreign exchange earnings for developing countries, a value greater than the combined net exports of rice, coffee, sugar, and tea (FAO, 2002). In spite of the important role that fisheries play in the national and local economies of many countries, fisheries around the globe are frequently overfished and overexploited as a result of not only weak governance, but of poor management, non-selective technology, perverse subsidies, corruption, unrestricted access and destructive fishing practices (FAO, 2002; World Bank, 2004). Reforming both the governance and management of these critical natural resources is essential to stable and long term economic development, future food security, sustainable livelihoods, poverty prevention and reduction, continuation of the ecosystem goods and services provided by these natural resources, and the conservation of biodiversity (Fisheries Opportunity Assessment, 2006; Christie et al., 2007; Sanchirico and Wilen, 2007).

Governance and management options

In most cultures, wild fisheries and marine resources are considered as common property and suffer from open, unregulated access to these valuable resources. The concept of land tenure and property rights has been instrumental in reforming terrestrial agriculture and empowering small-scale farmers. Similarly, the concepts of marine tenure and access privileges are needed to address the "wild frontier" attitude generated by open access to fisheries and to promote shared responsibilities and comanagement of resources (Pomeroy and Rivera-Guieb, 2006; Sanchirico and Wilen, 2007). Several traditional management approaches, such as in the Pacific Islands, have evolved that are based upon the concept of marine tenure.

For fisheries, major goals of zoning are to (1) protect the most productive terrestrial, riparian, wetland and marine habitats which serve as fisheries nurseries and spawning aggregation sites, and (2) allocate resource use—and thus stewardship responsibility—to specific users or user groups. Appropriate zoning would allow for the most sustainable use of various habitats types for capture fisheries, aquaculture, recreation, biodiversity conservation and maintenance of ecosystem health. Future zoning for specific uses and user groups would also shift shared responsibility onto those designated users, thus increasing self-enforcement and compliance (Sanchirico and Wilen, 2007). The greatest benefit would be in those countries where government, rule of law and scientific management capacity is weak.

Improving fisheries management is critical for addressing food security and livelihoods in many developing countries, where fishing often serves as the last social safety net for poor communities and for those who have no land tenure rights. Fisheries has strong links to poverty—at least 20% of those employed in fisheries earn less than US$1 per day—and children often work in the capture and/or processing sectors, where they work long hours under dangerous conditions.

Tenure and access privileges. Large-scale social and ecological experiments are needed to implement culturally appropriate approaches to marine tenure and access privileges that can be applied to both large-scale industrialized fisheries and small-scale artisanal fisheries (Fisheries Opportunity Assessment, 2006; Pomeroy and Rivera-Guieb, 2006). Rights-based or privilege-based approaches to resource access can alter behavioral incentives and align economic incentives with conservation objectives (Sanchirico and Wilen, 2007).

Seascape "zoning". As in terrestrial systems, zoning would protect essential and critical fisheries habitats that are necessary for "growing" fisheries populations and maintaining ecosystem health. The science of large-scale planning is relatively young and further research and implementation is needed. Future zoning should allow for the most sustainable use of various marine habitat types for capture fisheries, low trophic level aquaculture, recreation, biodiversity conservation and maintenance of ecosystem health. Ultimately, integrating landscape and seascape use designs are needed to conserve and protect ecosystem goods and services, conserve soils, reduce sedimentation and pollution runoff, protect the most productive terrestrial, wetlands and marine habitats, and promote improved water resources management.

Socioeconomic and environmental scenarios could be developed that explore the potential tradeoffs and benefits from applying different management regimes to improve wild fisheries management. Scenarios can guide the application of science to management decisions for reforming fisheries governance, both large-scale and small-scale fisheries, and incorporate cultural and traditional knowledge (Fisheries Opportunity Assessment, 2006; Philippart et al., 2007). The Locally Managed Marine Areas (LMMAs) approach in the Pacific builds upon cultural practices of setting aside specific areas as off-limits to fishing for rebuilding fisheries and biodiversity (www.LMMAnetwork.org).

Ecosystem-based management approaches focus on conserving the underlying ecosystem health and functions, thus maintaining ecosystem goods and services (Pikitch et al., 2004). Developing these approaches requires an understanding of large-scale ecological processes; identifying critical fisheries nurseries, habitats and linkages between habitats, such as between mangrove forests and coral reefs; understanding freshwater inflows into coastal estuaries and maintaining the quantity, quality and timing of freshwater flows that make wetlands some of the most productive ecosystems in the world; and how human activities, such as fishing, affects ecosystem function (Bakun and Weeks, 2006; Hiddinks et al,. 2006; Lotze et al., 2006; Olsen et al., 2006; www.worldfishcenter.org). Ecosystem based fisheries management also requires protection of essential fish habitats and large-scale regional use planning.

Ecosystem based fisheries management approaches are relatively new management tools. Given the ecological complexity of ecological systems, especially the tropical systems in many developing countries, the application of Ecosystem based fisheries management needs to be further developed and assessed. Major governance and ecological challenges exist as management is scaled up in geographic area. Institutional, governance and environmental challenges will require monitoring, evaluation and adaptive management (Christie et al., 2007).

Fisheries reserves. The design and establishment of networks of fisheries reserves are necessary to improve and protect fisheries productivity, as well as improve resilience in the face of climate change and increasing variability. Well-designed and placed fisheries reserves, which restrict all extractive uses, are needed to rebuild severely depleted ecosystems and fisheries and to serve as "insurance" against future risks; however, critical science gaps will need to be addressed before fishery reserves can be effectively utilized (Gell and Roberts, 2003).

Multispecies approaches. The concept of "maximum sustainable yield" and managing by a species-by-species or population-by-population approach has not proved effective for fisheries management given the complexity of ecosystems and foodwebs. Overfishing and "fishing down the food web" has occurred, seriously threatening the future productivity of wild fisheries (Pauly et al., 2005). Non-linear, multispecies models which incorporate trophic levels, reproductive potential and "maximum economic yield" need to be developed and applied for determining more sustainable levels, types and sizes of fish extracted (Pauly and Adler, 2005).

Environmentally friendly extraction technologies. New technology is needed that selectively removes target species and size classes, thus reducing wasteful "bycatch", allowing nonreproductive individuals to reach maturity, and protecting large individuals that disproportionately contribute to the next generation (Hsieh et al., 2006). Some advocate that destructive fishing practices—such as bottom-trawling and blast fishing—are illegal in some countries and should be prohibited and replaced with nondestructive methods (Bavinck et al., 2005; Dew and McConnaughey, 2005).

About 30% of capture fisheries are currently used to create "fish meal" destined for aquaculture and other livestock, and this percentage is expected to increase as aquaculture expands and more high-trophic level fish (such as salmon, grouper and tuna) are cultured and farmed. Ill-placed and designed aquaculture facilities have also reduced the productivity of wild fisheries and degraded environments through loss of critical habitats, especially mangrove forests and coral reefs; introduction of invasive species, pests and diseases; and use of pesticides and antibiotics.

Environmentally friendly and sustainable aquaculture. While aquaculture is one of the fastest growing food sectors in terms of productivity, this achievement has been at great cost and risk to the health and well-being of the environment, as well as the well-being of small-scale fishers and farmers. The future of aquaculture is truly at a crossroads: the future direction of aquaculture will affect the health and productivity of wild fisheries, the survival of many livelihoods, and global food security (World Bank 2006).

The future contribution of aquaculture to global food security and livelihoods will depend on the promotion of more environmentally sustainable and less polluting culture techniques; the use of low-trophic level species, especially filter-feeding species; the use of native species; appropriate siting and management approaches; and inclusion and empowerment of small-scale producers (World Bank, 2006). The culture of local, native species should be promoted to decrease the displacement of native species by escaped exotics, such as tilapia. Proper siting of aquaculture facilities is crucial to reduce environmental impact and ensure long-term sustainability and profitability; improperly sited aquaculture facilities, especially for shrimp farms, have led to the destruction of wetlands and mangrove forest that are vital to capture fisheries and the protection of coastal communities from storms, tsunamis and other coastal hazards. Enclosed, recirculating tanks that are properly sited show great promise in meeting some of these objectives and in decreasing the pollution of wild gene pools through escapes of species used in aquaculture. A more balanced approach to aquaculture is needed that incorporates environmental sustainability, integrated water resources management and equitable resources use and access to benefits (www.ec.europa.eu; www.icsf.net; www.worldfishcenter.org).

Greater emphasis is needed to develop sound fisheries "growth" practices and approaches—such ecosystem based fisheries management, networks of reserves, new quota models and new extraction technology—which will restore ecosystem productivity and resiliency. It is estimated that with proper fishing practices, capture fisheries production could be increased significantly, reversing present declines.

6.6 Improve Natural Resource Management and Habitat Preservation

6.6.1 The landscape management challenge

Losing habitats is the greatest threat to biodiversity; over the past 50 years people have destroyed or fragmented ecosystems faster and more extensively than in any period in human history (MA, 2005). Rapidly growing demands for food, freshwater, timber, and fuel driving this change have put enormous pressure on biodiversity. The creation of more conservation management areas, promotion of local biodiversity, increased participatory approaches to natural resource management (e.g., GELOSE project, Madagascar) and a close collaboration between all relevant stakeholders in biodiversity management initiatives (Mayers and Bass, 2004) will be vital to addressing further loss of existing habitats.

Restoration of fragile habitats is a way of improving degraded ecosystems or creating new areas to compensate for loss of habitat elsewhere. Enhancing transboundary initiatives (e.g., Agenda Transandina for mountain biodiversity in the Andes) has multiple benefits to conserve and restore fragile habitats. The appropriate use of technology, such as remote sensing or GIS can improve monitoring of ecosystem fragmentation (e.g., INBio Costa Rica) and can help in the protection of large areas of native vegetation within regions to serve as sources of species, individuals and genes. Landscape management can also help maintain or reestablish connectivity between native habitats at multiple scales with large contiguous areas of native vegetation for as wide a group of plant and animal species as possible. Remaining areas of native habitat within the agricultural landscape (giving priority to patches that are large, intact and ecologically important) can be conserved while further destruction, fragmentation or degradation prevented.

Active management of landscapes and land uses will be required to maintain heterogeneity at both patch and landscape levels, making agricultural systems more compatible with biodiversity conservation. Threats to native habitats and biodiversity can be identified and specific conservation strategies applied for species or communities that are of particular conservation concern. Areas of native habitat in degraded portions of the agricultural landscape can be restored and marginal lands taken out of production and allowed to revert to native vegetation.

For freshwaters, some management options include:

- Maintain or restore native vegetation buffers;
- Protect wetlands and maintain critical function zone in natural vegetation;
- Reestablish hydrological connectivity and natural patterns of aquatic ecosystems (including flooding);
- Protect watersheds with spatial configuration of perennial natural, planted vegetation and maintain continuous year-round soil cover to enhance rainfall infiltration

Nonnative, exotic species. Species that become invasive are often introduced deliberately, and many of these introductions are related to agriculture, including plants and trees introduced for agricultural and forestry purposes and species used for biological control of pests (Wittenberg and Cock, 2001; Matthews and Brandt, 2006). Policy for control of invasive species is essential, but AKST must also develop a better understanding of when and how species become invasive and how to best monitor and control them. Improved prediction and early detection of pest invasions, appears to rely heavily on the scale and frequency of introductions (not particular phenotypic characteristics of the invader) (Lavergne and Molofsky, 2007; Novak, 2007). Since the scale of introduction is a critical factor, commercial trade in all living organisms, including seeds, plants, invertebrates and all types of animals has the greatest potential to augment the invasion potential of exotic species. The most promising mechanism for targeting this critical phase in invasion is an increase in the capacity of exporting and importing nations to monitor the content of agricultural goods. This cannot be done effectively by individual countries; collective action is needed, through UN or other international bodies with appropriate global capacity development, e.g., UN Biodiversity Convention and the Cartagena Protocol.

6.6.2 Address poor land and soil management to deliver sustainable increases in productivity

The approach to addressing increased productivity will be distinctly different for fertile and low fertile lands (Hartemink, 2002).

6.6.2.1 Options for fertile lands

On-farm, low input options. The adoption of zero tillage prevents further water erosion losses, increases water use efficiency, soil organic carbon sequestration, and maintains good structure in topsoil (Díaz-Zorita et al., 2002; Bolliger et al., 2006; Steinbach and Alvarez, 2006; Lal et al., 2007).

About 95 million ha are under zero tillage management worldwide (Lal et al., 2007) in countries with industrialized agriculture, but the land area may increase in response to fuel prices and soil degradation. Zero tillage has well known positive effects upon soil properties; one negative effect is increased greenhouse gas emissions (N_2O, CH_4) due to higher denitrification rates (Baggs et al., 2003; Dalal et al., 2003; Passianoto et al., 2003; Six et al., 2004; Steinbach and Alvarez, 2006; Omonode et al., 2007). Tradeoffs between higher C sequestration and higher GHG emissions will need more assessment (Dalal et al., 2003; Six et al., 2004; Lal et al., 2007). Zero tillage can promote shallow compaction in fine textured topsoils (Taboada et al., 1998; Díaz-Zorita et al., 2002; Sasal et al., 2006) and no-till farming can reduce yield in poorly drained, clayey soils. Soil-specific research is needed to enhance applicability of no-till farming by alleviating biophysical, economic, social and cultural constraints (Lal et al., 2007).

Excessive soil compaction is of critical concern in industrial agriculture due to the use of heavier agricultural machines. A typical hazard is when high yielding crops (e.g., maize) are harvested during rainy seasons. Compaction recovery is not easy in zero tilled soils (Taboada et al., 1998; Díaz-Zorita et al., 2002; Sasal et al., 2006), which depend on soil biological mechanisms to reach a loosened condition. The alleviation and control of deep reaching soil compaction can be attained by adopting management strategies that control field traffic (Spoor et al., 2003; Pagliai et al., 2004; Hamza and Anderson, 2005; Spoor, 2006) and use mechanical (e.g., plowing) or biological (cover crop root channels) compaction recovery technology (Robson et al., 2002; Spoor et al., 2003).

A better understanding of biological mechanisms are needed, with particular focus on the role played by plant roots, soil microorganisms and meso- and macrofauna in the recovery of soil structure (Six et al., 2004; Taboada et al., 2004; Hamza and Anderson, 2005).

Increased botanical nitrogen-fixation can occur when legumes crops are rotated with cereals (Robson et al., 2002); green manure crops improve the N supply for succeeding crops (Thorup-Kristensen et al., 2003). In farms near animal production facilities (feed lots, poultry, pigs, dairy, etc.), organic animal manures may be a cheap source of essential plant nutrients and organic carbon (Edwards and Someshwar, 2000; Robson et al., 2002). The use of organic manures can be limited by problems associated with storage, handling, and transport (Edwards and Someshwar, 2000). In livestock grazing production systems, grazing intervals can be restricted and seasonal grazing intensity altered to reduce soil physical damage (Taboada et al., 1998; Menneer et al., 2004; Sims et al., 2005).

Continuous crop removal may eventually deplete native soil supplies of one or more nutrients. Some predict depletion of easily accessible P by 2025 at present annual exploitation rates of 138 million tonnes (Vance et al., 2003) while others estimate far less. Soil microbiology could potentially improve access to P, for example, through the use of P-solubilizing bacteria (Yadav and Tarafdar, 2001; Taradfar and

Claassen, 2005) and arbuscular mycorrhiza (Harrier and Watson, 2004). However, the use of microbes in P delivery to plants is complex. A better understanding of root growth is the optimal balance among plant, soil and microorganisms (Vance et al., 2003).

More field research is required to optimize the selection and production of crop varieties/species that enrich the diet with such elements as Ca, Zn, Cu, and Fe. Given the usually substantial residual effects of most of fertilizer nutrients (except N), they should be considered as investments in the future rather than annual costs. Replenishment of nutrients such as P, K, Ca, Mg, Zn through the use of agricultural by-products and biosolids and substitution and recycling of phosphorus (P) sources has been recommended (Kashmanian et al., 2000).

Soil conservation practices can reduce soil losses by wind and water erosion. Strategies for controlling sediment loss include (1) planting windbreaks and special crops to alter wind flow; (2) retaining plant residue after harvesting; (3) creating aggregates that resist entrainment, (4) increasing surface roughness; (5) improving farm equipment and (6) stabilizing soil surfaces using water or commercial products (Nordstrom and Hotta, 2004).

Improved management practices to prevent sediment loss may be effective (Nordstrom and Hotta, 2004). Many management techniques do not require sophisticated technology or great costs to implement, but they may require farmer willingness to change practices. Barriers to adoption of conservation measures include start-up or transition costs associated with new methods or equipment, inadequate education, reliance on past traditions, or a history of failed field experiments (Uri, 1999). Reluctance to implement soil conservation policies and practices can be overcome when severe erosion events associated with periods of drought remind society of the advantages of compatible methods of farming (Todhunter and Cihacek, 1999).

Shifting cultivation leads to deforestation and degradation, (Zhang et al., 2002). Most technical options to prevent agricultural expansion and abandonment are similar to those for preventing deforestation. They are also based on the promotion of off-farm employment (Mulley and Unruh, 2004), or the production of high-added value products combined with air transport. In order to increase farmers' natural capital and thereby increase long term flows of farm outputs, modifying the management of soil, water and vegetation resources, based on agroecology, conservation agriculture, agroforestry and sustainable rangeland and forest management, as well as wildlife biology and ecology has been supported (Buck et al., 2004).

Cultivation of new lands in some biomes would neither compensate nor justify the loss of irreplaceable ecological services. Other biomes are less sensitive and would not be similarly affected. The functional complementation of biomes is an effective land use option to explore on a broad scale (Viglizzo and Frank, 2006). For example, agricultural expansion in South America (Argentina, Bolivia, Brazil, Colombia) was based on the replacement of natural forests by cattle ranching and soybean cropping (Cardille and Foley, 2003; Vosti et al., 2003; Etter et al., 2006). There are potential benefits to conservation management that arise from agricultural land abandonment or extensification. In China conversion of cultivated land has not always decreased national food security, since many converted lands had low productivity (Deng et al., 2006). Abandonment of agricultural land does increase the vulnerability of farmers. Positive outcomes in one sector can have adverse effects elsewhere (Rounsevell et al., 2006). Modern biomass energy will gain a share in the future energy market and abandoned agricultural land is expected to be the largest contributor for energy crops; the geographical potential of abandoned land for 2050 ranges from about 130 to 410 EJ yr^{-1} and for 2100, from 240 to 850 EJ yr^{-1}. At a regional level, significant potentials are found in the former USSR, East Asia and South America (Hoogwijk et al., 2005).

Large scale, high input options. Large scale approaches to soil management are available and based on the replenishment of soil nutrients, site specific nutrient management and zero tillage. These approaches include: adoption of crop models to synchronize N supply with crop demand (Fageria and Baligar, 2005; Francis, 2005); adoption of precision agriculture and variable rate technologies for inputs such as nutrients, pesticides and seeds (Adrian et al., 2005); and improvement of N fertility for non-legumes by legume fixation, fertilizers, manures and composts.

Nitrogen use efficiency is currently less than 50% worldwide, thus increasing N efficiency may reduce the use of N fertilizers (Sommer et al., 2004; Fageria and Baligar, 2005; Ladha et al., 2005). Deep rooting crops could potentially serve to redistribute N for crops in areas with nitrate polluted groundwater (Berntsen et al., 2006).

Crop models assess tradeoffs among yield, resource-use efficiency and environmental outcomes (Timsina and Humphreys, 2006), but their effective adoption requires local calibration and validation, improved farmer knowledge, cost-effective and user friendly techniques (Ladha et al., 2005). The adoption of precision and variable rate technologies by farmers is significantly affected by their perception of usefulness and net benefit (Adrian et al., 2005). To be of more benefit to farmers, crop models need to more effectively couple the spatial variability of crop yields and soil properties obtained by remote sensing and variable rate machinery needs improvement. Motivations for widespread uptake adoption of these technologies may come from environmental legislation and public concern over agrochemical use (Zhang et al., 2002).

Efficient use of N fertilizer requires that the amount and timing of the fertilizer application be synchronized with the needs of the crop (Ladha et al., 2005). The availability of the soil to supply N to the crop is closely linked with soil organic matter; maintenance of soil organic matter is a key factor in maintaining N fertility (Robson et al., 2002). Legumes are grown in rotations both for the contribution to the residual N and for the value of the crop itself (i.e., forage or food). To encourage the adoption of modern agricultural technologies governments and others will need to ensure farmers have access to technical advice, economic incentives and public education programs.

Whereas N efficiency and uptake is key for some regions, in others soil erosion control practices, such as contour cropping and terracing in soils of better quality (Popp et al., 2002), are more viable options. Soil erosion control can be costly and hence difficult to implement in developing countries (Wheaton and Monke, 2001). Governments can help by providing technical advice, economic incentives and public education programs (Warkentin, 2001). Land care schemes have been successfully adopted in several countries, and are effective in promoting "land literacy" and good agricultural practices, including leys and crop rotations and growing cover crops (Lal, 2001).

6.6.2.2 Options for low fertility lands

Agroforestry. In tropical areas, low fertility is often found in deforested areas, where critical topsoil has washed away. The replacement of traditional slash and burn cultivation by more diversified production systems based on forest products, orchard products, and forages and food products (Barrett et al., 2001; Ponsioen et al., 2006; Smaling and Dixon, 2006) and applying agroecological principles creatively (Altieri, 2002; Dalgaard et al., 2003) can improve soil fertility.

The adoption of agroforestry can maintain land productivity, decrease land degradation and improve rural people's livelihood (Albrecht and Kandji, 2003; Oelberman et al., 2004; Schroth et al., 2004; Reyes et al., 2005; Jiambo, 2006; Rasul and Thapa, 2006). At the landscape scale, the spatial organization of tree and forest landscape elements can provide filters for overland flow of water and sediments as well as corridors for forest biota, connecting areas with more specific conservation functions. At plot and regional scales, the relationship is more variable because watershed functions not only depend on plot-level land use but also on the spatial organization of trees in a landscape, infiltration, dry-season flow, and other factors (Van Noordwijk et al., 2007).

Consecutive nutrient exports may lead to extremely low K and P levels (Alfaia et al., 2004), e.g., decreased N and P availability with alley cropping (Radersma et al., 2004). Some crops, e.g., sugarcane (*Saccharum officinarum*) seem to be unsuitable for agroforestry (Pinto et al., 2005). Ecological agriculture could become an alternative if market distortions created by subsidies were removed, financial benefits were provided to resource-conserving farmers, and extension, credit, research were available (Rasul and Thapa, 2003). The adoption of integrated soil fertility management strategies at the farm and landscape scale requires consensus building activities (Barrios et al., 2006). However, promoting and supporting participatory technologies have limited impact when they are not grounded in participatory policy development and implementation (Desbiez et al., 2004; De Jager, 2005). Labor-intenseive ecoagriculture will not succeed unless farmers and the agricultural sector have higher total factor productivity including total labor productivity (Buck et al., 2004).

Soil water conservation and storage. The adoption of conservation agriculture is key to increasing water storage in marginal lands, and in most places suitable equipment is available (hand, animal-drawn, or tractor-drawn) for resource-poor farmers (Bolliger et al., 2006). Adoption of conservation agriculture also reduces soil erosion losses, (den Biggelaar et al., 2003) decreases siltation and pollution of water bodies, and has benefits for human health and biodiversity. Efforts to promote soil water conservation and storage will need to address site-specific conditions (Knowler and Bradshaw, 2007). Widespread implementation will require integration into institutions, incentive structures, and education (Molden et al., 2007) and extension outreach.

Methods to be considered include (1) conservation agriculture, including the use of water-efficient crops; (2) supplemental irrigation in rainfed areas; and (3) water harvesting in drier environments (Goel and Kumar, 2005; Hatibu et al., 2006; Oweis and Hachum, 2006).

Soil amendments. Municipal waste materials, composted or uncomposted (such as leaves and grass clippings, sludges, etc.), can be valuable soil amendments for farms near cities or towns and are inexpensive if transport costs are low (Smith 1996; Kashmanian et al., 2000). Municipal sludges can be also applied to cropland provided they possess the qualities needed by their potential users and do not possess toxins or heavy metals, such as nickel or cadmium (Smith, 1996). Other developments such as N-fixation by non-legume crops (e.g., *Azospyrilllum*), P solubilizing bacteria, and mycorrhizal associations in tropical cropping systems are expected to result from future biotechnology investigations (Cardoso and Kuyper, 2006).

The high risk of crop failure from insufficient soil moisture hinders investments in soil fertility and tilth, which in turn diminishes the potential of soils to capture and retain water, therefore increasing the vulnerability to drought. A challenge for AKST will therefore be how to couple incremental improvements in crop water relations with low-cost investments to replenish soil fertility in order to break this cycle (Rockström, 2004; Sanchez, 2005). More widespread use of practices like green manuring, composting, farmyard manure management, and use of agricultural by-products and residues can guide decision-making.

6.6.3 Sustainable use of water resources to meet on-farm food and fiber demands

A major challenge over the next 50 years will be to meet food and fiber demand with minimal increases in the amount of water diverted to agriculture. Aquatic ecosystems and people whose livelihoods depend on them are likely to be the biggest losers as more and more fresh water is diverted to agriculture on a global scale.

AKST can provide options for improving water management in agriculture that can address the growing problem of water scarcity, ecosystem sustainability and poverty alleviation. Chapters 4 and 5 present projections concerning the land and water required at the global level to produce enough food to feed the world in 2050. These include reliance on various options including intensification and expansion of rainfed and irrigated agriculture and trade as entry points to reduce the need to expand water and land diverted to agricultural production. In an optimistic rainfed scenario, reaching 80% maximum obtainable yields, while relying on minimal increases in irrigated production, the total cropped area would have to increase by 7%, and the total increase in water use would be 30%, with direct water withdrawals increasing by only 19%. In contrast, focusing on irrigation first could contribute 55% of the total value of food supply by 2050. But that expansion of irrigation would require 40%

more withdrawals of water for agriculture, surely a threat to aquatic ecosystems and capture fisheries in many areas.

The factors that contribute to optimistic and pessimistic estimates of total water needs are primarily differences in water productivity. Without gains in water productivity, water resources devoted to agricultural production will likely increase by 70-90%. On top of this is the amount of water needed to produce fiber and biomass for energy. The real world is more complex than the scenarios. Improvements will need to be made in water management across all agricultural systems, rainfed, irrigated, and combinations in between. It will be necessary to look beyond increasing water productivity to target poor people and ecosystems to benefit from these improvements. AKST will be needed that targets both physical (not enough water to meet all demands) and economic (not enough investment in water) water scarcity. Climate change and bioenergy increase the scale of the challenge, by increasing pressures on resources, and by increasing climate variability, but do not alter the nature of the challenge.

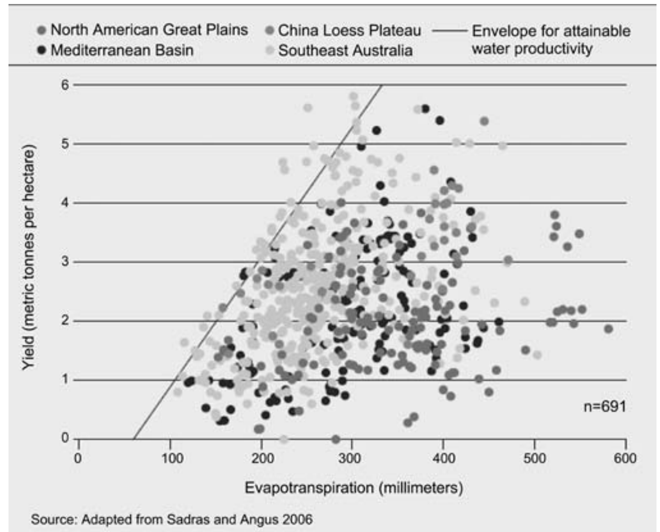


Figure 6-1. *Water productivity 'gap.'* Source: Sadras and Angus, 2006.

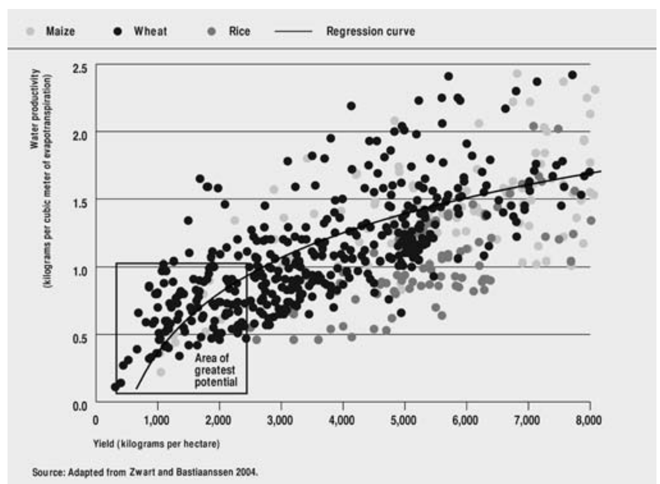


Figure 6-2. *Water productivity and yield.* Source: Adapted from Zwart and Bastiaanssen, 2004.

6.6.3.1 Managing evapotranspiration

Optimistic scenarios for mitigating increased water demand in agricultural systems require that water productivity be increased. This can be achieved with existing AKST, e.g., at the plot level in rainfed systems where evaporation can be very high and soil constraints are still significant, and at a system and basin level by reducing unproductive losses in landscapes. Crop breeding to gain increased benefit from water used and as yet unexplored opportunities to use precision water management to raise biomass/transpiration ratios are promising for intensive systems.

There is significant scope to reduce evapotranspiration (ET) per unit of yield by reducing evaporation and improving soil quality (Figure 6-1) (Molden et al., 2007). In many parts of the world, reducing evaporation and removing soil constraints are still important options for increasing water productivity. In very productive agricultural areas of the world, which produce most of the world's food, the historic sources of growth in water productivity—increased harvest index, soil nutrients—are being rapidly exhausted (Keller and Seckler, 2004). In contrast, currently areas with the greatest potential to increase water productivity in terms of ET are low production regions, especially sub-Saharan Africa and South Asia (Figure 6-2). These are also areas with high rates of poverty and high dependence of the poor on agriculture. Focus on these areas will both help reduce poverty, and also reduce the amount of additional water needed in agriculture.

Evaporation varies from 4-25% in irrigated systems (Burt et al., 2001), and from 30-40% and more in rainfed systems (Rockström et al., 2003) and depends on application method, climate and how much of the soil is shaded by leaves by the crop canopy; it can be very high in rainfed systems with low plant densities. Practices increasing water productivity such as mulching, plowing or breeding for early vigor of leaf expansion in order to shade the ground as rapidly as possible or longer superficial roots can reduce evaporation and increase productive transpiration.

Improvement of soil fertility can significantly improve transpiration efficiency and improving soil physical properties including infiltration and water storage capacity can reduce evaporation. Together these methods can result in 100% or larger increases in crop water productivity (Bossio et al., 2008). Recent examples of water productivity improvement potential through resource-conserving agricultural practices demonstrate this (Table 6-3). Only moderate effects on crop water productivity should be expected from plant genetic improvements over the next 15 to 20 years, because these gains have already been realized through breeding for increased harvest index in major grain crops. However harvest index gains through breeding strategies that target crops like millet and sorghum that have not received as much attention as the "green revolution" grains may be possible. An opportunity for improving value per unit of water also lies in enhancing nutritional quality of staple foods. Here perhaps biotechnology may offer significant potential over time (Molden et al., 2007). New precision ap-

Table 6-3. **Changes in water productivity (WP) by crop with adoption of sustainable agricultural technologies and practices in 144 projects.**

Crops	WP before intervention	WP after intervention	WP gain	Increase in WP
	-------------------kg food m^{-3} water ET-----------------			%
Irrigated				
Rice (n = 18)	1.03 (±0.52)	1.19 (±0.49)	0.16 (±0.16)	15.5
Cotton (n = 8)	0.17 (±0.10)	0.22 (±0.13)	0.05 (±0.05)	29.4
Rain-fed				
Cereals (n = 80)	0.47 (±0.51)	0.80 (±0.81)	0.33 (±0.45)	70.2
Legumes (n = 19)	0.43 (±0.29)	0.87 (±0.68)	0.44 (±0.47)	102.3
Roots and tubers (n = 14)	2.79 (±2.72)	5.79 (±4.04)	3.00 (±2.43)	107.5

Source: Pretty et al., 2006.

proaches to water management, such as irrigation of partial root systems may hold promise for increasing production per unit of water transpired in specialized production systems (Davies et al., 2002).

Besides crop and field practices, there is significant scope for reducing evaporation at the basin and landscape scales (Molden et al., 2007). High evaporation rates from high water tables and waterlogged areas can be reduced by drainage, or reducing water applications, after ensuring that these are not wetland areas supporting other ecosystem services. In degraded arid environments, up to 90% of rainfall evaporates back into the atmosphere with only 10% available for transpiration. Water harvesting in dry areas is an effective method of making available the non-beneficial evaporation of rainwater for crop transpiration (Oweis, 1999). Micro and macro-catchment techniques capture runoff and make it available for plants and livestock before evaporation, increasing the availability of beneficial rainwater, nearly halving evaporation and quadrupling increase in transpiration.

Another option is to increase the use of marginal quality water for agricultural production. While marginal-quality waters, (wastewater, saline or sodic water), potentially represent a valuable source of water for agricultural production, long term environmental and health risks are significant and must be mitigated. The prevalence of and opportunities for increasing, the use of marginal quality water in agricultural production was recently assessed (Qadir et al., 2007). Public agencies in several countries already implement policies on marginal-quality water. Egypt plans to increase its official reuse of marginal-quality water from 10% in 2000 to about 17% by 2017 (Egypt MWRI, 2004). In Tunisia in 2003 about 43% of wastewater was used after treatment. Wastewater use will increase in India, as the proportion of freshwater in agricultural deliveries declines from 85% today to 77% by 2025, reflecting rising demand for freshwater in cities (India CWC, 2002).

Worldwide, marginal-quality water will become an increasingly important component of agricultural water supplies, particularly in water-scarce countries (Abdel-Dayem, 1999). Water supply and water quality degradation are global concerns that will intensify with increasing water demand, the unexpected impacts of extreme events, and climate change in resource-poor countries (Watson et al., 1998). State of the art systems to maximize use of saline drainage waters are currently under development in California and Australia (Figure 6-3) (Qadir et al., 2007). AKST development for sustainable use of marginal quality water is an urgent need for the future.

6.6.3.2 Multiple use livelihoods approach

Poverty reduction strategies entail elements primarily related to policy and institutional interventions to improve access for the poor to reliable, safe and affordable water. AKST contributes to increase the effectiveness agricultural water utilization by the poor. To secure water use rights now and in the future and to avoid or control the risks of unsustainable water management, it is important to understand water as a larger "bundle of rights" (water access and withdrawal rights, operational rights, decision making rights) (Cremers et al., 2005; Castillo et al., 2007). Policy and institutional interventions are described in later chapters; here the focus is on AKST options that can contribute to poverty alleviation in the future, namely, multiple use system design, small scale water management technologies, and sustainable development of groundwater resources, primarily aimed at small scale farming systems in tropical countries.

While most water use analysis focuses on crop production (particularly in irrigated systems), it is possible to increase the productivity of other components of mixed systems to provide greater overall benefit for the rural poor (Molden et al., 2007), improve health for the local population and increase biodiversity. The design, development and management of water resources infrastructure from a multiple use livelihoods perspective, can maximize the benefits per unit of water, and improve health. The integration of various water use sectors including crop, livestock, fisheries and biodiversity in infrastructure planning can result in increased overall productivity at the same level of water use, and can be compatible with improving health and maintaining biodiversity.

Livestock. Although there are few examples of research and assessments that attempt to understand the total water needs of livestock and how animal production affects water

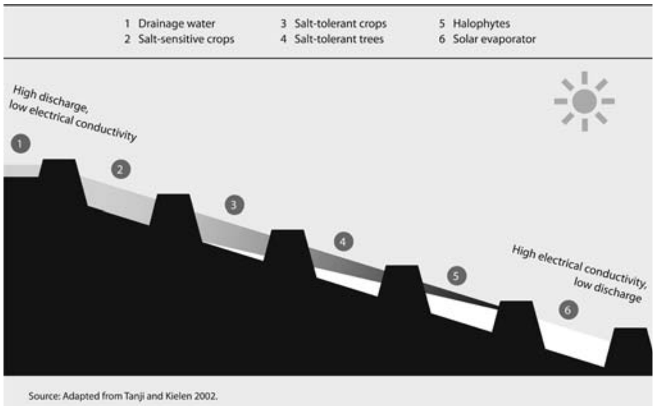


Figure 6-3. *Sequential reuse of drainage water on drainage affected lands.* Source: Qadir et al., 2007.

Note: As proposed in the San Joaquin Valley drainage Implementation Program, California.

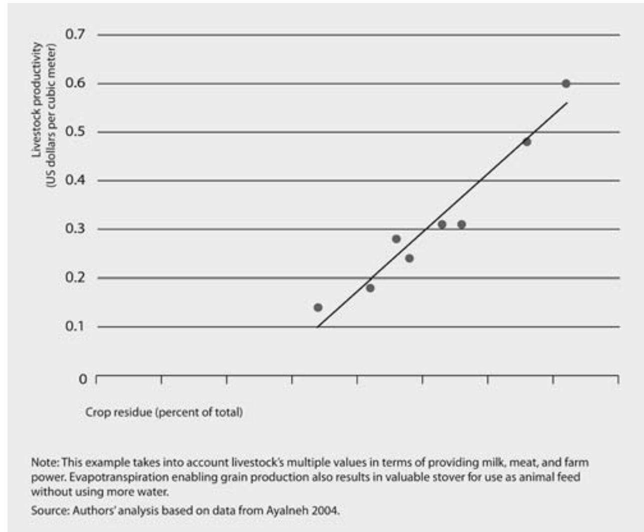


Figure 6-4. *Livestock water productivity relative to dietary crop residues and by-products in Ethiopia's Awash River Valley.* Source: Peden et al., 2007.

resources, a recent assessment (Peden et al., 2007) describes four entry points to maximize investment returns in water and livestock in mixed systems:

- Improving the source of feeds; e.g., in low productivity mixed systems in Ethiopia, livestock water productivity increases as the share of animal diets composed of crop residues increases (Figure 6-4) (Peden et al., 2007);
- Enhancing animal productivity through traditional animal science interventions in nutrition, genetics, veterinary health, marketing and animal husbandry;
- Conserving water resources critically need for grazing management; and
- Providing sufficient drinking water; water deprivation reduces feed intake and lowers production. For lactating cows water deprivation can greatly lower milk production (Staal et al., 2001).

While more research and site specific knowledge is needed, it is clear that securing improved outcomes in the development of agricultural water in the future will benefit from effective integration and consideration of animal use and their effect on water resources (Peden et al., 2007).

Fisheries. Fisheries can be enhanced in many existing and planned water management structures such as small dams, reservoirs, and impounded floodplains through stocking with appropriate species, greatly increasing productivity. Stocking technologies have produced high yields in lakes (Welcomme and Barley, 1998); in dams and reservoirs in Thailand, Indonesia, the Philippines and Malaysia (Fernando, 1977), in China (De Silva, 2003), and India (Sugunan and Katiha, 2004); and in floodplains in Hungary (Pinter, 1983), Bangladesh (Ahmed, 1998), and India (Sugunan and Sinha, 2001). Species introductions, and other enhancement technologies, such as fish holes, drain-in ponds, dugouts and finger ponds also effectively increase production (Dugan et al., 2007). Improved stocking management can increase production in integrated agriculture-aquaculture systems; a widespread type is integration of fish into rice paddies. While typically rice paddies produce 120-300 kg ha^{-1} yr^{-} of mixed fish which contribute directly to household diets, managed fish stocking and harvest can increase rice yields (due to weed control and the aeration of soils) by some 10% while producing up to 1,500 kg ha^{-1} fish (de la Cruz, 1994; Halwart and Gupta, 2004).

Health and water management systems. Under conditions that allow control of water levels, such as irrigated areas, dry season irrigation in monsoon areas and on relatively free draining soils, water management techniques can bridge the gap between agricultural and health departments (Bakker et al., 1999). These techniques include alternate wet and dry irrigation; water saving irrigation technologies; modernization of infrastructure to minimize standing water and reduce sites for disease vector breeding; and organizational initiatives such as Water Users Associations and improved extension services. Banning the use of the most toxic pesticides and promoting integrated pest management (IPM) is a high priority for preventing poisoning via water (Eddleston et al., 2002). In this case, human health and environmental interests (reducing pesticide loads) are complimentary. In addition, operation of existing dams can be re-optimized to improve health and environmental performance, such as to restore floodplain ecosystems, and new irrigation schemes can be planned and designed to minimize environmental impacts (Faurés et al., 2007).

Biodiversity. Water resources infrastructure and agricultural landscapes can be managed to maintain biodiversity and other ecosystem services beyond production of food and fiber. Water resources infrastructure can be planned and implemented in ways that minimize the impact on the native biodiversity. Biodiversity concerns need to be addressed from the earliest stages of project planning; e.g., situating infrastructure in such a way as to avoid harming critical habitats (Ledec and Quintero, 2003). At the landscape scale, the spatial organization of tree and forest landscape elements can provide filters for overland flow of water and sediments and corridors for forest biota, connecting areas with more specific conservation functions (Van Noordwijk et al., 2007). At plot and regional scales, the relationship is more variable because watershed functions not only depend on plot-level land use but also on the spatial organization of trees in a landscape, infiltration, dry-season flow, and other factors. Natural disturbance has a role in maintaining landscape biodiversity. Options for conserving biodiversity in irrigated agricultural systems include increasing water productivity and many water management designs and practices that support diverse landscapes, crops and connectivity for plant and animal movement (Molden and Tharme, 2004).

Traditional irrigation infrastructure development is one avenue for poverty alleviation; significant benefits have been demonstrated through a variety of primary and secondary effects of irrigation system development (Hussain, 2005; Castillo et al., 2007) and management strategies can improve equity in irrigation systems and can be complimentary to productivity enhancement (Hussain, 2005). As an example, land distribution that results in larger numbers of smaller holding can improve benefit sharing. Appropriate irrigation service charges can ensure adequate spending on operations and maintenance; this supports the poor, who tend to suffer the most when system level maintenance is inadequate.

6.6.3.3 Management and financing options

In order to maintain aquatic ecosystems, managers are increasingly pressed to maintain agricultural returns with reduced water delivery to irrigation systems. Reducing water delivered to irrigation requires two actions—a change in agricultural practice combined with a change in water allocation (Molden et al., 2007). Increasing blue water productivity by reducing water deliveries to agriculture, yet maintaining output, is an important strategy to retain water in aquatic ecosystems, to reallocate supplies, and to help in more precise water management, giving water managers more flexibility to deliver water to where it is needed, when it is needed. Excessive deliveries generate excessive drainage that are hard to control, require energy for pumping, reduce the quality of water and water bodies can provide breeding ground for disease vectors. Moreover, there are high ecological benefits in keeping water in rivers.

There are significant opportunities to improve irrigation water productivity through a combination of field and system management practices, and policy incentives that raise water productivity, manage salinity and increase yields (e.g., Van Dam et al., 2006). For example, there is substantial scope to reduce water deliveries to irrigation, especially to rice (Bouman et al., 2007). In addition to producing more food, there are ample opportunities in irrigation to generate more value and incur less social and environmental costs.

Supplemental irrigation, the addition of small amounts of water optimally timed to supplement rain, is probably the best way to increase water productivity of supplies. In Burkina Faso and Kenya, yields were increased from 0.5 to 1.5-2.0 tonnes ha^{-1} with supplemental irrigation and soil fertility management (Rockström et al., 2003). Yields can be further increased with deficit irrigation, where water supplied is less than crop requirements (Zhang, 2003). Increased precision in water management is more capital intensive and therefore particularly relevant to maintaining high productivity while decreasing water diversions. In Western Syria, yields increased from 2 to 5 tonnes ha^{-1} with the timely application of 100 to 200 mm of water (Oweis et al., 2003). It must be noted, however, that precision and deficit irrigation increase risk, and therefore are most appropriate under conditions where access to water is assured, and can be carefully managed.

A key point however, is that increasing productivity of water does not necessarily drive water savings; it may encourage increased water use because it is more productive (Ahmed et al., 2007). Thus changing allocation policies is also essential to realize reduced diversions of water.

Reducing deliveries also does not necessarily save water and can have unintended detrimental side effects that can be understood by considering what happens to drainage flows. A common misperception is that because irrigation is typically 40 to 50% efficient at converting irrigation water into evapotranspiration, the focus should be on increasing efficiency and therefore reducing drainage flows (Seckler et al., 2003). Increasing efficiency can be a valuable objective for reducing uptake of water in the system and thus diminishing energy costs of pumping and operation and maintenance. However, drainage water plays an important role. Because so much drainage flow is reused downstream, there is actually much less scope in saving water in irrigation than commonly perceived. In fact, in irrigated regions in dry areas it is common to document ratios of evapotranspiration to irrigation plus rain greater than 60% reaching to over 100% when aquifers are mined. These areas include the Gediz basin in Turkey (Droogers and Kite, 1999), Egypt's Nile (Keller and Keller, 1995), Chistian sub-division in Pakistan and the Bhakra irrigation system (Molden et al., 2000), the Liu Yuan Ku irrigation system (Khan et al, 2006), the Tunuyuan irrigated area in Argentina, the Fayoum in Egypt, and Nilo Coelho in Brazil (Bos, 2004). The perennial vegetation at Kirindi Oya has been shown to evapotranspire about the same volume of water as rice and generate valuable ecosystem services; giving a different picture (65% of inflows beneficially depleted) than if paddy rice were considered alone (22% of inflows depleted by rice) (Renaud et al., 2001). In these cases, the problem is not wastage, but that high withdrawals and ET rate reduce drainage and tend to dry up rivers and wetlands, and leave little to downstream use. It is important to consider each case from a basin perspective, i.e., considering the quality and quantity of water and how drainage flows are used downstream.

Technologies such as treadle pumps, small diesel pumps, low-cost drip, and low-cost water storage can increase productivity and incomes for poor farmers (Sauder, 1992; Shah et. al., 2000; Keller et al., 2001; Polak et al., 2004). These approaches provide water at lower unit costs than large scale hydraulic infrastructure, and can be available immediately, without the long delay times of larger scale projects. Innovative development and marketing approaches that focus on increasing local private enterprise capacities and market promotion have been credited with successful dissemination to the poor (Shah et al., 2000). Credit schemes focusing on women also can have a positive effect on poverty alleviation (Van Koppen and Mahmud, 1996). By improving the precision of water delivery, these technologies can also help to increase water use efficiency, under the right conditions. There are different niches where these technologies are useful. In general treadle pumps are most suitable when water tables are within 2-4 m of soil surface. This situation is common in monsoon Asia, and exists when treadle pumps are linked to rainwater harvesting structures, but is relatively rare outside wetland or direct pumping from lakes and water bodies in Africa.

Groundwater resources. Groundwater can provide flexible, on-demand irrigation to support diversified agriculture in all climate zones. Sustainable management requires that aquifer depletion be minimized and water quality be preserved. Overwhelming evidence from Asia suggests that groundwater irrigation promotes greater gender, class, and spatial equity than do large irrigation projects. Evidence from Africa, Asia, and Latin America also suggests that groundwater is important for poor farmers to improve their livelihoods through small scale farming based on shallow groundwater (Shah et al., 2007). Small scale technologies (see above) can improve access of the poor to groundwater resources. In all parts of the developing world key common priorities for AKST are to improve the data base, upgrade the understanding of groundwater supply and demand conditions, and create effective programs for public education in the sustainable use of groundwater resources (Shah et al., 2007). Participatory approaches to sustainable groundwater management will need to combine supply-side AKST such as artificial recharge, aquifer recovery, inter-basin transfer of water, with demand-side AKST such as groundwater pricing, legal and regulatory control, water rights and withdrawal permits (see chapter 7), and promotion of water-saving crops and technologies.

Decreasing land degradation. Water use efficiency, which is often as low as only 40%, in irrigated areas (Deng et al., 2006), can be increased. This is key to reducing recharge to naturally saline areas and water tables. Where soil salinity is high, leaching fractions must be applied to remove salt from the root zone, without adding it to groundwater or mobilizing it to the river system; this is difficult and requires well thought out, innovative drainage solutions. Recognized options for management of salinity risk, or to reduce existing areas of saline soil, are revegetation with alternative species, pumping to lower the water table and construction of ditch drains for control of surface water and shallow groundwater (Peck and Hatton, 2003).

Management of salinity is complex and requires integrated solutions at catchment and basin scale with the key being to minimize mobilization of salt and reduce the amount for disposal—disposal through the stream system is undesirable and environmentally costly. All options for management of salinity risk are constrained by the economics of dry land farming and pumping or drainage is further constrained by possible environmental impacts of disposal of saline water. In Australia, the bulk of effort has been directed at ”living with saline land and water,” with immense public and private investment in tree planting and the search for new low recharge farming systems (Peck and Hatton, 2003). Practices to improve water use efficiency include biological mechanisms of water-saving agriculture and irrigation technologies, including low pressure irrigation, furrow irrigation, plastic mulches, drip irrigation under plastic, rainfall harvesting and terracing (Deng et al., 2006).

6.7 Using AKST to improve Health and Nutrition

AKST can improve human health and nutrition through reductions in (1) malnutrition and micronutrient deficiencies; (2) food contaminants; and (3) the emergence and reemergence of human and animal diseases, including HIV/AIDS. Key driving forces over the coming decades for these challenges include not just AKST, but also demographic change; changes in ecosystem services; global environmental change; reductions in freshwater resources; economic growth and its distribution; trade and travel; rate of technology development; governance; degree of investment in public health and health care systems; and others.

In addition, some food systems are not providing the range of nutrients needed to ensure adequate nutritional status. Approaches to improve dietary quality are needed to ensure adequate availability, accessibility, and utilization of foods with nutrients appropriate to the needs of the population.

6.7.1 On-farm options for reducing malnutrition and micronutrient deficiencies

Integrated farm systems, based on a variety of foods, can help meet the challenge of micronutrient malnutrition (Tontisirin et al., 2002). Improving crop diversity is an important part of improving dietary diversity, and thereby dietary quality. The diversity of wild and cultivated traditional plant varieties in rural areas of low-income countries provides many opportunities to identify high quality, but underutilized, nutritious foods. Increased research on locally adapted traditional varieties could lead to the development of improved varieties that are higher yielding or more resistant to pests and abiotic stresses such as drought. Household processing of wild foods collected by subsistence farmers as part of a traditional diet would increase storage life and make additional foods available during periods when food is inadequate. For example, solar drying techniques have been used to preserve foods such as mangoes, bananas and sweet potatoes.

Possible improvement of these varieties through breeding is currently limited because private and public sector breeding programs rarely focus on minor crops. Identifying and exploiting the potential of these varieties will require increased research in both high- and low-income countries. In Kenya, when farmers produced underutilized leafy green vegetable varieties, consumption was increased among farmers, and the producers found a market among middle and high income consumers who began to purchase these novel varieties (Frison et al., 2006). Once researchers identify health promoting compounds in indigenous and underutilized plants, plant breeders can develop varieties of these foods that can be produced and consumed by small-scale farmers as well as sold in high value niche markets. Beyond increasing the availability of diverse foods, preservation methods must be improved to reduce the loss of micronutrients (Ndawula et al., 2004).

In addition to increasing the range of plant foods in the diet, animal source foods, such as meat, milk, and insects from wild and domesticated sources can provide critical nutrients that may be completely unavailable in plant-based diets, such as vitamin B_{12} (Neumann et al., 2002; for Kenyan example see Siekmann et al., 2003). An effective strategy to increase the intake of animal source foods could include the improved small-scale livestock production through the use of appropriate breeds, disease prevention and control, and affordable high quality animal feeds (Brown, 2003).

Improving soil management practices, such as increasing the organic matter in the soil and mineral fertilizers (Sheldrick and Lingard, 2004), can improve food security and enable farmers to produce sufficient yields and allow for more crop diversification. These practices can optimize plant nutritional quality. For example, crops grown on zinc deficient soils often produce grains with low zinc concentrations and these seeds may produce plants with lower grain yields and poorer seed quality (Rengel, 2001). Soil management solutions have the advantage of providing a wide range of nutrients, while other approaches, such as fortification and supplements are limited to specific nutrients.

6.7.2 Research needs for reducing malnutrition and micronutrient deficiencies

Biofortified crops developed through plant breeding can improve human nutrition. Biofortification has shown promise in feeding studies in the Philippines where iron biofortified rice consumption improved iron status in the study participants (Murray-Kolb et al., 2004). While conventional processed food fortification can work well to improve the availability of critical nutrients in the diet, rural subsistence producers may not have access to fortified foods. Thus, where food processing facilities are unavailable, biofortification can improve the availability of target nutrients. In addition, where government regulation and enforcement of food fortification is still in the nascent stages of development, biofortified crops can serve as a cost-effective source of micronutrients. Dietary quality can be improved by selection of crop varieties that are more nutritionally dense when these are substituted for less nutritious alternatives. Consumption of carotenoid-rich red palm oil in lieu of other vegetable oils has improved vitamin A status in Burkina Faso (Zagre et al., 2003), while lysine and tryptophan-rich maize may offer improved growth potential for undernourished children consuming diets with low protein quality (Graham et al., 1990).

While plant breeding efforts to biofortify staple crops are underway, plant-breeding programs can also target health-related qualities such as antioxidants in fruits or vegetables (HarvestPlus, 2006). For example, plant breeders can select for high lutein content, an antioxidant with beneficial effects on eye health (Seddon, 2007) in carrots (Nicolle et al., 2004). Plant breeding can include traditional techniques and approaches using advances in biotechnology, such as rDNA. Conventional plant breeding methods have been used to develop biofortified crops and rDNA approaches have increased carotenoid content in rice (Beyer et al., 2002). While approaches using rDNA and similar techniques have the potential to contribute to developing nutritionally improved crop varieties, research, monitoring, and evaluation are needed to ensure there are no adverse unintended consequences to human and environmental health.

Reducing food contaminants. When present in food systems, heavy metals and other contaminants, veterinary drug residues, pesticide residues, pathogens, and the toxins produced by pathogens such as mycotoxins can cause a range of short- and longer-term adverse human health consequences.

Good agricultural practices (GAPs) can lead to safer use of pesticides and veterinary drugs. GAPs can also enable the management of risks associated with pathogen contamination of foods such as fruits and vegetables. FAO has developed guidance for governments and the private sector on conducting risk assessments and to implementing risk management options throughout food systems, including on-farm practices and in food processing facilities (FAO/WHO, 2006). Hazard analysis critical control point principles can be used to target issues of biosecurity, disease monitoring and reporting, safety of inputs (including agricultural and veterinary chemicals), control of potential foodborne pathogens, and traceability (Olson and Slack, 2006). The development and adoption of GAPs for specific production systems and food safety/quality issues can be facilitated by approaches that involve broad participation. Plants can become susceptible to infection with the fungus that produces aflatoxins when they are exposed to water stress or insect damage (Dowd, 2003). There are readily available approaches management approaches (preharvest, harvest, and postharvest) to reduce aflatoxin (Mishra and Das, 2003); e.g., in tree nuts, peanuts, and cereals such as maize.

In addition, dietary approaches are being developed to counteract the effects of mycotoxins (Galvano et al., 2001). Additional research is needed to verify the detoxification ability of the proposed food components, their long-term efficacy and safety, and their economic and technical feasibility. To manage risks associated with pathogens such as *Escherichia coli* O157:H7 in fruit and vegetable production, sanitation systems throughout the food production chain are integral to GAPs guidance for preventing the presence of these organisms (Fairbrother and Nadeau, 2006). Additional strategies are being developed to reduce foodborne pathogens, e.g., chlorate as a food supplement to prevent colonization of food-producing animals by *E. coli* and other pathogens (Anderson et al., 2005).

Achieving fuller deployment of GAPs to improve food safety and public health requires establishing effective national regulatory standards and liability laws that are consistent with international best practice, along with the necessary infrastructure to ensure compliance, including sanitary and phytosanitary surveillance programs for animal and human health, laboratory analysis and research capabilities, and training and auditing programs. Challenges include harmonization of regulations establishing upper levels of intake of nutrients and other substances (Bennett and Klich, 2003), and improving food safety without creating barriers for poor producers and consumers.

Heavy metal contamination in soils affects the quality and safety of foods. For example, rice grains can accumulate cadmium (Cd) from Cd-contaminated soils, thereby exposing consumers to serious health consequences from consumption of locally produced rice (Chaney et al., 2004). Undernourished populations are particularly at risk, as iron and zinc deficiencies can cause increases in Cd absorption from the food supply (Anderson et al., 2004). While increased soil pH or maintaining soil flooding until grain maturation can reduce Cd levels in rice grains, yields can be affected (Chaney et al., 2004). Bioremediation with selected ecotypes of *Thlaspi caerulescens,* a hyperaccumulator of Cd, could effectively reduce levels in contaminated soil (Chaney et al., 2000). However, these wild ecotypes of *T. caerulescens* need to be improved for commercialization before practical applications of this technology would be available (Chaney et al., 2004).

6.7.3 Reduce factors that facilitate the emergence and reemergence of human and animal diseases

Communicable diseases are the primary cause for variations in life expectancy across countries (Pitcher et al., 2008). AKST is important for three broad categories of infectious diseases: diseases whose incidence is affected by agricultural systems and practices (e.g., malaria and bovine spongiform encephalopathy), foodborne zoonotic diseases, and epidemic zoonotic disease (e.g., avian influenza). For example, the expansion of irrigated agriculture, as a result of the need to further intensify food production and to better control water supplies under increased climate variability and change, is expected to contribute to an increased incidence of malaria in some areas and the rapidly increasing demand for livestock products could increase the likelihood of BSE to spread more widely.

The geographic range and incidence of many human and animal diseases are influenced by the drivers of AKST. Currently, 204 infectious diseases are considered to be emerging; 29 in livestock and 175 in humans (Taylor et al., 2001). Of these, 75% are zoonotic (diseases transmitted between animals and humans). The number of emerging plant, animal, and human diseases will increase in the future, with pathogens that infect more than one host species more likely to emerge than single-host species (Taylor et al., 2001). Factors driving disease emergence include intensification of crop and livestock systems, economic factors (e.g., expansion of international trade), social factors (changing diets and lifestyles) demographic factors (e.g., population growth), environmental factors (e.g., land use change and global climate change), and microbial evolution. Most of the factors that contributed to disease emergence will continue, if not intensify, this century (IOM, 1992). The increase in disease emergence will affect both high- and low-income countries.

Serious socioeconomic impacts can occur when diseases spread widely within human or animal populations, or when they spill over from animal reservoirs to human hosts (Cleaveland et al., 2001). Animal diseases not only affect animal and human health and welfare, they also influence perceptions of food safety, result in trade restrictions, adversely affect rural incomes and livelihoods, adversely affect non-livestock rural industries, have detrimental environmental effects, and adversely affect national economies for countries heavily dependent on agriculture Even small-scale animal disease outbreaks can have major economic impacts in pastoral communities (Rweyemamu et al., 2006).

6.7.3.1 On-farm options

The adoption integrated vector and pest management at the farm level, have been tested for reducing the persistence of human and animal diseases. These include environmental modification, such as filling and draining small water bodies, environmental manipulation, such as alternative wetting and drying of rice fields, and reducing contacts between vectors and humans, such as using cattle in some regions to divert malaria mosquitoes from people (Mutero et al., 2004; Mutero et al., 2006).

Specific farming practices can facilitate infectious disease emergence and reduce the incidence of certain diseases, such as malaria, in endemic regions (van der Hoek, 2004). However, the relationships between agriculture and infectious disease are not always straightforward. For example, whereas rice irrigation increases breeding grounds for the mosquito that carries malaria, in some regions the prevalence of malaria in irrigated villages is lower than in surrounding villages because better socioeconomic conditions allow greater use of antimalarials and bed nets (Ijumba et al., 2002) and/or because the mosquito vector tends to preferentially feed on cattle (Mutero et al., 2004). However, in other regions, intensification of irrigated rice reduces the capacity of women to manage malaria episodes among children, leading to a higher prevalence of malaria (De Plaen et al., 2004). Therefore, greater understanding is needed of the ecosystem and socioeconomic consequences of changes in agricultural systems and practices, and how these factors interact to alter disease risk.

In areas affected by high rates of HIV/AIDS, labor-saving agricultural technologies and systems are needed to support sustainable livelihoods. Ensuring access to diverse diets can also reduce the adverse impacts of disease on livelihoods and health. Agroforestry interventions, in particular, can improve communities' long-term resilience against HIV/AIDS and other external shocks in ways that agricultural interventions alone cannot (Gari, 2002).

In addition, improved agricultural information and knowledge exchange between experienced farmers and youth and widows is needed (Peter et. al., 2002). Agroforestry technology can respond to the cash, labor and shortages confronted by AIDS-affected communities, both in the short term and in the long term. Medicinal plants and trees often provide the only source of symptomatic relief available to the poor. Future agroforestry programs and forest policies in general should be reviewed to assess their effects on key determinants of HIV vulnerability (Villarreal et al., 2006). Using less labor intensive crops that need fewer inputs can help households allocate labor more efficiently in food producing activities (Ngwira et al., 2001). While diversifying food crop production to reduce labor demands can be helpful, the nutritional quality of the total diet must be considered.

6.7.3.2 Research and technological options beyond the farm

Resource poor farmers have limited resources to mitigate the spread of diseases. Controlling emerging infectious diseases requires early detection, through surveillance at national, regional, and international levels, and rapid intervention. For animal diseases, traceability, animal identification, and labeling also are needed. The main control methods for human and animal diseases include diagnostic tools, disease investigation facilities, and safe and effective treatments and/or vaccines. AKST under development can facilitate rapid detection of infectious pathogens, e.g., genetic tools were used in recent HPAI outbreaks to identify the viruses involved and to inform development of appropriate control programs (FAO/OIE/WHO, 2005). Syndromic surveillance of farm animals coupled with notification using internet-accessible devices is being used in some high-income countries to detect emerging diseases (Vourc'h et al., 2006).

The increasing importance of zoonotic diseases requires better integration of human and veterinary public health approaches for their detection, identification, monitoring, and control. Decreased funding in recent decades has eroded the required infrastructure and training underlying veterinary services and surveillance activities (Vallat and Mallet, 2006). Incentives to report cases of disease at the local and national levels and pay for culling of animals when appropriate could facilitate early identification of outbreaks. There is an urgent need to replenish basic capacity in many high-income countries and to increase capacity in middle- and low-income countries. Linkage of regional and international organizations and agencies is critical. Improved understanding is needed of disease transmission dynamics in order to develop more effective and efficient diagnostic systems and interventions. Diagnostic systems should be designed to process large numbers of samples and identify multiple infectious agents.

Although vaccines are a cornerstone of primary prevention, vaccine effectiveness is severely limited in remote rural areas with high infectious disease burdens, particularly Africa, South America, and Asia, due to the lack of vaccines, the lack of resources to afford vaccines, or the logistical problems of trying to use temperature-sensitive vaccines. Marker vaccines are needed so that vaccinated/treated animals can be distinguished from subclinically infected or convalescent animals in real time during epidemics (Laddomada, 2003).

The emergence and dissemination of bacteria resistant to antimicrobial agents is the result of complex interactions among antimicrobial agents (e.g., antibiotics), microorganisms, disease transmission dynamics, and the environment (Heinemann, 1999; Heinemann et al., 2000). The increasing incidence of antimicrobial resistant bacterial pathogens will limit future options for prevention and treatment of infectious diseases in animals and humans (McDermott et al., 2002). The World Health Organization has called for human and veterinary antimicrobial agents to be sold only under prescription, and for the rapid phaseout of antimicrobial agents used as growth promotants (WHO 2003). They also recommend that all countries establish monitoring programs for tracking antimicrobial use and resistance. Research on the use of other treatments, such as probiotics and vaccines, holds promise (Gilchrist et al., 2007). The ongoing costs of research and development, and challenges to delivery will prevent acute drug treatments from ever becoming a stand-alone solution.

6.7.4 Tackling persistent chemicals to protect human health and the environment

Persistent chemicals include potentially toxic elements like heavy metals and organic pollutants that are normally present at relatively low concentrations in soils, plants, or natural waters, and which may or may not be essential for the growth and development of plants, animals, or humans (Pierzynski et al., 2000).

6.7.4.1 On-farm options

More effective and less costly *in situ* management strategies are available to mitigate the effects of persistent chemicals and to restore soil quality. The load of persistent chemicals such as fertilizer and pesticide residues, to ground and surface waters can be significantly reduced by available technologies, such as precision agriculture. Restorative technologies like bioremediation and phytoremediation (plant based remediation) are costly and still in development. Basic research is needed on the factors affecting biotransformation processes (Adriano et al., 1999; Khan, 2005).

Intrinsic remediation using indigenous organisms can degrade industrial solvents (e.g., PCBs) and many pesticides on affected sites (Sadowski and Turco, 1999). *In situ* bioremediation can potentially treat organic and inorganic pollutants, clean soil without excavation and it is more cost effective than excavating and treating the soil on site bioremediation techniques. Such treatments remove the mobile and easily available fractions but cannot complete removal of all the contaminants (Doelman and Breedveld, 1999).

Phytoremediation refers to the extraction of contaminants via root uptake to shoot biomass and has wide application in the remediation of surface-polluted soils. Further analysis and discovery of genes for phytoremediation may benefit from recent developments in biotechnology (Krämer, 2005). Phytoremediation has potential risks, such as those associated to the use of transgenic techniques, release of nonindigenous species (potential weed) and transfer of toxic compounds to the other environmental compartments (Wenzel et al., 1999; Alkorta and Garbisu, 2001).

6.7.4.2 Off-farm technology

More effective and sensitive technologies for identifying early effects of pollution on ecosystems can also be developed. Damage could be prevented if the source of the pollution and the presence of the pollutants could be identified at minimal concentrations. Preventing or limiting the flow of chemical pollutants into the environment should be more effective than limiting damage by remediation.

New technologies that significantly increase awareness of biological impacts include biosensors and chemical approaches (Water Science and Technology Board, 2001; Heinemann et al., 2006). These approaches can also use indigenous organisms, e.g., ecotoxicological assessments of soils polluted with chromium and pentacholorophenol. The portal DATEST (http://projects.cba.muni.cz/datest) is a web-based engine that complements and stores information about a wide range of ecotoxicological tests and bioindication methods used in Ecological Risk Assessment (Smid et al., 2006).

6.7.5 Information and knowledge systems

6.7.5.1 Traditional, local knowledge options

Traditionally, many innovations for improving AKST occurred at the community level, and were diffused through community institutions (Gyasi et al., 2004). Traditional communities have domesticated dozens of plant species, have bred and conserved thousands of crop varieties and animals, and have developed farming (cropping and animal) systems and practices adapted to specific conditions (Kaihura and Stocking, 2003). Tapping on those resources and capacities and giving them recognition as well as legitimacy is a key development goal. A focus on agroecology can enrich the production and deployment of new farming practices and technologies that are environmentally, socially and culturally sustainable (Koontz et al., 2004).

Options for enhancing agricultural knowledge and innovation in local and indigenous societies include:

- Enhance local and traditional knowledge systems and grassroots innovation capacities;
- Empower communities to access knowledge and to participate in innovation processes so they have more options to respond to future changes and to biodiversity and livelihood challenges (Colfer, 2005);
- Develop a new agenda that builds on agricultural knowledge and innovation in local and indigenous societies: increase projects of international agricultural research institutions such as Bioversity International (formerly IPGRI);
- Foster participatory agricultural and environmental research projects that bring together traditional and western science (Brookfield et al., 2003; Colfer, 2004), journals such as *Etnoecologica*, and academic courses that include traditional and local knowledge.

Farmer field schools (see Chapter 2) could play a vital part as a community-based initiative for participatory research, enabling farmers to define and analyze problems, and experiment with options. Seed fairs can facilitate the selection of varieties better adapted to local conditions (Orindi and Ochieng, 2005) and adaptation to climate change. The establishment of "lead farmers" and the implementation of various grassroots extension mechanisms could reinforce the role of communities in the production and diffusion of knowledge.

6.7.5.2 Science and technology options

Advances in nanotechnology, remote sensing (RS), geographic information systems (GIS), global positioning systems (GPS) and information communication technology (ICT) can enhance progress in the application of precision and site-specific agriculture (PA).

A concern in precision agriculture is the accessibility and affordability of the technology for small farming systems. This is not surprising considering that the general trend is that farmers with large farmlands of more than 300 ha, tend to be the first to invest in the new technology, whereas small farmers are more reluctant to invest in GPS equipment (Pedersen et al., 2004). A nationwide survey in the USA concluded that adoption of PA technologies was related to farm size and large farmers are the first to adopt (Daberkow and McBride, 2001). Adoption rate is also faster in regions with larger farm sizes and more specialized in certain cash crops (Blackmore, 2000; Fountas et al., 2005). Adoption is likely to continue in countries where labor is scarce, and vast tracts of land exist, with rates of adoption accelerating when commodity prices are high and interest rates low (Swinton and Lowenberg-DeBoer, 2001).

Particularly for developing countries, the use of yield monitors, sensors, GIS and GPS, supported by advanced tools such as computer, digital camera, image processing technique, laser technology, and network system appear too complex for small-scale farmers, particularly for those whose field operations are not mechanized. Nevertheless, since precision farming being a management approach not a technology, it can be applied to developing countries industrialized countries, but the implementation may be different (Griepentrog and Blackmore, 2004).

Precision agriculture practices that can easily be adapted in developing countries include site specific nutrient management (SSNM) and simple integrated crop management (ICM) version like rice check (Lacy et al., 1999; Fairhurst et al., 2007; PhilRice, 2007). Thus, while the ownership of precision farming technologies is still an emerging option for small-scale agriculture, the adoption strategy can be adapted. Custom services can be used to help build precision farming databases while small-scale farmers gain experience with the spatial variability of their fields (Lowenberg-DeBoer, 1996).

6.7.5.2.1 Remote sensing technology

Remote sensing (RS) has a broad range of applications (urban and transportation planning, applied geosciences, land use, environmental change, etc.) in many countries, especially Europe and the United States where it is widely used, and can enhance agricultural planning for low productivity areas in developing countries.

For agriculture, RS techniques play an important role in crop identification, crop area inventory, crop yield forecasting, crop damage detection, soil and water resources inventory, and assessment of flood damage (Syam and Jusoff, 1999; Van Neil and McVicar, 2001; Patil et al., 2002). It also provides required inputs for land and water resources development plans, wasteland mapping and reclamation, irrigation development, crop-yield and crop-weather models, integrated pest management, integrated nutrient management, watershed management, agrometeorological services, and more recently, precision farming (Patil et al., 2002). Remote sensing contributes to the information needs of precision agriculture (PA) in the assessment of soil and crop conditions using multispectral imagery (Barnes and Floor, 1996).

Remote sensing is currently not widely applied in most developing countries because of timeliness, limited accessibility and cost of satellite data, and financial constraints in gathering ground data that can be correlated to the remote sensing data. It has, however, potential in improving agricultural planning in developing countries particularly in addressing food security, poverty alleviation, and sustainable development issues.

If combined with other sources of data (e.g., traditional method agrometeorological data collection) remote sensing can improve accuracy and effectiveness of various agricultural planning in developing countries. For example, RS estimates of crop yields and production of staple foods based on preharvest crop acreage and production can serve as input to a number of policy level decisions on buffer food stock (Van Neil and McVicar, 2001).

Remote sensing data can provide a sampling frame construction for agricultural statistics, crop acreage estimation, and cropland data layer or map (Allen, Hanuschak, and Craig, 2002; Saha and Jonna, 1994; Rao, 2005). Mapping soils can reveal soil properties across production fields (Dalal and Henry, 1986; Shonk et al., 1991; Mzuku et al., 2005). Remote sensing information also aids analysis of soil degradation and risk of soil erosion in agricultural lands (Thine, 2004).

By combining RS with GIS techniques, and hydrologic modeling, irrigation management can be improved for more complex water management tasks such as irrigation system performance evaluation, snowmelt runoff forecasts, reservoir sedimentation and storage loss assessments, prioritization of watersheds and their treatment, environmental impact assessment of developmental projects, prospecting of under ground water, locale specific water harvesting and recharge, interlinking of rivers and monitoring of spatial and temporal distribution of rainfall (Thiruvengadachari and Sakthivadivel, 1996). Given more time and resources, applications of RS in agricultural planning can be greatly enhanced in developing countries.

Remote sensing can also be applied to global agroenvironmental health and resources monitoring and assessment. Remote sensing can be used to assess biodiversity through (1) direct mapping of individual plants or associations of single species in relatively large, spatially contiguous units; (2) habitat mapping and predictions of species distribution based on habitat requirements; and (3) establishment of direct relationships between spectral radiance values recorded from remote sensors and species distribution patterns recorded from field observations (Nagendra, 2001; Zutta, 2003; Rao, 2005).

Satellite RS is increasingly becoming an important source of agrometeorological data (humidity, rainfall, temperature, wind, global radiation) as it can complement traditional methods of agrometeorological data collection (Sivakumar and Hinsman, 2004). Indian satellite systems, for example, operationally support disaster management by providing emergency communication links, cyclone warnings, flood forecasting data, rainfall monitoring and crop condition assessments (Rao, 2005).

Remote sensing can be used to globally monitor and assess natural resources and ecosystem for sustainable development, providing more accurate and timely information on the condition and health of agroenvironmental resources. There are, however, some technical issues and limitations of current remote sensing technologies use (Table 6-4).

6.7.5.2.2 Information and communications technology (ICT)

ICT models can be mainstreamed and upscaled to enhance delivery of services and access to market.

Market information. In Uganda, ICT is providing farmers with reliable price data for better farm gate prices. A market information service network reaching over 7 million people each week uses conventional media, Internet, and mobile phones to enable farmers, traders, and consumers to obtain accurate market information. Over the past four years the number of markets dominated by farmers' associations has increased from 4 to 8 (Ferris, 2004).

Weather forecasting. In Africa, ICT is enabling more rapid dissemination of locally analyzed weather data. The European Meteosat Second Generation (MSG) satellite is providing detailed data and high-resolution spectral and spatial images that are expected to revolutionize the process of forecasting short-term extreme weather events, such as thunderstorms, fog and small but intense depressions that can lead to devastating storms, as well as other applications, e.g., agrometeorology, climate monitoring, and natural resource management (Taube, 2006).

Web-based marketing systems. New business models are rapidly evolving that can suit the needs of small farmers, e.g., the www.B2Bpricenow.com a free agriculture e-marketplace that provides updates via SMS messaging to farmers in the Philippines (www.digitaldividend.org/pubs/pubs_01_overview.htm). In India, e-Choupal kiosks of the agriexporter ITC Limited and "Parry's Corners" of EID Parry agricultural company provide farmers with valuable information, and allow them to sell their produce directly to these companies eliminating the middleman. E-commerce platform can also allow small farmers and farmer cooperatives to expand distribution channels for their produce (Ninomiya, 2004).

E-consultation, advisory system and training. ICT can provide farmers with electronic forums and e-consultations by email, or permit the participation of a wider electronic community in location-based seminars (Painting, 2006). Farmers can also access tools for both diagnosing field problems and making crop management decisions (e.g., TropRice [124.81.86.181/rkb/knowledgeBank/troprice/default.htm#Introduction_to_TropRice.htm] and Rice Knowledge Bank [www.knowledgebank.irri.org]). The so called "virtual academy for farmers" in the Philippines and India uses ICT through a virtual network that provides information on-demand, online learning and content development of information based on farmers' needs. Trained farmers and extension workers serve as resource persons in cyber communities thereby making ICTs accessible and user-friendly.

E-governance. India is enhancing rural development programs and improving the delivery of public services with the use of government computerization schemes, satellite com-

Table 6-4. **Current remote sensing technologies for global agroenvironmental health and resources monitoring and assessment for sustainable development.**

Types of remote sensing	Sensor description	Example of imaging sensors	Resolution	Limitations	Application in agriculture	Other applications
1. Optical Imaging a. Panchromatic	Single channel detector sensitive to broad wavelength range produce black and white imagery	IKONOS Pan	Spatial: 1 m Spectral: 1 band Temporal: 1-3 days	• Unlike microwave remote sensing, acquisition of cloud free image using optical bands is impossible because of its short wavelength that cannot penetrate clouds and rain	• Precision farming • Property damage control and verification of crop damage, e.g., drought and hail.	• Highly detailed land use discrimination, urban mapping, natural resources and natural disasters mapping, environmental planning, land registration, public health, biodiversity conservation, coastal monitoring, homeland security.
		SPOT Pan	Spatial: 10 m Spectral: 1 band Temporal: 1-26 days		• Farm planning, precision farming	• Urban planning, feature and asset mapping, land use mapping
b. Multispectral	Multichannel detector with a few spectral bands. Sensitive to radiation with narrow wavelength band. The image contains brightness and color information of the targets.	Landsat MSS	Spatial: 50-80 m Spectral: 5 bands Temporal: 18 days	• Resolution tradeoff: High spatial resolution associated with low spectral resolution.	• General vegetation inventories and classification	• Environmental monitoring, land use mapping and planning, forest mapping, statistical land-use survey global-change, urban area mapping, detection of silt-water flowing and landscape analysis.
		Landast TM	Spatial: 25 m Spectral: 7 bands Temporal: 16 days		• Discrimination of vegetation types and vigor, plant and soil moisture measurement, Cropping pattern mapping, chlorophyll absorption, biomass survey, plant heat stress	• Water penetration, differentiation of snow and ice landscape analysis, lineament detection, lithological classification, urban environment assessment, delineation of water bodies, hydrothermal mapping.
1. Optical Imaging c. Superspectral	Imaging sensor has many more spectral channels (typically >10) than a multispectral sensor. The bands have narrower bandwidths that capture finer spectral characteristics of the targets.	SPOT HRV-XS	Spatial: 20 m Spectral: 3 bands Temporal: 1-26 days	• Multi, super and hyper spectral have resolution trade off: Sensors with high multispectral resolution can only offer low spatial resolution.	• Vegetation mapping and monitoring, soil erosion, agricultural boundary detection,	• Urban mapping, forestry mapping and planning, land use and land cover discrimination, maritime and coastal management, resource stewardship monitoring, habitat supply planning, wildfire mapping, landslide and mudflow detection, and rapid urban change.
		KOOS MS	Spectral: 4 bands Temporal: 1-3 days		• Precision farming, vegetation mapping, disease detection	• Environmental analysis, land management, urban growth mapping and updating, disaster mitigation and monitoring Highly detailed land use discrimination
		MODIS	Spatial: 250,500,1000 m Spectral: 36 bands Temporal: 1-2 days		• Drought detection, vegetation monitoring and forecasting	• Atmospheric temperature measurement, ozone/cloud/atmospheric properties, ocean color, phytoplankton, biogeochemistry, land cover mapping, land use planning land cover characterization and change detection.

Table 6-4. **Continued.**

Types of remote sensing	Sensor description	Example of imaging sensors	Resolution	Limitations	Application in agriculture	Other applications
1. Optical Imaging (continued) d. Hyperspectral	It acquires images in about a 100 or more contiguous spectral bands. The precise spectral information enables better characterization and identification of targets.	ENVISAT MERIS	Spatial: 300, 1200 m Spectral: 15 bands Temporal: 3 days		• Inventory and yield estimation. • Crop type mapping • Monitoring of seasonal land cover changes. • Global vegetation monitoring	• Evaluation of tropohospheric aerosol properties, hazard monitoring
2. Microwave Imaging	Encompasses both active and passive remote sensing. It covers long wavelengths from 1cm-1m, which can penetrate through cloud cover, haze, dust, and all but the heaviest rainfall all day and all weather imaging.	Hyperion	Spatial: 30 m Spectral: 220 bands Temporal: 16 days		• Precision farming, crop type mapping, monitoring of crop health, moisture and maturity.	• Measures sea surface temperature, color and surface roughness • Coastal management (monitoring of phyto-planktons, pollution and bathymetry changes)
(widely used bands) a. C Band	8,000-4,000 MHz; (3.8-7.5 cm)	RADARSAT-SAR (5.6 cm)	Spatial: 8,25,30,50, 100m Spectral: C band Temporal: 24 days	• Image distortions. Extensive shadowing of areas characterized with relief. • Coarse resolution, especially for passive applications. • Radar images are rather difficult to deal with. The few commercial software packages that exist to deal with radar imagery offer a limited amount of functions. • Results are better when combined with optical images as they have been proven complimentary	• Crop monitoring and forecasting, crop mapping	• Flood detection, for disaster management, risk assessment, pollution control (oil spill), coastline mapping.
b. L Band	2,000-1,000 MHz; (15.0-30.0 cm)	ALOS-PALSAR (1270 MHZ)	Spatial: 10-100 m Spectral: L band Temporal: 46 days		• Agricultural monitoring	• Distinction of forest from grassland, land cover classification volcanic activity monitoring, flood monitoring, landslide and earthquake detection, detection of oil slick, forest biomass estimation.
3. Light Detection and Ranging (LIDAR)	An active sensor that transmits laser pulses to the targets and records the time the pulse returned to the sensor receiver. Laser is able to provide light beam with high intensity, high collimation, high coherence, high spectral purity, and high polarization purity.	LIDAR (airborne)	Spatial: 0.75 m Spectral: 1.045-1.065 µm Temporal: dependent on flight schedule	• Disadvantages are low coverage area and high cost per unit area of ground coverage. It is not cost-effective to map a large area using an airborne remote sensing system.	• Crop monitoring, plant species detection, can be used for agricultural planning and crop estimation	• Forestry management, shoreline and beach volume changes lines, flood risk analysis, habitat mapping, subsidence issues, emergency response, urban development, and monitoring of environmental changes.

Source: Authors' elaboration.

munications, and distance education and training via the Internet. Some of these projects have been quite successful suggesting that the potential impact of IT on development can be enormous, particularly in terms of improved health, hygiene, nutrition, and education (Pigato, 2001

ICT can complement conventional methods to meet the growing demand of stakeholders in accessing improved technologies and timely information and support services, improving productivity and livelihoods in poor rural communities. Although ICT allows greater and faster flow of information, due to the technical and knowledge requirements, not all people have the same level of access. ICT can further widen the "digital divide" between developed and developing countries, as well as between rural and urban communities within a country (Herselman and Britton, 2002).

6.7.5.2.3 Nanotechnology

Nanotechnology (see Glossary) may improve agriculture and resource management, particularly soil fertility, crop/animal production, pest management, veterinary medicine, product safety and quality, and farm waste management. Applications of nanotechnology in agriculture are rapidly expanding and developing (Binnig and Rohrer, 1985; Mills et al., 1997; Huang et al., 2001; Dutta, and Hofmann, 2004; Hossain et al., 2005; Graham-Rowe, 2006). Investment on nanotechnology R&D from both public and private sectors has been increasing (Kuzma and VerHage, 2006). The potential of nanotechnologies in terms of environmental impacts, including those with agriculture applications (waste management, water purification, environmental sensors, and agricultural pollution reduction) has been assessed (Defra, 2007).

Biosensors developed into nanosensors expedite rapid testing and analysis of soil, plants, and water making nutrient and water management in the farm more efficient and less laborious (Birrel and Hummel, 2001; Alocilja and Radke, 2003). Nanoporous materials such as zeolites can help release the right dosage of fertilizer at the right time owing to well-controlled stable suspensions with absorbed or adsorbed substances. Nanoelectrocatalytic systems could optimize purification of highly contaminated and salinated water for drinking and irrigation; and nanostructured materials may offer clean energy solutions through the use of solar cells, fuel cells, and novel hydrogen storage (Court et al., 2005).

Nanomaterials can provide environmental filters or as direct sensors of pollutants (Dionysiou, 2004). Nanoparticles have been used in photocatalysis that enhance degradation process in solid, farm or wastewater treatment (Blake, 1997; Herrmann, 1999). Air pollution could also be reduced (Peral et al., 1997) through on the use of photocatalysis for purification, decontamination, and deodorization of air.

The integration of nanotechnology, biotechnology, and information and communications technology could revolutionize agriculture this century (Opara, 2004).These technologies could contribute to reducing hunger and improving nutrition by optimizing plant health and eliminating pathogens or other organisms that might contaminate food.

Despite the rapidly expanding products and market of nanotechnology (nanotechnology food market in 2006 was about US$7 billion in 2006 and may reach a total of $20.4 billion by 2010 (HKC, 2006), there are some biosafety and IPR concerns. Their application in agriculture will directly introduce them into ground and surface water catchments where they may accumulate in concentrations that may undermine the goals of food safety and environmental sustainability (NSTC, 2000; ETC Group, 2005). Nanomaterials are built from nanoparticles that may be too diverse for stereotypical risk assessments (Colvin, 2003). However, since nanoscale particles have minute dimensions in common, these can direct research to likely exposure routes. For example, their small size but large-scale release may lead to their accumulation in groundwater because even particles that are not soluble in water can form colloidal species that can be carried in water (Colvin, 2003).

As with biotechnology, nanotechnologies are not evenly distributed: wealthier industrial nations produce and own the technologies. A single nanoscale innovation can be relevant for widely divergent applications across many industry sectors and companies, and patent owners could potentially put up tolls on entire industries. IP will play a major role in deciding who will capture nanotech's market, who will gain access to nanoscale technologies, and at what price (ETC Group, 2005).

6.7.5.3 Participatory approaches to AKST

Efforts to preserve natural resources and guarantee the provisioning of essential ecosystem services are frequently characterized by social, political and legal conflicts (Wittmer et al., 2006). Broad-scale approaches are necessary to face problems that extend beyond a local site and a short time span.

The asymmetric administration of shared lands and natural resources is a potential source of conflict in many trans-boundary eco-regions of the world (Viglizzo, 2001). The cross-border externalization of negative environmental impacts due to asymmetries in land conversion and intensity of farming represents a challenge to neighboring countries. The problem may become critical in shared basins with interconnected rivers and streams where downstream countries often have to pay the cost of negative impacts that have not been properly internalized upstream.

AKST can be employed to prevent or mitigate consequences of conflict over environmental resources, particularly through the use of participatory approaches supported to enhance the commitment of stakeholders to the decision-making process and to share the responsibility of managing common resources. Strategies include (1) developing stakeholder appreciation for importance of trans-boundary basin management (2) jointly designed land-use strategies to prevent potential conflicts due to negative externalities from neighboring areas, (3) environmental impact assessment for ex-ante evaluation of potentially conflicting projects, and (4) acceptance of third party independent arbitration to face current or potential conflicts when necessary.

Agricultural and environmental conflicts are characterized by the interaction of both ecological and societal complexity (Funtowicz and Ravetz, 1994). Participatory approaches (De Marchi et al., 2000) and multicriteria analysis (Paruccini, 1994) can help resolve agroenvironmental conflicts. Multiple criteria analysis uses different approaches (normative, substantive and instrumental) to deal with different types and levels of conflict resolution; it can be a powerful analytical tool in cases where a single decision-making criterion fails and where impacts (social, ecological or environmental) cannot be assigned monetary values.

Currently, most agricultural technology aims at resolving environmental problems that occur at the small spatial scale (e.g., the plot and farm level), but broad-scale technologies (Stoorvogel and Antle, 2001) are necessary to reveal impacts that are not perceived with site-specific studies. The importance of information technology increases as we scale-up to undertake problems that occur at broader geographical scales. The integration of maps, remote-sensing images, and data bases into geographic information systems (GIS) is needed to assess, monitor and account critical resources and large-scale agroenvironmental processes. This information base, coupled to models and expert systems (De Koning et al., 1999), can help support the application of participatory approaches and multicriteria analysis to resolve present or potential conflicts. Likewise, these tools become tools to support decision-making on large-scale land-use policies and managerial schemes.

The impact of climate change may exacerbate risks of conflict over resources and further increase inequity, particularly in developing countries where significant resource constraints already exist. An estimated 25 million people per year already flee from weather-related disasters and global warming is projected to increase this number to some 200 million before 2050 (Myers 2002); semiarid ecosystems are expected to be the most vulnerable to impacts from climate change refugees (Myers, 2002). This situation creates a very serious potential for future conflict, and possible violent clashes over habitable land and natural resources such as freshwater (Brauch, 2002), which would seriously impede AKST efforts to address food security and poverty reduction.

6.8 Adaptation to Climate Change, Mitigation of Greenhouse Gases

The effectiveness of adaptation efforts is likely to vary significantly between and within regions, depending on geographic location, vulnerability to current climate extremes, level of economic diversification and wealth, and institutional capacity (Burton and Lim, 2005). Industrialized agriculture, generally situated at high latitudes and possessing economies of scale, good access to information, technology and insurance programs, as well as favorable terms of global trade, is positioned relatively well to adapt to climate change. By contrast, small-scale rainfed production systems in semi-arid and subhumid zones presently contend with substantial risk from seasonal and interannual climate variability. Agricultural communities in these regions generally have poor adaptive capacity to climate change due to the marginal nature of the production environment and the constraining effects of poverty and land degradation (Parry et al., 1999).

AKST will be confronted with the challenge of needing to significantly increase agriculture output—to feed two to three billion more people and accommodate a growing urban demand for food—while slowing the rate of new GHG emissions from agriculture, and simultaneously adapting to the negative impacts of climate change on food production. Agriculture will have to become much more efficient in its production if it is to accomplish this without significantly increasing its climate forcing potential. All of this will have to be achieved in a future where agricultural crops may be in direct competition with crops grown for energy purposes as well as without significant extensification and loss of biodiversity.

6.8.1 AKST innovations

6.8.1.1 Technological (high-input) options

Modeling. Climate simulation models indicate the intensification of the hydrologic cycle, climatic conditions which will significantly challenge efforts to control soil erosion and rehabilitate degraded lands even in well-endowed production environments (Nearing, 2004). Tropical soils with low organic matter are expected to experience the greatest impact of erosion on crop productivity because of the poor resilience of these soils to erosive forces, and the high sensitivity of yields to cumulative soil loss (Stocking, 2003; Nearing, 2004). Evidence of significant soil erosion can often be difficult to detect, and its impact on crop productivity can be masked by use of inorganic fertilizer (Knowler, 2004; Boardman, 2006). Extreme events, which significantly contribute to total erosion, are very likely to increase with climate change (Boardman, 2006), as will climate-induced changes in land use that leave soils vulnerable to erosion (Rounsevell et al., 1999).

The improvement of soil erosion modeling capacity can address the role of extreme events in soil erosion and encompass the influence of socioeconomic factors on land use change (Michael et al., 2005; Boardman, 2006). One new technique estimates the impact of more frequent extreme events under different climate scenarios by using meteorological time series projections (Michael et al., 2005). The effects of extreme events on erosion can be more simply modeled with two-dimensional hill slope approaches (Boardman, 2006); GIS can be used to develop landslide hazard maps (Perotto-Baldiviezo et al., 2004).

Recent developments in modeling techniques show potential for estimating the future impact of extreme events, through downscaling from General Circulation Models. Global climate models, however, will continue to be limited by uncertainties (Zhang, 2005). The lack of quantitative data and the technological complexity of many contemporary models are likely to limit the applicability of soil erosion modeling in less developed steep land regions (Morgan et al., 2002; Boardman, 2006). Better field-level assessments of current erosion under different crops and management practices, and, where possible, through integrating GIS into land-use planning could help developing countries assess the impacts of climate change.

Agroecological zone (AEZ) tools used by FAO (FAO, 2000) to determine crop suitability for the world's major ecosystems and climates has potential to enhance efforts to develop crop diversification strategies. The AEZ methodology, which combines crop modeling with environmental matching, allow assessment of the suitability of particular crop combinations given future climate scenarios. However, the data sets that underlie AEZ need to be improved in order to realize the full potential of these tools for crop diversification. For example the current scale of the FAO world soil maps at 1:5,000,000 needs finer resolution (FAO, 2000).

Early warning, forecasting systems. Timely forecasts, including the starting date of the rainy season, average weather conditions over the coming season, conditions within the season that are critical to staple crops and animals, and appropriate responses can increase the economic, environmental, and social stability of agricultural systems and associated communities. Advances in atmospheric and ocean sciences, a better understanding of global climate, and investments in monitoring of the tropical oceans have increased forecasting skill at seasonal to interannual timescales. Early warning systems using seasonal forecasts (such as the FAO Global Information and Early Warning System) and monitoring of local commodity markets, are increasingly used to predict likely food shortfalls with enough advance warning for effective responses by marketing systems and downstream users.

Traditional coping mechanisms depend on the ability to anticipate hazard patterns, which are increasingly erratic with the advent of climate change. One option for improving early detection and warning would be to broaden the use of GIS-based methodologies such as those employed by the Conflict Early Warning and Response Network (CEWARN), the Global Public Health Information Network (G-PHIN).

Early warning systems are important because they help to untangle the multiple but interdependent crises that characterize complex emergencies, particularly in response to climate change. In other words, continuous information gathering serves to identify the socioecological ingredients of complex crises before they escalate into widespread violence. This means technological systems are also needed. To this end, the added value of technological early warning systems should therefore be judged on their empowerment of local people-centered systems that build on the capacity of disaster-affected communities to recover with little external assistance following a disaster. Further applied research is needed on local human adaptability in decentralized settings as well as self-adaptation in dynamic disaster environments.

Linking early warning to more effective response requires a people-centered approach to climate change (UN, 2006). The quest for early warning must be more than just an "exercise in understanding how what is happening over there comes be known by us over here" (Adelman, 1998). Instead, the international community should focus on the real stakeholders and add to their capacity for social resilience. On the policy front, the lack of institutionalized early warning systems that survey the localized impact of climate change on ecological and political crises inhibits the formulation of evidence-based interventions (Levy and Meier, 2004). Regrettably, little collaboration currently exists between the disaster management and conflict prevention communities despite obvious parallels in risk assessments, monitoring and warning, dissemination and communication, response capability and impact evaluation (Meier, 2007).

Bringing climate prediction to bear on the needs of agriculture requires increasing observational networks in the most vulnerable regions, further improvements in forecast accuracy, integrating seasonal prediction with information at shorter and longer time scales, embedding crop models within climate models, enhanced use of remote sensing, quantitative evidence of the utility of forecasts for agricultural risk management, enhanced stakeholder participation, and commodity trade and storage applications (Giles 2005; Hansen, 2005; Hansen et al., 2006; Doblas-Reyes et al., 2006; Sivakumar, 2006). For seasonal climate forecasts to be an effective adaptation tool, advances in forecasting skills need to be matched with better pathways for dissemination and application, such as by linking forecasts to broader livelihood and development priorities, and by training organizations, such as extension agencies, to facilitate the end users' ability to make effective decisions in response to forecasts (Ziervogel 2004; Garbrecht et al., 2005; Hansen 2005; Vogel and O'Brien, 2006). Substantial investments by national and international agricultural and meteorological services are needed.

Improve crop breeding potential for drought, salinity and heat tolerance. Abiotic stress of agricultural crops is expected to increase in most regions due to warmer temperatures, experienced both as episodic heat waves and mean temperature elevation, prolonged dry spells and drought, excess soil moisture, and salinity linked to higher evapotranspiration rates and salt intrusion. Expected temperature increases of 2-3°C by mid-century could significantly impair productivity of important staple crops of the developing world, such as wheat, and in truly marginal areas, millet. One-third of irrigated agricultural lands worldwide are affected by high salinity, and the area of salt-affected soils is expected to increase at a rate of 10% per year (Foolad, 2004). The magnitude of these impacts could test our capacity to achieve breakthroughs in germplasm improvement equivalent to the challenge at hand.

Advances in plant genomics, linked to the Arabidopsis model system, and the integration of genomics with physiology and conventional plant breeding could lead to the development of new varieties with enhanced tolerance to drought, heat, and salinity. Emerging genomic tools with future potential include whole-genome microarrays, marker-assisted selection using quantitative trait loci, bioinformatics, and microRNAs (Edmeades et al., 2004; Foolad, 2004; Ishitani et al., 2004; White et al., 2004; Denby and Gehring, 2005). Phenological adaptation, e.g., matching crop duration to available season length, is central to successful breeding efforts; thus conventional breeding, augmented with genomic tools, is a likely configuration of future plant breeding programs. An example of this would be the integration of phenotyping (differences in crop germplasm performance under different stress environments) with functional genomic approaches for identifying genes and mechanisms (Edmeades et al., 2004; Ishitani et al., 2004). Improvement in seasonal forecasting and in the use of remote sensing and other observational tools could also be used to further support breeding programs, through better characterization of cropping environments.

Future breakthroughs in understanding how crop plants respond to abiotic stress are very likely, given the scientific resources dedicated to investigating the *Arabidopsis thaliana*, a model system used for plant genetics and genomics studies with a small, completely sequenced genome and a short life cycle. For example, progress in genomics related to salt tolerance in Arabidopsis mutants has enhanced understanding of gene function, which could provide opportunities to exploit these mechanisms in crop species (Foolad, 2004; Denby and Gehring, 2005). However, direct extrapolation of single gene responses, gained through Arabidopsis studies, to functional abiotic tolerance of cultivated crop species could continue to be limited by differences in gene sequence between Arabidopsis and crop species (Edmeades et al., 2004; White et al., 2004). Moreover, gene expression in Arabidopsis changes when exposed to field conditions (Miyazaki et al., 2004, as reviewed by White et al., 2004), as would be expected given the influence of genotype by environment interactions. Genes for heat tolerance have been identified in a number of species, including rice, cowpea, and groundnut, which is likely to provide future opportunities for heat-tolerance breeding.

Attaining more effective use of genomics for abiotic stress-tolerance breeding will depend on closer integration of this discipline with physiology, which could lead to better understanding of how genes confer changes in whole-plant biological function and agronomic performance (genotype-to-phenotype relationships) (Edmeades et al., 2004; White et al., 2004). However, the current imbalance between genomic research and field-based physiological studies, in favor of the former, could undermine future AKST progress towards developing new stress-tolerant germplasm. Lastly, the scope of abiotic stress research needs to be extended to include more investigations of stress caused by mineral deficiencies and toxicities (Ishitani et al., 2004), as these factors strongly influence root development with implications for tolerance to climatic extremes (Lynch and St. Clair, 2004). For example, many tropical agricultural soils have high levels of exchangeable Al which stunt root system development. Bringing mineral stress tolerance more closely into the realm of abiotic stress research, while increasing the complexity of the breeding challenge, could possibly avoid short-circuiting progress on drought, heat and salinity breeding efforts when scaling up to actual field conditions where multiple and complex stresses occur.

Technological breakthroughs in breeding for abiotic stress tolerance could ultimately be limited by a potential loss of crop wild relatives to climate change. In the next 50 years, 16 to 22% of species that are wild relatives of peanut, potato, and cowpea could become extinct as a result of temperature increases and shifts in rainfall distribution, and most of the remaining species could lose over 50% of their range size (Jarvis et al., 2008). These three crops are important for food security in low-income countries, and their wild relatives are a vital genetic resource for developing future drought and pest resistant crop varieties, as well as varieties with enhanced nutritional value. Greater efforts to collect seed for gene banks (*ex situ* conservation) and to target *in situ* conservation, such as through addressing habitat fragmentation, could help to mitigate these potential losses. Strengthening links between conservation, breeding, and farmers' groups is an important component of this effort. However, diversity for its own sake is not useful, as farmers retain varieties for specific traits, not for the sake of conservation (Box 6-2).

Agronomic and genetic improvement of underutilized (or "lost") crops could provide a good opportunity to enhance agricultural diversification, particularly in Africa where approximately 2,000 underutilized food species are consumed (NRC, 1996). Crops such as the legume Bambara groundnut (*Vigna subterranean*) and the cereal fonio (*Digitaria exilis* and *Digitaria iburua*) still figure prominently in the African diet. Fonio has very good prospects for semi-arid and upland areas because it is widely consumed, tolerates poor soil and drought conditions, matures very quickly (6-8 weeks), and has an amino acid profile superior to today's major cereals (NRC, 1996). Unlocking the genetic potential of this cereal through conventional breeding and biotechnology to address low yields, small seeds, and seed shattering could help meet development and sustainability goals (Kuta et al., 2003; NRC, 1996). Similar potential exists for Bambara groundnut (Azam-Ali, 2006; Azam-Ali et al., 2001), which is still cultivated from landraces. Research needs for underutilized crops include germplasm collection, marker assisted breeding, assessments of agronomic characteristics and nutritional content, development of improved processing technologies, and market analyses. While these crops cannot replace the major cereals, their improvement could significantly enhance food security options for rural communities confronted with climate change.

Diversification of agriculture systems is likely to become an important strategy for enhancing the adaptive capacity of agriculture to climate change. Diversification strategies in the near term will need to be flexible, given that the disruptive impacts of climate change are projected to be experienced more in terms of increased variability, than as mean changes in climate. Therefore, improved skill in predicting how short-term climate phenomena, such as the El Niño Southern Oscillation and the North Atlantic Oscillation, affect seasonal and interannual variability, and the timely dissemination of forecasts will be essential for farmer decisions about whether to grow high or low water-consumptive crops and use of drought-tolerant varieties (Adams et al., 2003; Stige et al., 2006).

6.8.1.2 On-farm (low input) options

The knowledge and tools currently available could be better deployed to reduce the vulnerability of rainfed agriculture to seasonal climate variability. For example, poor crop establishment is a significant but solvable constraint in semiarid farming environments (Harris, 2006). Similarly, seasonal dry spells can be bridged using improved rainfall catchment and incremental amounts of fertilizer (Rockström, 2004). By focusing on the "manageable part of climatic variability" (Rockström, 2004), AKST could have a significant positive impact on improving the adaptive capacity of rainfed agriculture to climate change. It is also important to recognize that risk aversion practices are themselves an adaptation to climate variability, and to understand the functional linkages between existing coping strategies and future climate change adaptation.

The greatest period of risk in rainfed agriculture is the uncertainty around the timing of sufficient rainfall for crop sowing. High rainfall variability and poor quality seed leads to slow germination and emergence, causing patchy stands, and multiple and delayed replanting, making poor crop establishment a significant contributor to the productivity gap in semiarid agriculture (Harris, 2006). Emphasis can be put on targeting technologies and practices that reduce the ex-

Box 6-2. The importance of crop varietal diversification as a coping strategy to manage risk.

A study of traditional practices of conserving varieties of yam, *Dioscorea* sp., and of rice, *Oryza glaberrima*, was carried out in Ghana in 2003-2004 under an IPGRI-GEF-UNEP project on crop landraces in selected sub-Saharan African countries (Gyasi et al., 2004). It identified 50 varieties of yam and 33 varieties of rice that are managed by a wide diversity of locally adapted traditional practices in the study sites located in the semiarid savanna zone in the northern sector. The case study findings underscore the importance of crop varietal diversification as security against unpredictable rainfall, pest attack, fluctuating market and other such variable environmental and socioeconomic conditions, not to mention its importance for modern plant breeding and wider use of farm resources, notably labor and the diversity of on-farm ecological niches.

posure of sensitive crop growth stages to seasonal climate variability.

Options for addressing this challenge include improving farmer access to quality seed, adoption of improved crop establishment practices, and the use of healthy seedlings in transplant systems. Seed priming—soaking seeds in water for several hours but short of triggering germination—is an example of a simple but effective technology for improving crop establishment. Priming of some seeds results in more even and fuller stand establishment, accelerates seedling emergence and improves early growth, often leading to earlier flowering and maturity, avoidance of late-season drought and improved yields (Harris et al., 2001; Harris, 2006). Experimental crop transplanting methods in millet-sorghum areas of Africa can also reduce planting risk; e.g., staggered transplanting from seedling nurseries to allow for variable onset of the rainy season (Young and Mottram, 2001; Mottram, 2003; CAZS, 2006). This method, though more labor intensive, results in faster crop establishment with fewer gaps, and a harvest 2-3 weeks earlier than conventional seeding methods, leading to higher grain and stover yields.

By reducing crop establishment risk and decreasing the time to maturity, these technologies provide a small measure of flexibility to farmers in high-risk environments. Technologically simple approaches to improve crop establishment and seedling vigor generally have minimal downside risks, immediate and tangible benefits, and can be easily tailored to producer needs; thus they are appropriate options for small-scale rainfed systems. Seed priming, which has been tested in a wide array of dryland cereals and pulses, consistently results in average 30% increases in yield with minimal farmer investment (Harris, 2006). Similar mean yield increases have been observed with seedbed solarization of rice nurseries, though with somewhat greater farmer investment in material and time. While these are simple technologies, they do require some local testing and training to ensure that proper techniques are followed. Millet transplanting systems show good potential, though labor shortages could be an issue in some regions. An analysis of the tradeoff between labor for transplanting versus the labor and extra seed required for multiple resowing of millet fields would help to clarify the issue of labor expenditure.

Soils. Improved adoption of soil conserving practices can also mitigate the damaging effects of climate variability. Methods include the use of cover crops, surface retention of crop residues, conservation tillage, green manures, agroforestry, and improved fallow (Sanchez, 2000; Benites and Ashburner, 2003; Lal, 2005). Although these are very sound practices for soil protection, achieving broad-scale and long-term adoption of them will be a significant challenge given the current and likely future, disincentives to investment as described in the previous subchapter (Stocking, 2003; Knowler, 2004; Cherr et al., 2006; Patto et al., 2006). The resilience of conservation farming systems in the Central American highlands to recent El Niño drought (Cherrett, 1999), and to the catastrophic soil losses from Hurricane Mitch (Holt-Gimenez, 2001) provide strong evidence of conservation agriculture's potential as an adaptation response to increased rainfall variability and storm intensity with climate change.

Long-term investment in rehabilitating degraded lands is another option for addressing the negative feedback between high rainfall risks and declining soil fertility. Recent evidence of revegetation and agricultural intensification in the Sahel, catalyzed by a crisis of diminished rainfall and declining yields (Herrmann et al., 2005; Reij et al., 2005; Tappan and McGahuey, 2007; USAID, 2006), could inform future AKST efforts at integrating soil and water conservation and land reclamation into adaptation planning. Technologies and practices deployed in these areas to reclaim declining or abandoned land include rock lines, rock "Vs", and manure-amended planting pits. These techniques were used to break soil crusts, enhance water capture and retention, and regenerate N-fixing trees to improve soil fertility. Soil reclamation using these methods encompassed several hundred thousand ha in Burkina Faso and Mali, and well over a million ha in Niger (Reij et al., 2005; Tappan and McGahuey, 2007; USAID, 2006).

Important elements gleaned from these studies include:

- Legal code reforms that provided farmer, rather than government, ownership of trees was an essential precondition; the former sometimes taking the lead and the latter following;
- By improving land and claiming ownership, women were one of the main beneficiaries, and improved household food security one of the most tangible outcomes;
- Investment in fertilizer occurred after farmers invested in measures to conserve soil moisture and increase soil organic matter.

AKST could play an important role in documenting the effectiveness of these practices for seasonal climate risk management, e.g., investigating how these soil improvement practices affect soil fertility, soil moisture retention, and crop yields over a range of variable rainfall years, as well as conducting detailed socioeconomic analyses of how the benefits are distributed in local communities. Local control of the resource base is necessary for creating the enabling conditions that spur local action towards natural resource improvements, and an understanding of this dynamic is needed to effectively support local initiatives. Stabilizing and improving the natural resource base of agriculture are essential preconditions for investing in technologies for long-term adaptation to climate change (Stocking, 2003; Sanchez, 2005).

Reduction of greenhouse gas emission for agriculture. Reduction of N_2O emissions from agriculture could be achieved by better matching fertilizer application with plant demand through the use of site-specific nutrient management that only uses fertilizer N to meet the increment not supplied by indigenous nutrient sources; split fertilizer applications; use of slow-release fertilizer N; and nitrification inhibitors (DeAngelo et al, 2005; Pampolino et al., 2007). Another option to address N_2O emissions would be the use of biological means to inhibit or control nitrification in soils. Gene transfer from species exhibiting biological nitrification inhibition to cultivated species could offer another way to reduce N_2O emissions to the atmosphere and nitrate pollution of water bodies (Fillery, 2007; Subbarao et al., 2007).

Improved management of agriculture and rangelands targeted at soil conservation, agroforestry, conservation tillage (especially no-till), agricultural intensification, and rehabilitation of degraded land can yield C sequestration benefits (IPCC, 2000; Izaurralde et al., 2001; Lal, 2004). Carbon sequestration potential in soils is greatest on degraded soils (Lal, 2004), especially those with relatively high clay content (Duxbury, 2005; Lal, 2004).

Another promising approach would be to use plant material to produce biochar and store it in soil (Lehman, 2007a). Heating plant biomass without oxygen (a process known as low-temperature pyrolysis) converts plant material (trees, grasses or crop residues) into bioenergy, and in the process creates biochar as a coproduct. Biochar is a very stable compound with a high carbon content, surface area, and charge density; it has high stability against decay, and superior nutrient retention capacity relative to other forms of soil organic matter (Lehmann et al., 2006). The potential environmental benefits of pyrolysis combined with biochar application to soil include a net withdrawal of atmospheric CO_2, enhancement of soil fertility, and reduced pollution of waterways through retention of fertilizer N and P to biochar surfaces (Lehmann, 2007b). Future research is needed to more fully understand the effect of pyrolysis conditions, feedstock type, and soil properties on the longevity and nutrient retention capacity of biochar.

The robustness of soil carbon sequestration as a permanent climate change mitigation strategy has been questioned because soil carbon, like any other biological reservoir, may be reverted back to the atmosphere as CO_2 if the carbon sequestering practice (e.g., no till practice) were to be abandoned or practiced less intensively. Increasing soil organic matter through carbon sequestering practices contributes directly to the long-term productivity of soil, water, and food resources (IPCC, 2000; Lal, 2004). Thus it would seem unlikely that farmers would suddenly abandon systems of production that bring so many economic and environmental benefits. Other reports suggest that certain soil carbon sequestering practices, such as no till, may increase N_2O emissions (Ball et al., 1999; Duxbury, 2005). This outcome, however, may be location specific (e.g., humid climatic conditions) as revealed by a comprehensive review of Canadian agroecosystem studies (Helgason et al., 2005).

Globally, farmers continue to adopt no-till as their conventional production system. As of 2001, no-till agriculture had been adopted across more than 70 million ha worldwide with major expansion in South America (e.g., Argentina, Brazil, and Paraguay) (Izaurralde and Rice, 2006). With an area under cropland estimated globally at 1.5 billion ha, there exists a significant potential to increase the adoption of no-till as well as other improved agricultural practices, which would have other environmental benefits such as improved soil quality and fertility, reduced soil erosion, and improved habitat for wildlife. Much work remains to be done, however, in order to adapt no-till agriculture to the great variety of topographic, climatic, edaphic, land tenure, land size, economic, and cultural conditions that exist in agricultural regions of the world.

In developing strategies all potential GHG emissions need to be considered for example, efforts to reduce CH_4 emissions in rice can lead to greater N_2O emissions through changes in soil nitrogen dynamics (Wassmann et al., 2004; DeAngelo et al., 2005; Yue et al., 2005; Li et al., 2006). Similarly, conservation tillage for soil C sequestration can result in elevated N_2O emissions through increased fertilizer use and accelerated denitrification in soils (Ball et al., 1999; Duxbury, 2005). However, one of the most comprehensive long-term studies of GHG emissions across several land use practices in Michigan (Robertson et al., 2000) revealed that no-till agricultural methods had the lowest Global Warming Potential when compared to conventional and organic agricultural methods.

From a GHG mitigation standpoint, strategies that emphasize the avoidance of N_2O and CH_4 emissions have a permanent effect as long as avoided emissions are tied to higher productivity, such as through increased energy efficiency and better factor productivity (Smith et al., 2007). Indeed, many of the practices that avoid GHG emissions and increase C sequestration also improve agricultural efficiency and the economics of production. For example, improving water and fertilizer use efficiency to reduce CH_4 and N_2O emissions also leads to gains in factor productivity (Gupta and Seth, 2006; Hobbs et al., 2003) while practices that promote soil C sequestration can greatly enhance soil quality (Lal, 2005). Improved water management in rice production can have multiple benefits including saving water while maintaining yields, reducing CH_4 emissions, and reducing disease such as malaria and Japanese encephalitis (van der Hoek et al., 2007). There is significant scale for achieving this "win-win" approach, with the approach largely determined by the size and input intensity of the production system, e.g., N-fixing legumes in smallholder systems and precision agriculture in large systems (Gregory et al., 2000).

There is potential for achieving significant future reductions in CH_4 emissions from rice through improved water management. For example, CH_4 emissions from China's rice paddies have declined by an average of 40% over the last two decades, with an additional 20 to 60% reduction possible by 2020 through combining the current practice of mid-season drainage with the adoption of shallow flooding, and by changing from urea to ammonium sulfate fertilizer, which impedes CH_4 production (DeAngelo et al., 2005; Li et al., 2006). There is also potential to achieve CH_4 reduction through integrating new insights of how the rice plant regulates CH_4 production and transport into rice breeding programs (Wassmann and Aulakh, 2000; Kerchoechuen, 2005).

Emerging technologies that could provide future options for reducing CH_4 and N_2O emissions from livestock include: adding probiotics, yeasts, nitrification inhibitors, and edible oils to animal feed that reduce enteric CH_4 and N_2O emissions from livestock systems (Smith et al., 2007) and controlling methanogenic archae, microorganisms that live in the rumen and generate CH_4 during their metabolism More extensive use of the antibiotic Rumensin® (monensin sodium), currently used to improve feed efficiency and prevent *Coccidiosis*, a parasitic intestinal infection, would improve energy utilization of feedstuffs through increased production of proprionic acid by rumen microorganisms and reduce the production of CH_4. However, because Rumensin is also toxic to methanogenic bacteria, it should not be fed to cattle whose waste is to be used for CH_4 generation.

Seeds. A viable option for small-scale production systems would be to refine and more widely disseminate the practice of adding small quantities of fertilizer to seed, such as through seed coating (Rebafka et al., 1993) or soaking/priming (Harris, 2006) methods. Addition of fertilizer P and micronutrients to seed, rather than soil, is an inexpensive but highly effective means for improving plant nutrition and increasing yield (> 30% average yield increase reported) on drought-prone, acidic, low fertility soils. Seed priming with dilute fertilizer has average benefit/cost ratios 20 to 40 times greater than that achieved with fertilizer addition to the soil.

This is could be an effective strategy for small-scale systems, though there are several impediments such as low availability of quality fertilizer in local markets, lack of extension services for conveying technical information, and inability of farmer to pay for fertilizer-treated seed. Imbedding these technologies within larger efforts to overhaul the seed sector, which could include credit for purchasing improved seed and information about improved crop establishment practices could facilitate farmer adoption of these technologies. These technologies also could be disseminated into local communities by targeting farmers that have made prior land improvements to increase soil water retention, and may therefore be less risk adverse.

Water resources and fisheries. While the broad implications of climate change on marine systems are known—including rising sea levels, sea surface temperatures, and acidification—the degree and rate of change is not known, nor are the effects of these physical changes on ecosystem function and productivity (Behrenfeld et al., 2006). To adjust and cope with future climatic changes, a better understanding of how to predict the extent of change, apply adaptive management, and assign risk for management decisions is needed (Schneider, 2006).

To ensure the survival of many communities, their livelihoods and global food security, new approaches to monitoring, predicting, and adaptively responding to changes in marine and terrestrial ecosystems need to be developed. Ecosystem resilience can be built into fisheries and essential fish habitats (including wetlands and estuaries) and approaches developed that reduce risk and ensure continuation of ecosystem goods and services (Philippart et al., 2007). Rising sea levels will alter coastal habitats and their future productivity, threatening some of the most productive fishing areas in the world. Changes in ocean temperatures will alter ocean currents and the distribution and ranges of marine animals, including fish populations (di Prisco and Verde, 2006; Lunde et al., 2006; Sabates et al., 2006; Clarke et al., 2007). Rising sea surface temperatures will result in additional coral reef bleaching and mortality (Donner et al., 2005). Rising atmospheric CO_2 will lead to acidification of ocean waters and disrupt the ability of animals (such as corals, mollusks, plankton) to secrete calcareous skeletons, thus reducing their role in critical ecosystems and food webs (Royal Society, 2005).

Precautionary approaches to management of fish and freshwater resources are needed to reduce the impacts from climate change, including conserving riparian and coastal wetlands that can buffer changes in sea level rise and freshwater flows. Human-induced pressures on fish populations from overfishing must be reduced so that fish populations have a chance of withstanding the additional pressures from warming seas and changes in seasonal current patterns. Human demand for increasing freshwater supplies needs to be addressed through water conservation and water reuse, thus allowing environmental flows to maintain riparian and wetland ecosystems.

Small-scale fishers, who lack mobility and livelihood alternatives and are often the most dependent on specific fisheries, will suffer disproportionately from such large-scale climatic changes. In Asia, 1 billion people are estimated to be dependent upon coral reef fisheries as a major source of protein, yet coral reef ecosystems are among the most threatened by global climate change. The combined effects of sea surface temperature rise and oceanic acidification could mean that corals will begin to disappear from tropical reefs in just 50 years; poor, rural coastal communities in developing countries are at the greatest risk and will suffer the greatest consequences (Donner and Potere, 2007; www.icsf.net). Climate change is a major threat to critical coastal ecosystems such as the Nile, the Niger and other low-lying deltas, as well as oceanic islands which may be inundated by rising sea levels. The environmental and socioeconomic costs, especially to fisheries communities in developing countries, could be enormous.

Water related risk can be reduced through adaptation and adoption of strategies to improve water productivity in rainfed farming systems. These strategies entail shifting from passive to active water management in rainfed farming systems and include water harvesting systems for supplemental irrigation, small scale off-season irrigation combined with improved cropping system management, including use of water harvesting, minimum tillage and mulch systems, improved crop varieties, improved cropping patterns (Molden et al., 2007), and particularly mitigation of soil degradation (Bossio et al., 2007). These existing technologies allow active management of rainfall (green water), rather than only managing river flows (blue water) (Rockstrom et al., 2007).

The scope for improvement is tremendous (Molden et al., 2007): rainfed farming covers most of the world croplands (80%), and produces most of the world's food (60-70%). Poverty is particularly concentrated in tropical developing countries in rural areas where rainfed farming is practiced (Castillo et al., 2007). Half of the currently malnourished are concentrated in the arid, semiarid and dry subhumid areas where agriculture is very risky due to extreme variability of rainfall, long dry seasons, and recurrent droughts, floods and dry spells (Rockstrom et al., 2007). Current productivity is generally very low (yields generally less than half of irrigated systems and in temperate regions where water risks are much lower). Even in these regions, there is generally enough water to double or often quadruple yields in rainfed farming systems. In these areas the challenge is to reduce water related risks rather than coping with absolute scarcity of water. With small investments large relative improvements in agricultural and water productivity can be achieved in rainfed agriculture. Small investments providing 1000 m^3 ha^{-1} (100 mm ha^{-1}) of extra water for supplemental irrigation can unlock the potential and more than double water and agricultural productivity in small-scale rainfed agriculture, which is a very small investment compared to the 10000-15000 m^3 ha^{-1} storage infrastructure required to enable full surface irrigation (Rockstrom et al., 2007). Provided that there are sufficient other factor inputs (e.g., N), the major hurdle for rain water harvesting and supplemental irrigation systems is cost effectiveness. Investment in R&D for low cost small scale technologies is therefore important to realize gains. This approach can address seasonal variability in rainfall (expected to increase with climate change) but have little impact in conditions of more severe interannual variability (very low rainfall), which can only be addressed by systems with storage (dams and groundwater) or buffering (lag in hydrologic response to that river flows are substantially maintained through drought periods).

Climate change will require a new look at water storage, to mitigate the impact of more extreme weather, cope with changes in total amounts of precipitation, and cope with changing distribution of precipitation, including shifts in ratios between snowfall and rainfall. Developing more storage (reservoirs and groundwater storage) and hydraulic infrastructure provides stakeholders with more influence in determining the precise allocation to desired activities including agriculture and hydropower production.

In the process of adapting to climate change multiple interests at the basin scale can be incorporated and managed, and tradeoffs with other livelihood and environmental interests included in the planning (Faurés et al., 2007). Storage will itself be more vulnerable to climatic extremes resulting from climate change, and therefore be less reliable. Furthermore, it will have proportionately greater impacts on wetland and riverine ecosystems, which are already under stress. The arguments on the relative merits of further storage will become sharper and more pressing (Molden et al., 2007). The role of groundwater as a strategic reserve will increase (Shah et al., 2007) How to plan appropriate and sustainable storage systems that address climate change is a pressing need for future AKST development.

6.8.2 Sustainable use of bioenergy

6.8.2.1 Liquid biofuels for transport

Current trends indicate that a large-scale expansion of production of 1st generation biofuels for transport will create huge demands on agricultural land and water—causing potentially large negative social and environmental effects, e.g., rising food prices, deforestation, depletion of water resources (see Chapter 4) that may outweigh positive effects. The following options are currently being discussed as means to alleviating these problems.

Reducing land and water requirements through increasing yields of agricultural feedstocks. Efforts are currently focused on increasing biofuel yields per hectare while reducing agricultural input requirements by optimizing cropping methods or breeding higher yielding crops. For example, Brazil has been able to increase yields and reduce crop vulnerability to drought and pests by developing more than 550 different varieties of sugar cane, each adapted to different local climates, rainfall patterns and diseases (GTZ, 2005). Both conventional breeding and genetic engineering are being employed to further enhance crop characteristics such as starch or oil content to increase their value as energy crops. There is a great variety of crops in developing countries that are believed to hold large yield potential but more research is needed to develop this potential (Cassman et al., 2006; Ortiz et al., 2006; Woods, 2006). However, even if yields can successfully be increased, several problems will persist for the production of liquid biofuels on a large scale.

Total land area under cultivation will still need to expand considerably in order to meet large-scale demand for biofuels and food production (Table 6-5).

Land availability and quality as well as social and environmental value and vulnerability of this land differ widely by country and region and needs to be carefully assessed at the local level (FAO, 2000; WBGU, 2003; European Environment Agency, 2006). Moreover, various studies predict that water will be a considerable limiting factor for which feedstock production and other land uses (e.g., food production, ecosystems) would increasingly compete (Giampietro et al., 1997; Berndes, 2002; De Fraiture et al., 2007). In addition to these environmental problems, special care must be taken to avoid displacement and marginalization of poor people who often have weakly enforceable or informal property and land-use rights and are thus particularly vulnerable (Fritsche et al., 2005; FBOMS, 2006; The Guardian, 2007).

Economic competitiveness will continue to be an issue. Even in Brazil, the world leader in efficient ethanol production, biofuels are competitive only under particularly favorable market conditions. To increase total land area under production, less productive areas would have to be brought into production, either for bioenergy feedstocks directly or for other agricultural crops which may be displaced on the most productive lands. This depends on economic incentives for farmers and investments in productivity enhancements and could have strong effects on agricultural systems and further accentuate food price effects.

Environmental concerns, associated with issues such as high-input feedstock production, the conversion of pristine land for agricultural production, the employment of trans-

Table 6-5. **Land area requirements for biofuels production.**

Percentage of total 2005 global crude oil consumption to be replaced by bioenergy	Energy yield			
	1st generation biofuels		Next generation biofuels	
	40 GJ/ha	60 GJ/ha	250 GJ/ha	700 GJ/ha
5% ~ 1500 million barrels/year	230 million ha	153 million ha	37 million ha	13 million ha
10% ~ 3010 million barrels/year	460 million ha	307 million ha	74 million ha	26 million ha
20% ~ 6020 million barrels/year	921 million ha	614 million ha	147 million ha	53 million ha

Conversion factors: 1 GJ=0.948 million BTU; 1 barrel of oil ~ 5.8 million BTU

Source: Avato, 2006.

genic crops, the depletion of water resources as well as the problematic resemblance of some biofuels feedstocks with invasive species (Raghu et al., 2006) need to be carefully assessed with special emphasis on the local context.

Producing biofuels from inedible feedstock and on marginal lands. It is often argued that using inedible energy crops for the production of biofuels would reduce pressures on food prices. Moreover, many of these crops, e.g., *Jatropha*, poplar and switchgrass, could be grown productively on marginal land, without irrigation and potentially even contributing to environmental goals such as soil restoration and preservation (GEF, 2006; IEA, 2004; Worldwatch Institute, 2006).

Inedible feedstocks. Food price increases can be caused directly, through the increase in demand for the biofuel feedstock, or indirectly, through the increase in demand for the factors of production (e.g., land and water). For example, land prices have risen considerably in the US "corn belt" over the past years—an effect that is largely attributed to the increased demand for ethanol feedstocks (Cornhusker Economics, 2007; Winsor, 2007). Such factor price increases lead to increasing production costs of all goods for which they are used as inputs. Thus, using nonedible plants as energy feedstocks but growing them on agricultural lands may only have a limited mitigating effect on food prices.

Marginal lands. Cultivating energy crops on degraded land or other land not currently under agricultural production is often mentioned as an option but it is not yet well understood. Several key issues deserve further attention: (1) The production of energy crops on remote or less productive land would increase biofuels production costs (due to lower yields, inefficient infrastructure, etc.), leading to low economic incentives to produce on these lands. In fact, while estimates of available marginal land are large, especially in Africa and Latin America (FAO, 2000; Worldwatch Institute, 2006), much of this land is remotely located or not currently suitable for crop production and may require large investments in irrigation and other infrastructure. (2) Environmental effects of bringing new stretches of land into production are problematic and need to be carefully analyzed, especially with regards to soil erosion, water resources and biodiversity.

Development of next generation biofuels. Significant potential is believed to lie with the development of new energy conversion technologies—next generation biofuels. Several different technologies are being pursued, which allow the conversion into usable energy not only of the glucose and oils retrievable today but also of cellulose, hemicellulose and even lignin, the main building blocks of most biomass. Thereby, cheaper and more abundant feedstocks such as residues, stems and leaves of crops, straw, urban wastes, weeds and fast growing trees could be converted into biofuels (IEA, 2006; Ortiz et al., 2006; Worldwatch Institute, 2006; DOE, 2007). This could significantly reduce land requirements, mitigating social and environmental pressures from large-scale production of 1st generation biofuels (Table 6-5). Moreover, lifecycle GHG emissions could be further reduced, with estimates for potential reductions ranging from 51 to 92% compared to petroleum fuels (IEA, 2004; European Commission, 2005; GEF, 2005; Farrell et al., 2006). However there are also environmental concerns associated with potential overharvesting of agricultural residues (e.g., reducing their important services for soils) and the use of bioengineered crops and enzymes.

The most promising next generation technologies are cellulosic ethanol and biomass-to-liquids (BTL) fuels. Cellulosic ethanol is produced through complex biochemical processes by which the biomass is broken up to allow conversion into ethanol of the cellulose and hemicellulose. One of the most expensive production steps is the pretreatment of the biomass that allows breaking up the cellulose and removing the lignin to make it accessible for fermentation. Research is currently focused on how to facilitate this process, e.g., through genetically engineering enzymes and crops. BTL technologies are thermo-chemical processes, consisting of heating biomass, even lignin-rich residues left over from cellulosic ethanol production, under controlled conditions to produce syngas. This synthetic gas (mainly of carbon monoxide and hydrogen), is then liquefied e.g., by using the Fischer-Tropsch (FT) process to produce different fuels, including very high-quality synthetic diesel, ethanol, methanol, buthanol, hydrogen and other chemicals and materials. Research is also focusing on integrating the production of next generation biofuels with the production of chemicals, materials and electricity in biorefineries (Aden et al., 2002; IEA, 2004; GEF, 2006; Hamelinck and Faaij, 2006; IEA, 2006; Ledford, 2006; Ragauskas et al., 2006; Woods, 2006).

Next generation biofuels have to overcome several critical steps in order to become a viable and economic source of transport fuels on a large scale and be able to contribute to the development and sustainability goals. First, next generation biofuels technologies have not yet reached a stage of commercial maturity and significant technological challenges need to be overcome to reduce production costs. It is not yet clear when these breakthroughs will occur and what degree of cost reductions they will be able to achieve in practice (Sanderson, 2006; Sticklen, 2006; DOE, 2007). The U.S. Department of Energy has set the following ambitious goals for its cellulosic ethanol program: reducing the cost per liter from US$0.60 to 0.28 and capital investment costs from currently $0.80 to 0.49 by 2012 (DOE, 2007). Second, even if these breakthroughs occur, biofuels will have to compete with other energy technologies that are currently being developed in response to high oil prices. For example, with regards to transport fuels, technological progress is currently reducing costs of conventional (e.g., deep sea) and unconventional (e.g., tar sands) oil production and also of coal and gas to liquid technologies. Third, while countries like South Africa, Brazil, China and India are currently engaged in advanced domestic biofuels R&D efforts, high capital costs, large economies of scale, a high degree of technical sophistication as well as intellectual property rights issues make the production of next generation biofuels problematic in the majority of developing countries even if the technological and economic hurdles can be overcome in industrialized countries.

6.8.2.2 Bioenergy and rural development

Living conditions and health of the poor can be considerably improved when households have the opportunity to upgrade from inefficient, polluting and often hazardous traditional forms to modern forms of energy. Through their importance for the delivery of basic human needs such as potable water, food and lighting, these modern energy services are among the primary preconditions for advancements in social and economic development (Barnes and Floor, 1996; Cabraal et al., 2005; Modi et al., 2006). Moreover, bioenergy and ancillary industries may promote job creation and income generation. However, the balance of positive and negative effects of different forms of bioenergy is subject to significant debate and is highly context specific. Careful assessments of local needs, economic competitiveness as well as social and environmental effects are needed to determine under which circumstances modern bioenergy should be promoted.

The domestic production of biofuels from agricultural crops (1st generation) is often credited with positive externalities for rural development through creating new sources of income and jobs in feedstock production and energy conversion industries (e.g., Moreira and Goldemberg, 1999; von Braun and Pachauri, 2006; Worldwatch Institute, 2006). However, the actual effect of 1st generation biofuels production on rural economies is complex and has strong implications for income distribution, food security and the environment.

Economically, the major impact of biofuels production is the increase in demand for energy crops. In fact, biofuels have historically been introduced as a means to counteract weak demand or overproduction of feedstock corps, e.g., this was a principal reason for Brazil to introduce its ProAlcool Program in 1975 (Moreira and Goldemberg, 1999). On the one hand, this additional demand can increase incomes of agricultural producers, increase productivity enhancing investments and induce dynamic processes of social and economic development (FAO, 2000; Coelho and Goldemberg, 2004; DOE, 2005; Worldwatch Institute, 2006).

On the other hand, this needs to be evaluated against economic, social and environmental costs that may arise from large increases in biofuels production. First, even if biofuels can be produced competitively, at least part of the rise in agricultural incomes would represent a mere redistribution of income from consumers of agricultural products to producers. The extent of this redistribution depends on the degree to which food prices are affected. Second, in cases when biofuels are promoted despite having higher costs than petroleum fuels, an analogous redistribution from energy consumers to agricultural producers takes place. In both cases the effects on poverty are highly complex. Some rural poor may gain if they can participate in the energy crop production, biofuel conversion and ancillary sectors or otherwise benefit from increased economic activity in rural areas. This depends critically on aspects such as production methods (e.g., degree of mechanization) and institutional arrangements (e.g., structure of the agricultural sector, property rights of agricultural land and security of land tenure). Conversely, those rural and urban poor people who spend a considerable share of their incomes on energy and especially food are bound to lose if they have to pay higher prices. Food-importing developing countries would also suffer under globally rising food prices. Time lags in the response of producers to increased feedstock demand may lead price increases to be more accentuated in the short-term than in the medium to long-term.

Biofuels are considerably more labor intensive in production than other forms of energy such as fossil fuels and thus they are often proposed as a means for improving employment in the agricultural sector as well as in other downstream industries that process by-products such as cakes and glycerin (Goldemberg, 2004; Worldwatch Institute, 2006). However, estimating actual effects on employment is highly complex. First, any newly created employment needs to be weighed against jobs that are displaced in other sectors, including jobs that would have been created in the feedstock production sector even in the absence of biofuels production. These dynamics are complex and may involve very different industries, e.g., the livestock industry, food processors and other major user of agricultural crops (CIE, 2005).

Second, while bioenergy is labor intensive compared to other energy industries, it is not necessarily labor intensive compared to other forms of farming. In fact, energy crop production very often takes the form of large-scale mechanized farming. Thus, in cases where traditional farming is replaced by less labor intensive energy crop production, jobs may actually be lost. Similarly, no new jobs are created if biofuels production simply displaces other agricultural crops. It is unsure whether such job substitution is actually beneficial, especially considering that many jobs in feedstock production are temporary and seasonal (Fritsche et al., 2005; Kojima and Johnson, 2005; Worldwatch Institute, 2006).

Consequently, the overall effects on employment and incomes are highly complex and context specific and there is no consensus on magnitude or even direction of net effects. Even if in certain cases longer term dynamic effects may dominate for the economy as a whole, the considerable risks of welfare losses for certain stakeholders warrant careful consideration—especially with regard to the most vulnerable persons. More research is needed to develop and apply interdisciplinary tools that assess these issues more clearly (e.g., economic cost-benefit analysis).

Development of small-scale applications for biodiesel and unrefined bio-oils. The environmental and social costs of producing biofuels can be considerably lower in small-scale applications for local use due to more contained demands on land, water and other resources. At the same time, the benefits for social and economic development may be higher, especially in remote regions, where energy access and agricultural exports are complicated by high transport costs (Kojima and Johnson, 2005). Landlocked developing countries, small islands, and also remote regions within countries may fall into this category—if they can make available sufficient and cheap feedstock without threatening food security. Especially biodiesel offers potential in small-scale applications as it is less technology and capital intensive to produce than ethanol. Unrefined bio-oils offer similar benefits and their production for stationary uses such as water pumping and power generation is being analyzed in several countries, e.g., focusing on *Jatropha* as a feedstock (Indian Planning Commission, 2003; Van Eijck and Romijn, 2006). Such schemes may offer particular potential for local communities when they are integrated in high intensity small-scale farming systems which allow an integrated production of food and energy crops. More research is needed on the costs and benefits to society of these options, taking into consideration also other energy alternatives.

Conduct R&D on electricity and heat generation technologies from biomass to improve operational reliability. Some forms of bioelectricity and bioheat can be competitive with other off-grid energy options (e.g., diesel generators) and therefore are viable options for expanding energy access in certain settings. The largest potential lies with the production of bioelectricity and heat when technically mature and reliable generators have access to secure supply of cheap feedstocks and capital costs can be spread out over high average electricity demand. This is mostly the case on site or near industries that produce biomass wastes and residues and have their own steady demand for electricity, e.g., sugar, rice and paper mills. The economics as well as environmental effects are particularly favorable when operated in combined heat and power mode. Biomass digesters and gasifiers are more prone to technical failures that direct combustion facilities, especially when operated in small-scale applications without proper maintenance. More research and development is needed to improve the operational stability of these technologies as well as the design of institutional arrangements, including potential integration with biomass processing industries, livestock holdings and mixed farming. However, modern bioenergy is only one of several options available for advancing energy access and in each case local alternatives need to be compared regarding economic costs as well as social and environmental externalities (Table 6-6).

Table 6-6. **Bioenergy: Potential and limitations.**

Technological Application	Potential Benefits	Risks and Limitations	Options for Action
1st Generation Biofuels	• Energy security • Income and employment creation • GHG emission reductions	• Limited economic competitiveness • Social concerns, (e.g., pressures on food prices) • Environmental concerns (e.g., depletion of water resource, deforestation) • GHG emission reductions strongly dependent on circumstances	• R&D on improving yields of feedstocks and fuel conversion • More research on social, environmental and economic costs and benefits • Policies/initiatives furthering social and environmental sustainability
Next Generation Biofuels	• Larger production potential and better GHG balance than 1st generation • Less competition with food production	• Unclear when technology will be commercially viable • High capital costs and IPR issues limit benefits for developing countries and small-scale farmers • Issues with over-harvesting of crop residues, GMOs	• Increase R&D to accelerate commercialization • Develop approaches to improve applicability in developing countries and for small-scale farmers
Bioelectricity and Bioheat (large-scale)	• Low GHG emissions • Favorable economics in certain off-grid applications (e.g., bagasse cogeneration)	• Issues with operational reliability and costs • Logistical challenges of feedstock availability	• Develop demonstration projects, product standards • Disseminate knowledge • Access to finance
Bioelectricity and Bioheat (small-scale)	• Potential for increasing energy access sustainably in off grid areas with low energy demand using locally available feedstocks	• Costs, operational reliability, maintenance requirements	• R&D on small-scale stationary uses of biodiesel and bio-oils • Capacity building on maintenance

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