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AGRICULTURE AND RURAL DEVELOPMENT & ENVIRONMENT DEPARTMENTS

AGRICULTURAL DEVELOPMENT UNDER A CHANGING CLIMATE:

Opportunities and Challenges for Adaptation

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF **BOXES**

LIST OF ACRONYMS

3H	Huang-Huai-Hai River Basin
AEZ	agroecological zone
AFTAR	Africa Agriculture and Rural Development Unit
AIACC	Assessment of Impacts and Adaptation to Climate Change
AOGCM	atmospheric-ocean general circulation climate model
APDAI	Andhra Pradesh Drought Adaptation Initiative
APSIM	Agricultural Production Systems Simulator
CDM	Clean Development Mechanism
CERs	Certified Emissions Reductions
CGIAR	Consultative Group on International Agricultural Research
CH_4	methane
CIAT	International Center for Tropical Agriculture
CIFOR	Center for International Forestry Research
CIMMYT	International Maize and Wheat Improvement Center
CO_2	carbon dioxide
COF	climate outlook forum
CWR	crop wild relatives
DFID	U.K. Department for International Development
DREB	Dehydration-Responsive Element Binding
DSSAT	Decision Support System for Agrotechnology Transfer
ENSO	El Niño-Southern Oscillation
EPIC	Erosion Productivity Input Calculator
EWS	early warning systems
FAO	UN Food and Agriculture Organization
FSE	farmer seed enterprise
GAEZ	Global Agroecological Zone
GCM	general circulation model, or global climate model
GDP	gross domestic production
GEF	Global Environment Facility
GIS	Geographic information systems

GISP	Global Invasive Species Programme
GLAM	general large-area model
IAIL3	Agriculture Intensification Project III
IAS	invasive alien species
ICARDA	International Center for Agricultural Research in the Dry Areas
ICASA	International Consortium for Agricultural Systems Applications
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICT	information and communication technology
IGP	Indo-Gangetic Plain
IIASA	International Institute for Applied Systems Analysis
IITA	International Institute of Tropical Agriculture
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
IRRI	International Rice Research Institute
ISC	integrated *Striga* control
ISFM	integrated soil fertility management
IWMI	International Water Management Institute
IWRM	integrated water resource management
KACCAL	Adaptation to Climate Change in Arid Lands in Kenya
LCDI	low-cost drip irrigation
LULUCF	land use, land-use change, and forestry
N	nitrogen
N_2O	nitrous oxide
NARES	national agricultural research and extension service
NARS	national agricultural research service
NERICA	New Rice for Africa
NGO	non-governmental organization
NMS	National Meteorological Services
NRM	natural resource management
PES	payment for environmental services
PFP_N	partial factor productivity
PPB	participatory plant breeding

PTM	potato tuber moth
PVS	participatory varietal selection
R&D	research and development
RCM	regional climate model
RWH	rainwater harvesting
SADC	Southern African Development Community
SARCOF	Southern Africa Regional Climate Outlook Forum
SLCP	Sloping Land Conservation Program
SLD	shared learning dialogues
SRES	Special Report on Emissions Scenarios
SST	sea surface temperature
SVF	seed vouchers and fairs
SWC	soil and water conservation
TTL	Task Team Leader
UNFCCC	UN Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Recovery
UPA	urban and peri-urban agriculture
USAID	US Agency for International Development
USGS	U.S. Geologic Survey
WDR	World Development Report
WMO	World Meteorological Organization
WRI	World Resources Institute
WUA	water-user association

PREFACE

Climate change presents a profound challenge to food security and development. Negative impacts from climate change are likely to be greatest in regions that are currently food insecure and may even be significant in those regions that have made large gains in reducing food insecurity over the past half-century. In response to this challenge, the World Bank, along with other donor and development agencies, is developing strategies for addressing climate change adaptation and is providing assistance to countries so that they can begin to implement appropriate risk-reduction measures. Adaptation in the agricultural sector is being given a high priority within this effort because of the inherent sensitivity of food production to climate and the strong inter-linkages that exist between climate, agriculture, and economic growth and development.

The purpose of this report is to identify and summarize potential climate change impacts on agriculture in regions served by the World Bank, examine the causes of vulnerability, provide information on where investments are needed to better climate-proof agriculture, and describe the relevance of current efforts to achieve more sustainable agriculture to that of managing climate risks for adaptation. The report's target audience is World Bank staff, client governments of the World Bank, and the donor and development communities, more generally. This report is intended to provide an in-depth analysis of climate change and the agricultural sector. It is hoped that the information contained in this report will stimulate a closer examination of how to bring better awareness of climate risks to the Bank's investments in agriculture and rural development.

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SUMMARY FOR DEVELOPMENT PRACTITIONERS

The purpose of this report is to review the major effects of climate change on the agricultural sector; to examine the causes of vulnerability; and to suggest a range of potential options and investment opportunities for supporting adaptation efforts and, more generally, for building adaptive capacity. This report primarily focuses on appropriate strategies for adapting to climate change impacts that are projected to occur over the next one to two decades, although several issues covered in this report are important for long-term adaptation needs as well. Measures to support adaptation that are discussed in this report include:

- Building or enhancing systems for conveying climate information to rural populations.
- Diversifying rural economies to reduce reliance on climate sensitive agricultural practices.
- Promoting greater agricultural research and development (R&D).
- Addressing land degradation
- Reconfiguring irrigated production systems to use water more efficiently and to accommodate the use of marginal quality water.
- Increasing capture and retention of rainwater.
- Improving heat tolerance of livestock.
- Strengthening pest management systems to cope with increased threats from insects, pathogens, and weeds.

This report also describes opportunities for linking adaptation and mitigation, and it discusses the importance of mainstreaming adaptation into development.

I. Overview of Climate Change and Its Impacts on Agriculture

Climate Change Is Already Occurring

The last several decades have witnessed warmer temperatures across the globe, with more rapid warming observed during the last half of the 20th century compared with the first. Heavy rainfall events have increased, longer and more intense droughts have occurred, and the El Niño-Southern Oscillation (ENSO) phenomenon has become the dominant mode of climate variability in some subregions, exerting a significant influence on the prevalence and severity of droughts and floods. The negative effects of climate change are already being felt, especially in food-insecure regions. Currently, and over the next few decades, climate change impacts on agriculture are more likely to arise from increased climate variability and increased frequency and intensity of extreme events, rather than from changes in mean climatic conditions.

Climate Change Will Intensify Over the Span of This Century

The rate of warming is expected to accelerate, and extreme climate events are likely to increase in frequency and intensity. Long-term shifts in precipitation patterns are projected to lead to an overall drying trend in some subtropical regions (including southern Africa, the Mediterranean Basin, and parts of Central America) and increased precipitation in other regions (including East Africa and North and Southeast Asia). Significant disagreement among climate models still remains regarding the long-term direction of precipitation for large areas of tropical South America, Africa, and Asia, reflecting knowledge gaps of convective precipitation processes in the tropics. Across regions, precipitation is likely to become increasingly aggregated, with the possibility that wet years will become wetter and dry years drier, while the frequency of extreme wet and dry years is expected to increase. In addition, intra-annual rainfall variability could increase, resulting in a greater number of heavy rainfall events, a decrease in the overall number of rainy days, and longer intervals between rains.

Climate Change Will Be an Important Driver of Food Security

Food security has reemerged as a core development concern as extreme climate events, rising energy prices, low global food stocks, changing urban diets, and growth in biofuels converge to push up prices of basic commodities around the globe. Climate change could further disrupt food production and bring uncertainty and volatility to food prices, with disproportionate effects on the world's poor. While impossible to quantify exactly how much climate change will influence the global food supply relative to other drivers, a common consensus is emerging around the likelihood of the following impacts:

- Frequency and intensity of extreme events (heat waves, droughts, and floods) are likely to increase, leading to reduced yield levels and disruptions in production.
- Temperature rise and changes in timing, magnitude, and distribution of precipitation are likely to increase moisture and heat stress on crops and livestock, with the subtropical regions being among the most affected.
- Agricultural systems will face increasing risks of soil erosion, runoff, landslides, and pest invasions.
- Climate change impacts will become increasingly magnified where poverty is pervasive and social safety nets weak.

The Major Impacts of Climate Change

Temperature Rise Temperature rise is likely to result in reduced food production within the next couple of decades in regions already facing food insecurity. For example, yields of major cereal crops (rice, wheat, maize, sorghum) in the tropics and subtropics are expected to decline with a temperature increase as small as 1°C, such as could occur by around 2030. While adaptation measures could offset some of the expected productivity decline, impacts from a temperature increase of 3°C or more, which may well occur by the end of the century, could result in a significant loss of productivity in low-latitude regions and diminished effectiveness of adaptation measures.

Temperature rise of this magnitude could significantly reduce the dry-season supply of glacial meltwater, an important water source for irrigated agriculture in South and Central Asia, the Andean Region, and western China. Higher inputs of glacier meltwater from warming are expected to increase the risk of flooding over the next several decades, after which reduced glacier runoff could dramatically decrease river flows in the dry season. Impacts caused by the diminution or loss of glaciers will be much greater than those incurred solely by a net change in the quantity of the water resource. Glaciers play a critical role in regulating regional climate and weather conditions; maintaining ecosystem integrity; and providing water for agriculture, human consumption, and hydropower generation. In addition, agriculture in highly productive river deltas could become significantly less viable due to saltwater intrusion from sea-level rise.

Impacts on Agricultural Water Supplies Even in the absence of reduced mean precipitation, increased water stress could occur where higher temperatures in warm regions increase moisture losses from evapotranspiration. Warming of the atmosphere, changes in rainfall abundance, and frequency and severity of extreme events will exert significant pressures on agricultural water use, with several regions currently experiencing water deficits likely to face further shortages. In dryland areas, marginal cropland could convert to rangeland, and some crop- and rangelands could no longer be suitable for food production. Over-appropriation of water for irrigation is already placing acute pressures on water supplies in some regions, and the future availability of water for agriculture could be further constrained by the increasing urbanization and industrialization of society.

Impacts on Livestock Climate change is expected to significantly affect the livestock sector through heat stress that directly impacts livestock physiological processes, indirect impacts on crop and rangeland resources (which affect feed allocation), and increased disease pressure on livestock. Greater drought frequency may inhibit crop and animal system recovery, resulting in long-term degradation of grazing resources, continual reduction in herd size, and destabilization of the social and economic standing of resource-poor livestock keepers.

Secondary Impacts Secondary (indirect) impacts from climate change—such as increased rates of runoff and soil erosion and increased crop losses from insects, diseases, and weeds—could magnify production losses. In fact, increased flood and landslide risks from heavy storms and observations that higher temperatures are causing expansion of the over-winter range of some crop pathogens provide early evidence that climate change is already intensifying these indirect effects. Secondary impacts are not well represented in climate impact models, if represented at all.

II. Regional Impacts of Climate Change on Agriculture

Climate Change Impacts on Agriculture Will Vary by Region

Climate change impacts on subtropical and tropical regions will be predominately negative, especially where agriculture is currently marginal with respect to high-temperature and moisture-deficit conditions. The most vulnerable agricultural systems occur in arid, semi-arid, and dry subhumid regions in the developing world, home to half of the world's malnourished populations, where high rainfall variability and recurrent droughts and floods regularly disrupt food production and where poverty is pervasive.

Agriculture in cold-limited (high-latitude and high-altitude) areas could benefit from modest levels of warming that effectively increase the length of the growing season. Regions expected to benefit from a poleward shift in agriculture under future warming include northern China, eastern Europe, northern North America, and the South American cone. However, agriculture in these newly productive areas will have to be carefully administered in order to efficiently manage water and reduce risks from secondary climate change impacts.

Specific Impacts by Region

From a food security perspective, Sub-Saharan Africa is arguably the most vulnerable region, given its repeated exposure to extreme climate events, very high reliance on rainfed agriculture for basic food security and economic growth, and entrenched poverty. Climate change is certain to amplify these vulnerabilities given projections of warming temperatures, potential for increased activity attributable to the ENSO, and trends of increased aridity in southern Africa and other regions within Africa.

In the Middle East and North Africa, agriculture has become increasingly vulnerable to the combined effects of population growth, climate change, and natural resource base degradation. High temperatures, low and erratic precipitation, prolonged drought, and land degradation currently constrain agriculture, and intensification of these factors with climate change is likely to make food production increasingly untenable.

In South Asia, the Indian monsoon is projected to intensify, but it could also become more variable, possibly leading to a higher incidence of flooding in flood-prone areas and persistence of drought in semi-arid areas. Temperature rise is expected to cause reductions in both yield and area of suitability of the region's two main cereal crops, wheat and rice, and long-term changes to the region's water resources caused by the loss of glacier meltwater. Sea-level rise is a threat to rice production in low-lying coastal zones and river deltas.

In East Asia and the Pacific, temperature rise, flooding in Southeast Asia, sea-level rise in the Mekong and other major river deltas, and an increased intensity of El Niño–induced drought in Indonesia are among the major climate change effects anticipated to impact the production of rice, the region's major crop. In eastern China, the 3H (Huang-Huai-Hai) River Basin, responsible for roughly half of the country's grain output, could experience a decrease in wheat and maize yields. On the other hand, agricultural productivity in northern Asia could increase as a result of temperature rise, with potential benefits being greatest where water is not limited.

Irrigated agriculture in Central Asia could experience increased flood and drought risks from glacier retreat. Flood risks could increase where there is higher and earlier discharge of glacial meltwater in the spring, and drought risks could result from the eventual loss or reduction of meltwater for the region's extensive irrigated croplands. Northern Europe and northern Central Asia could benefit from a longer growing season, while southeastern Europe could be negatively affected by temperature rise and increased moisture deficits.

Climate change is expected to intensify moisture deficits in northeastern Brazil and parts of the Amazon and Central America, and increase flood risk in southern Central America and southeastern South America. Positive benefits to agriculture could occur in the southern cone region of South America from an increase in the number of frost-free days. Temperature rise is projected to be more pronounced in high-elevation mountain ranges compared with adjacent low-elevation areas, which will have profound effects on water budgets in the Andes, as glaciers retreat over the next several decades.

III. Adaptation in the Agricultural Sector

Agricultural Development and Adaptation to Climate Change can be Complementary Goals

Adaptation to climate change is more urgent than ever, given both the climate risks facing agriculture and the increasing opportunity costs of failing to address entrenched resource degradation and poverty associated with underinvestment and misinvestment in agriculture. Fortunately, there is good potential to realize "double dividends" in agricultural development and adaptation, because both pursuits require greater support for agricultural R&D, tighter integration of natural resource management into agricultural production, increased household access to production assets, and education and skill development for rural diversification. Examples of the potential overlap between development and adaptation include:

- Improving access to new varieties and other production factors, which can help farmers improve overall production and better manage risks from droughts and floods.

- Enhancing the resilience of the resource base to extreme climate events through conservation agricultural practices that protect soils against runoff and erosion, promote biodiversity, and conserve water.
- Modernizing irrigation systems, which can increase water-use efficiency, bring greater flexibility to water delivery for agriculture, and help farmers diversify to better manage climate risks.
- Improving coordination around the containment and management of invasive alien species, which is needed for managing both current risks from invasive species and for building the capacity to cope with an expected increase in this risk with climate change.
- Creating opportunities for rural livelihood diversification, which can lead to increased economic security and less reliance on climate-sensitive agricultural activities.

The urgent threat from climate change requires a focused and rapid scaling up of appropriate agricultural development measures. There are several specific entry points through which agricultural development can support climate risk management and adaptation. They are discussed next.

Water Resource Management Better capture and storage of rainwater is a key strategy for managing climate risks in rainfed agriculture. Rainwater harvesting methods range from simple technologies that increase the capture of surface water flow and concentrate runoff to more complex measures for storage of water in macro-catchments. In irrigated agriculture, policy reform measures that push water costs closer to its shadow price through changing incentive structures, and efforts to modernize irrigation infrastructure through both "hard" (control structures to reduce seepage and evaporation) and "soft" (institutional reforms to create more demand responsiveness) measures are important for helping agriculture adapt to future climate risks. Measures to improve water productivity (the conversion of water into food) through conservation tillage, improved soil fertility management, use of improved crop varieties, and better crop pest management are important under current climates and will become increasingly so for managing risks from climate change.

Crop Breeding The potential for developing crop varieties with superior stress tolerance is promising, given recent advances in molecular biology and genomics, with implications for both conventional and transgenic breeding. However, the long-term success in breeding crops adapted to climate change may be constrained by a potential loss of genetic diversity caused by temperature rise and shifts in precipitation that lead to range reduction or extinction of crop wild relatives. To counter this risk, support is needed for strategies that begin defining the scope of the climate change threat to crop wild relatives, policies that engage local communities in their conservation, and the formulation of priority-determining mechanisms.

Seed Systems Failures in seed supply systems compound vulnerability to extreme events, particularly in dryland areas where no formal seed networks exist. Climate change will seriously challenge seed system functioning to the extent that multiyear droughts or more pronounced drought/flood cycles increase the magnitude of acute crises and aggravate underlying vulnerabilities. Adapting to climate variability and change in seed-insecure farming environments requires that current emergency seed relief policies are better addressed. This can be done through seed voucher and fair programs, as well as through promoting rural credit programs, improved seed storage facilities, and measures for increased productivity that improve supply of and access to seeds.

Integrated Pest Management An increase in extreme events, changes in moisture conditions, temperature rise, and elevated CO_2 concentrations are expected to magnify pest (insect, pathogen, and weed) pressures on cropping systems through range expansion of existing pests, increased pressure from invasive alien species, and disruption of the temporal and geographical synchronization of pests and beneficial insects. A comprehensive assessment of the pest threat is needed, along with investments in infrastructure, training, and education in order to better manage existing pest problems, as well as to develop sufficient capacity to respond to new threats. Such investment areas include improving surveillance capabilities through building remote-sensing and GIS capacity, policy support for information sharing, institutional coordination, and inter-sectoral planning related to managing invasive alien species.

Livestock Adapting livestock to increased heat stress is a priority. Measures to achieve this include increased support for animal breeding efforts to produce breeds with increased ability to shed or reflect heat, better feed management and nutrition to reduce heat production during rumination, and the development of physical structures that provide grazing animals with shade in order to produce microclimates that lower animal heat loads.

Urban/Peri-Urban Agriculture The urban poor are heavily involved in agricultural activities, with an estimated 800 million urban dwellers worldwide involved in urban/peri-urban agriculture. Climate risks to urban agriculture include increased flooding, high temperatures in urban areas, and increased activity of waterborne pathogens and parasites. Policies to reduce these potential risks—such as through formally incorporating urban agriculture into urban planning, better managing health and environmental risks associated with using wastewater for irrigation, and strong governance to enforce land-use policies—will help the urban poor to better cope with future climate risks.

Economic Diversification Through the development of microenterprises, smallholder production systems can be diversified and exposure to climate risk reduced.

Areas where investments are needed to make microenterprise more viable include greater R&D in horticultural crops, including breeding for heat tolerance; integrating climate change scenarios into economic and agronomic assessments of horticultural crops, livestock, and other microenterprises; building capacity in the seed sector and other input markets; and improving enabling conditions for smallholder entry into horticulture through extension of credit, matching funds for smallholder investments, and women-oriented programs.

Access to Forecasts and Other Climate Information Seasonal climate forecasting can aid agricultural decision making to enhance climate risk management. However, realizing the full potential of this technology will require significant investments in education and outreach to build trust in the forecasts, improving the linkages between hydrometeorological services and agriculture research and extension, integrating climate forecast information into existing knowledge dissemination platforms, and linking forecasts with timely access to agricultural inputs.

Good Opportunities Exist for Linking Adaptation and Mitigation

Greenhouse gas emissions associated with agricultural activities are expected to increase until at least mid-century, driven by a rise in the use of nitrogen fertilizer, land use conversion and increased rates of land degradation, and changes in diet toward increased meat consumption. Major improvements in how food is produced will be needed to slow the rate of new emissions. This can be achieved through improvements in nitrogen-use efficiency and through reconfiguring production systems to enhance carbon sequestration. Potential entry points through which both mitigation and adaptation needs can be met in the process of securing more sustainable food production systems include:

- Avoiding emissions through increased production efficiency and system reconfiguration to reduce reliance on external inputs and more closely tailor fertilizer nitrogen needs to crop needs, improve water management in flooded rice production, and adopt improved livestock feeding practices and use of supplements.
- Enhancing land-based carbon sequestration through the adoption of conservation tillage, agroforestry, and integrated soil fertility management, which maintain and build soil carbon reserves and increase aboveground carbon storage, while improving the resilience of agricultural land to increased risks from soil erosion, landslides, drought, and flooding.

IV. Rural Investments and Policies, Capacity Building, Coordination, and Knowledge Sharing

Promoting comprehensive rural development is important for enhancing the uptake and dissemination of adaptation-relevant measures. Broadening the potential for uptake and dissemination of the measures described in the preceding sections will require complementary investments in rural infrastructure, integrated participatory approaches to R&D and extension, as well as attention to rural development policies to assess where risks associated with adoption are substantial. Relevant considerations include making sure that:

- Input and output markets are sufficiently robust so as to provide incentives for farmers to invest in adaptation measures.
- Support for the private sector in input markets is adequate.
- Land tenure and resource ownership policies are complementary to the adoption of adaptation measures and do not exclude marginal groups that are often the most vulnerable to climate risks.
- Outreach efforts are gender specific to meet the needs of women farmers.
- Opportunities for participatory research exist that improve the relevance of technologies to local needs and marginal environments.
- Efforts to enhance linkages among research, extension, and nongovernmental organizations (NGOs) are promoted.
- Financial and capital barriers to adoption are addressed by supporting social-fund financing and local credit systems and community-based management systems that can initiate cost-sharing and labor-saving measures.
- Policies are developed that link (or package) production innovations with access to long-range weather and seasonal climate forecasts where possible.

Coordination Is Critical for Adaptation Planning and Implementation

Adaptation is an integrated process that requires robust coordination and communication among key actors. At the national level, coordination among government ministries and between ministries and other relevant institutions is critical for planning and implementing adaptation. Causes of poor institutional coordination that need to be considered in developing an adaptation project or program include:

- Poorly matched mandate and expertise of the lead ministry to a national-level project. For example, the environment ministry often assumes a lead role in climate change–related issues even though the agriculture ministry may be the most suitable lead institution for an agriculture-related adaptation initiative.
- Inordinate influence over the process by a single ministry, such as when poor coordination between the finance ministry and those responsible for overseeing adaptation work constrains planning and implementation. Remedial measures, such as creating a ministerial steering committee for adaptation projects, can help resolve these bottlenecks.
- Poor inter-institutional communication that constrains integrated planning. For example, policies to encourage better

coordination between agricultural and health ministries and institutions will become increasingly important in areas where efforts to increase surface water impoundment for agriculture increases the potential for malaria transmission or where the expanded use of marginal quality water for crop production increases health risks to rural communities.

- Lack of mechanisms for sharing of data between ministries and other institutions. A variety of different data (climatic, environmental, and socioeconomic) are needed for adaptation planning, but often such data have significant gaps, are not centrally housed, or are not willingly shared among ministries.
- Coordination between national, district, and local institutions and stakeholder groups requires innovations in communication that facilitate bottom-up and top-down information exchange and education and training of intermediaries on climate issues.

Generating and Sharing Knowledge and Data for Adaptation Will Require Significant Support for Building Institutional Capacity

Given the substantial knowledge and information needs for adaptation, greater effort is needed to build national and regional capacities to generate, interpret, apply, and share climate data and information. This will require:

- Filling knowledge gaps in observing networks and data collection through support for meteorological field campaigns that improve climate models for data-sparse regions.
- Compiling and centralizing country-scale data related to secondary effects of climate change for the range of co-stressors affecting socioeconomic systems and building capacity to generate and use resource models based on these data.
- Improving access to online sources of information. Climate data portals and adaptation wikis can help development practitioners plan adaptation activities through providing quick and readily accessible climate and climate-related data. However, low Internet bandwidth in the developing world can make it difficult to access data-intensive tools.
- Promoting opportunities for policy makers and others to use climate information through strengthening coordination and communication between information generators (climate modelers and hydrometeorological services) and users (agricultural research and extension, commodity boards, market intermediaries, and farmer groups). Building climate literacy of the latter group through targeted training is important.
- Supporting education initiatives that will increase skills in climate and crop modeling, developing climate curricula for universities, and establishing Web-based networks that can support learning mechanisms for using climate and environmental information.
- Providing support for both top-down and bottom-up processes that convey information and knowledge about impacts, vulnerability, and adaptation between local communities and policy makers.

Areas where knowledge and information collection and exchange can be enhanced include:

- Developing shared learning dialogues that serve to better integrate local information, knowledge, and priorities with those of ministries and other national-level institutions.
- Fortifying information and communication technology services in rural areas.
- Building the capacity of existing local networks, such as water user associations and farmer cooperatives and associations.
- Supporting participatory workshops and other processes that improve the reach of climate information and that bring local perspectives and knowledge into adaptation planning.

V. Adaptation, Now, and in the Future

An important theme running throughout this report concerns the need to better manage current climate risks to agriculture now to ensure that a wider range of options are available in the future to adapt as the climate system changes. A key starting point for managing climate risks is the current adaptation "deficit," where climate change and variability overwhelm present coping strategies of vulnerable regions and communities. The adaptation deficit is a significant hindrance to sustainable development and contributes to entrenched poverty and reduced adaptive capacity in many developing world regions. Narrowing this deficit provides a basis for pursuing "no-regrets" adaptation options, through which numerous entry points exist for both creating more sustainable food production systems and building adaptive capacity to future climate change. Targeting these potential win–win solutions can ensure buy-in from national governments, as well as from local communities. Adaptation is a reiterative process; societies adapt and readapt in response to climate change impacts and access new knowledge and information. Development gains realized from better managing current and near- and medium-term climate risks (one to two decades) can help prepare society to better adapt to long-term climate change.

CHAPTER 1: INTRODUCTION

The purpose of this report is to review the major impacts of climate change on the agricultural sector; examine sources of vulnerability in agriculture and rural communities; and suggest a range of potential options and investment opportunities for supporting adaptation efforts and, more generally, for building adaptive capacity. The report primarily focuses on appropriate strategies for adapting agriculture to climate change effects projected to occur over the next two to three decades, although several issues covered in this report are also important for long-term adaptation needs as well. It is targeted at World Bank employees and clients as well as the larger development community, including donors and practitioners.

This report is presented in nine chapters.

- Chapter 1 provides a broad introduction of how climate variability and change could affect agriculture.
- Chapter 2 reviews the projected impacts of climate change on specific regions. Impacts common across regions—such as land degradation, water shortages, and pest infestation—are examined in detail in subsequent chapters.
- Chapter 3 provides an overview of issues related to vulnerability, mainstreaming adaptation into agricultural development, adaptation considerations in rural policies, and avenues for enhancing knowledge and information flows to support adaptation.
- Chapter 4 explores issues of climate-scenario generation for agricultural applications and technical progress and capacity-building needs in climate-crop modeling, seasonal climate forecasting, and early warning systems.
- Chapter 5 discusses impacts and adaptation issues related to water use for rainfed and irrigated production systems, as well as adaptation options for flood-prone agricultural areas.
- Chapter 6 discusses options for combining mitigation with adaptation in the agricultural sector and examines adaptation options for sustainable land management and for livestock.
- Chapter 7 discusses progress toward developing crop cultivars that will be better adapted to future climate change and how the potential loss of agricultural biodiversity from climate change could negatively affect future plant-breeding efforts. It also examines seed systems as they relate to climate risk management and adaptation.

- Chapter 8 examines how climate change could influence pest and disease pressure in agriculture, and it identifies potential adaptation options.
- Chapter 9 discusses diversification strategies for agriculture, with particular focus on rural microenterprises, high-value enterprises, and peri-urban agriculture.

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I. Climate Variability, Climate Change, and Extreme Events

Climate change has the potential to significantly undermine future efforts to achieve food security and sustainably manage the natural resource base of agriculture. Rising temperatures, increased frequency and severity of extreme climatic events, and changes in the distribution, quantity, and timing of rainfall—projected over the course of this century—could have strongly negative impacts on crop and livestock production. These impacts will further compound the already substantial challenges facing agriculture, including increasing population pressure on the resource base, land degradation, loss of agricultural biodiversity, and damage from pests and diseases.

The past several decades have witnessed warmer temperatures across all regions, with a faster warming rate occurring in the latter half of the 20th century compared with the first half and increased climate variability. Heavy rainfall events have increased, longer and more intense droughts have occurred, and the El Niño-Southern Oscillation (ENSO) phenomenon has become the dominant mode of climate variability in many regions, exerting a significant influence on the prevalence and severity of drought and flooding in the tropics (Trenberth et al. 2007). These negative effects from climate change are already being felt in food-insecure regions.

Warming trends are projected to accelerate over the course of this century, and the frequency and intensity of extreme events are likely to increase. Regional shifts in precipitation patterns are projected to lead to an overall drying trend in some subtropical regions, such as southern Africa, the Mediterranean Basin, and southeastern Europe and Central America, and to increased rainfall in other regions, including North, South, and Southeast Asia and East Africa (Christensen et al. 2007)[1]. Precipitation is likely to become increasingly aggregated, with wet years projected to become wetter and dry years drier, while the frequency of extreme wet and dry years is expected to increase. On an annual (seasonal) time scale, the number of rainfall events is likely to decrease, while rainfall intensity is likely to increase due to greater atmospheric moisture retention with increased air temperatures. Potential manifestations of increased seasonal

1 There is strong agreement among climate models regarding precipitation trends for the subregions listed, as indicated in Christensen et al. However, significant uncertainties remain as to the direction and magnitude of mean precipitation change across many regions, particularly in the tropics.

variability include more extreme hot days during the growing season, a shift in precipitation toward heavier but less frequent rainfall events, and longer periods between rains—which, when coupled with increased rates of evapotranspiration under warmer temperatures, could negatively affect crop growth (Huntingford et al. 2005, and references therein).

The projected increase in large storms and heavy precipitation events with climate change is very likely to intensify flooding (Kundzewicz et al. 2007). For example, South Asia could experience increased severity of flooding given the projected intensification of the Indian monsoon with climate change, combined with land cover changes that enhance the flooding effect. A shift in rainfall intensity toward more extreme rainfall events in the last half of the 20th century has increased flood risks in India (Goswami et al. 2006), and these effects have been observed in Latin America as well (Magrin et al. 2007).

Large-scale weather patterns generated by the Asian and West African monsoons, as well as the ENSO, are prominent climatic features of low-latitude zones, influencing the welfare of more than a third of the Earth's human population (Paeth et al. 2008). Changes in the characteristics of these systems from climate change could have an enormous influence on future food security. The characteristics of the ENSO could also change, though there are significant uncertainties as to how that change will manifest itself (**Box 1.1**). Future changes in the intensity of the West African monsoon also remain uncertain.

II. Effects of Temperature Rise

The effects of rising temperatures on crop productivity vary depending on the characteristics of the crop, the timing of heat stress in relation to crop development, and the conditions under which it is grown. Maximum daytime temperature accelerates crop maturity, resulting in reduced grain filling, while higher minimum nighttime temperatures increase respiration losses. In addition to mean temperature rise, episodic heat waves also have a strong negative impact on yields, particularly when they occur during sensitive phenologic stages, such as during reproductive growth causing increased sterility or during seedling emergence, which affects crop stand establishment. Moreover, decreased solar radiation resulting from higher cloud and aerosol formation linked to temperature rise can suppress crop biomass production.

The extent to which a carbon dioxide (CO_2) fertilization effect could offset damage to crop production caused by rising temperatures remains highly uncertain. Initial estimates of a positive effect appear to have been overly optimistic in light of recent evidence that other constraints to the system, such as nitrogen deficiency, dampen the response of the plant to increased CO_2 concentrations (Long et al. 2006). Coupled

Box 1.1
HOW IMPORTANT IS THE ENSO TO CLIMATE CHANGE?

The ENSO (El Niño-Southern Oscillation) refers to periodic (two- to seven-year) anomalies in sea surface temperatures over a large area of the eastern equatorial Pacific Ocean that alter large-scale weather patterns. The warm (El Niño) and cool (La Niña) phases of the ENSO have variable effects over land areas. In Africa, El Niño events often lead to drought in southern Africa and flooding in eastern Africa, whereas La Niña events generally cause the inverse. In Latin America, severe droughts in northeastern Brazil and parts of Mesoamerica and flooding in the Andes have been attributed to the ENSO. In Asia, ENSO activity has become more prominent in recent decades, causing severe drought in Indonesia and droughts and flooding in eastern and southern China, respectively. El Niño and La Niña phases can occur in tandem, with severe impacts on agriculture, forests, hydropower generation, and industrial output, as occurred in the late 1990s. In addition, the ENSO is positively correlated with outbreaks of infectious and vector-borne diseases in many regions of the developing world.

The late 20th century was an exceptionally active ENSO period, with the ENSO becoming the dominant mode of inter-annual climate variability in areas of the subtropics and tropics. The ENSO's increased influence over global weather patterns in the 20th century has prompted concerns that a more "El Niño-like" climate could evolve in a greenhouse world, with serious implications for society. Given its sensitivity to climatic conditions, the ENSO could change; however, an outcome of more intense or more frequent El Niño events is far from certain given the substantial variability in predicted future ENSO activity (Cane 2005; Paeth et al. 2008). At the very least, sea surface temperatures in the eastern equatorial Pacific are projected to increase 5°C by 2100, a warming threshold comparable to that which currently triggers the ENSO.

crop-climate simulation modeling has shown yield stimulation from elevated CO_2 to be more than offset by elevated temperatures under tropical conditions (Challinor and Wheeler 2008).

Agriculture in cold-limited (high-latitude and high-altitude) areas could benefit from a modest temperature rise that increases the length of the growing season. Regions where agricultural production is expected to benefit from climate change, based on projected temperature rise alone, include northern China, eastern Europe, northern North America, the South American cone, and highland areas of East Africa. However, in some cases, water shortages and increased pest damage may diminish these benefits.

III. Effects of Crop Water Stress

The projected increase in temperature, changes in rainfall abundance, and frequency and severity of extreme events is expected to exert severe water pressures on agriculture. Several regions already experiencing water deficits are likely to face further shortages in the future. The time horizon over which climate change influences on water supply will be felt is short, and the decrease in precipitation need not be large for substantial impacts to occur. For example, the Intergovernmental Panel on Climate Change (IPCC) estimated that 75 to 250 million more people in Africa will face increased water stress by 2020, and a 10 percent drop in precipitation in semi-arid areas of this region could decrease surface drainage volumes by 50 percent, according to deWit and Stankiewicz (2006). Other water-scarce areas, including the Mediterranean Basin and parts of Mesoamerica and Central Asia, are projected to face long-term drying trends by the end of this century.

Increased flooding risks followed by severe shortages of freshwater are expected in the wake of glacier retreat in South America, South and Central Asia, and China. Intensively irrigated production systems are vulnerable to climate change, where over-appropriation of water for irrigation is already placing acute pressures on regional water supplies, including in North Africa and the Middle East, Central and South Asia, China, and Latin America. Sea-level rise is a threat to rice production and other agriculture production in coastal lowland areas and river deltas.

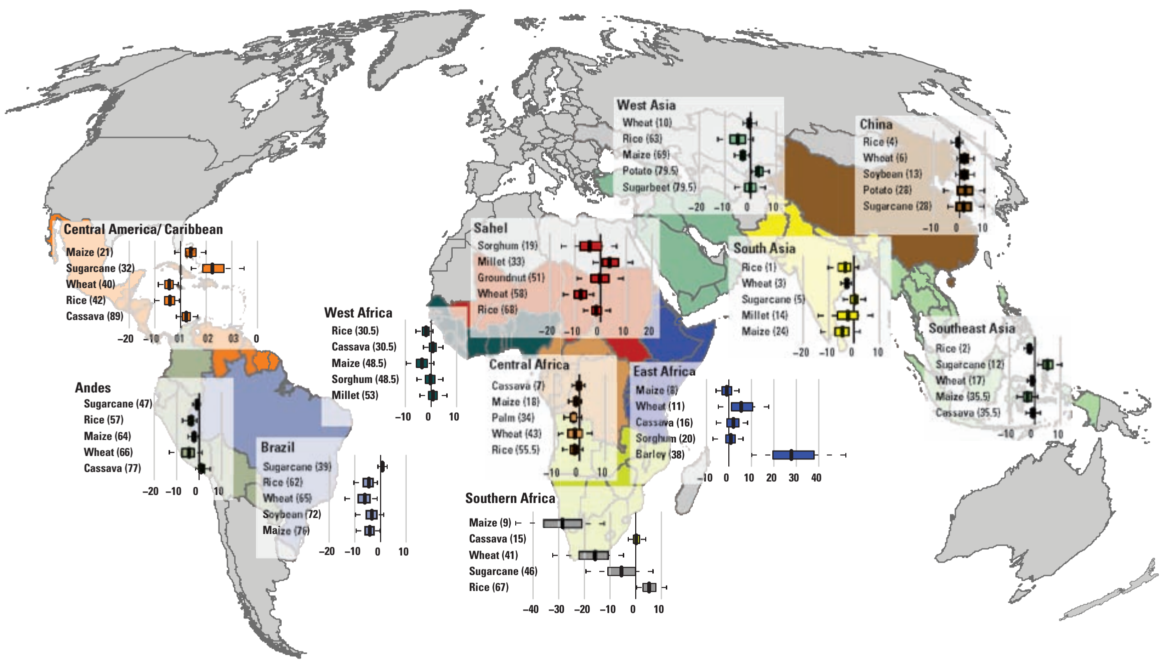
IV. Effects of Secondary Climate Change Impacts

Sensitivity to climate variability and extreme climate events is magnified in agricultural systems that contend with a high degree of nonclimatic stresses, such as low and declining soil fertility, soil and water degradation, and pest and disease pressure. In turn, climate variability and extreme events aggravate the impact of these stresses on productivity and food security. These secondary (indirect) effects of climate change are poorly represented, if represented at all, in climate impact models. However, they are very likely to create significant additional pressure on the long-term viability of agricultural systems, especially where factor productivity is low or declining. Important secondary impacts include accelerated rates of soil erosion and land degradation, increased pest damage, loss of agrobiodiversity, and higher rates of malnutrition and disease among agricultural communities that could diminish labor input. (See Chapters 5, 6, 7, and 8.)

V. Regions Vulnerable to Climate Change

The negative effects of climate change on agriculture are likely to be greatest in Africa, South and Central Asia, and the Mediterranean Basin (Easterling et al. 2007). Latin America, while not projected to experience a significant loss of agricultural gross domestic product (GDP) from climate change on a regional basis, does contain subregions that are highly vulnerable to climate change, including semi-arid northeastern Brazil and semi-arid areas in Central America and the Andes (Magrin et al. 2007). Significantly negative impacts of climate change on food security could occur as early as 2030 for several crops and regions (**Figure 1.1**), with the

FIGURE 1.1 Projected impacts of climate change by 2030 for five major crops in each region



For each crop, the dark vertical line indicates the middle value out of 100 separate model projections, boxes extend from the 25th to 75th percentiles, and horizontal lines extend from the 5th to 95th percentiles. The x-axis represents the percent yield change compared with the 1980–2000 baseline period.

The number in parentheses is the overall rank of the crop in terms of importance to food security, calculated by multiplying the number of malnourished in the region by the percent of calories derived from that crop. The models assume an approximate 1°C temperature rise between the baseline (1980–2000) and the projected (2020–2040) period.

Source: Lobell et al. 2008a,b

most severe effects projected for South Asia, Southern Africa, the West African Sahel, and Brazil, according to Lobell and others (2008a). Chapter 2 provides a detailed description of regional impacts.

Conclusions

- The potential disruption to agriculture from climate change over the next few decades and across regions is more likely to arise from increased intra-annual (seasonal) and inter-annual climate variability, and from an increased frequency of extreme events, than from changes in mean climatic conditions.
- Long-term risks to agriculture from climate change are likely to involve increased climate variability and prevalence of extreme events combined with an acceleration of warming, glacier retreat and sea-level rise, regional changes in mean precipitation, and increased risks of land degradation and crop loss from agricultural pests.

CHAPTER 2: REGIONAL IMPACTS

SUMMARY: This chapter examines the range of potential climate change impacts on agriculture in the developing world resulting from temperature rise and changes in precipitation. The chapter also briefly describes secondary impacts, including accelerated rates of soil erosion and salinization, increased damage from pests, and loss of water sources from glacier retreat. Subsequent chapters examine secondary impacts in greater detail. In addition, past and current climate trends, as well as future climate change projections, are described for each region.

I. Sub-Saharan Africa

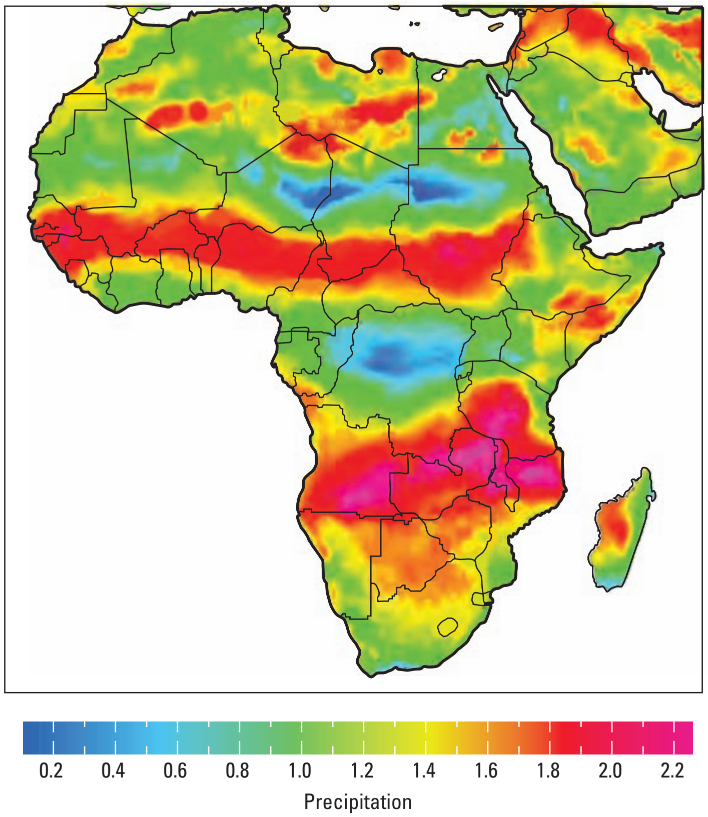
Sub-Saharan Africa is highly vulnerable to the negative impacts from climate variability and change, given the combination of its repeated exposure to droughts and floods, high reliance on rainfed agriculture for basic food security and national economic growth, and widespread degradation of its agricultural resource base. Climate change is certain to amplify these vulnerabilities given projections of warming temperatures; potential for increased activity attributable to the El Niño-Southern Oscillation (ENSO); and trends of increased aridity in parts of the region, particularly in southern Africa. During the last half of the 20th century, the continent became warmer, rainfall variability increased, and semi-arid areas of West and southern Africa became drier (Hulme 2005; Sivakumar and Hansen 2005).

Climate variability at intra- and inter-annual and multi-decadal time scales is an important contributor (along with such factors as population growth, land degradation and deforestation) to diminished food security (**Table 2.1; Figure 2.1**). During the past several decades, the ENSO has become the dominant source of inter-annual climate variability in East and southern Africa, and has been linked to several recent severe climatic events, although anomalous rainfall years in Africa do occur independently of ENSO activity. Food production in southern Africa has become more volatile over the past several decades, in part because of the sensitivity of maize production to ENSO effects. The greatest vulnerability to the ENSO occurs in southern Africa, where drought risk has been estimated to increase by 120 percent during warm, El Niño phases, causing maize yield losses in excess of 50 percent (Stige et al. 2006).

Climate Change

Southern Africa is one of the most vulnerable regions to future climate change, due to projected long-term drying trends (Christensen et al. 2007) and high sensitivity of its predominantly maize-based production systems to drought and flooding effects from the ENSO.

FIGURE 2.1 Coefficient of variability for precipitation in a typical 12-month annual cycle



Source: Casey Brown, International Research Institute for Climate and Society (IRI), Columbia University. *Water and Growth: Statistics from Africa,* presented at the World Water Week Conference, Stockholm, 2006

TABLE 2.1 Recent extreme climate events and their impacts on agriculture in Sub-Saharan Africa

Country or Region	Period	Climatic Event	Impact
Kenya	1997–2000	Severe flooding followed by drought	10% loss of national GDP (Grey and Sadoff 2006)
Malawi	1991–1992	Drought	60% maize yield loss (Clay et al. 2003)
	2000–2001	Floods	30% maize yield loss
Zimbabwe and Zambia	1992	Drought	8%–9% loss of GDP from agriculture (Benson and Clay 1998)
Mozambique	2000	Floods	2 million people affected
	2002–2006	Drough	800,000 people affected (Hellmuth et al. 2007)

A strong negative shift in the suitability of cereal production is predicted by the 2080s (Fischer et al. 2005), while climatic changes projected for as early as 2030 could cause significant declines in maize yields (Lobell et al. 2008a,b, and Figure 1.1). Scenarios developed by Hewitson (2007) project that southern Africa's long-term drying trend will be more severe in the western part of that region compared with the east. Climate model output from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report indicated that East Africa is projected to experience a mean increase in precipitation, though a recent analysis by Funk and others (2008) suggests that warming in the Indian Ocean could produce the opposite effect, resulting in reduced continental rainfall for that area. The Congo Basin is projected to become wetter, while the direction of future precipitation trends in West Africa is uncertain, although seasonal dry spells could become longer. Median temperature rise[1] by 2080 is expected to range from 3.2°C to 3.6°C across the continent.

Rainfed agriculture currently constitutes about 90 percent of Africa's staple food production, making it highly sensitive to reduced rainfall, shifts in timing and distribution, and decreased growing season length. Thornton et al. (2006) estimate that large areas of the semi-arid and dry subhumid regions could lose 5 to 20 percent of their growing season length, with the Sahel potentially experiencing a greater than 20 percent loss by 2050 and the percentage of failed seasons predicted to increase throughout the continent. Land degradation is an important driver of regional climate change in Sub-Saharan Africa (for more on this, see Chapter 6).

1 Estimates of annual median warming reported in this chapter come from the IPCC Fourth Assessment Report, Working Group 1, Chapter 11 Regional Climate Projections, Christensen et al. 2007.

II. Middle East and North Africa

The Middle East and North Africa region is highly vulnerable to climate change and variability, given the severe constraints currently imposed on agriculture by high temperatures, low and erratic precipitation, prolonged drought, and land degradation. In the latter half of the 20th century, climate in the region experienced a warming trend (~0.2°C per decade); increased drought frequency; and changes in precipitation patterns, including a shortening of the rainy season and an increase in heavy rainfall events and flooding (Agoumi 2003).

Climate Change

The trends mentioned earlier are likely to continue, with the Mediterranean Basin projected to become warmer (3.5°C by the end of this century) and drier (Christensen et al. 2007) and the greatest temperature increase expected to occur during the summer. A trend toward more extreme precipitation events is also projected, with the region already highly vulnerable to heavy runoff and erosion events from rainfall. For example, in the western Mediterranean, Gonzalez-Hidalgo, Peña-Monné, and de Luis (2007) estimated that up to 75 percent of total annual soil erosion occurred as a result of as few as three high-intensity storms. In addition, changes in climate coupled with population growth are expected to put additional stress on the region's water budget, with the effects being particularly severe in North Africa, where between 100 and 150 million more people will be confronted with increasing water stress by 2055 (Boko et al. 2007).

Agriculture in the region could become increasingly untenable, given the combined effects of population growth, climate change, and natural resource base deterioration. The most productive rangeland ecosystems in the eastern Mediterranean Basin could incur major losses in ecosystem services in the event of their transformation from subhumid mesic Mediterranean and Mediterranean environments to semi-arid or arid environments (Fleischer and Sternberg 2006). The semi-arid and arid rangelands in the Maghreb (Algeria, Morocco, and Tunisia) are at high risk for desertification caused by increased aridity, widespread land degradation, and shrub encroachment in the grassland steppes (Puigdefábregas and Mendizabal 1998).

As a result of these changes, crop production will occur in a hotter, drier, and, in the case of irrigated agriculture, increasingly saline environment. Regional water supplies for irrigation are already severely stressed from overexploitation, and poor management of irrigated lands has led to widespread waterlogging and salinity, with approximately one-fourth of all irrigated land in the Mediterranean currently salt affected. Climate change will present an additional and significant stress to irrigated systems, driven by increased crop water demand to compensate for higher evaportranspiration losses, increased salt accumulation from rapid drying of soil surfaces, and reduced precipitation. Moreover, population growth will likely increase the pressure on agriculture to use increasingly marginal water sources, such as brackish or reclaimed effluent water for irrigation, which could further magnify problems of low crop productivity from salt stress.

Crop yield losses in the Maghreb could exceed 20 percent for cereals, legumes, and tuber crops—even with the carbon dioxide (CO_2) fertilization effect (Giannakopoulos et al. 2005). Adaptation strategies, such as changing sowing dates or crop varieties, may offset some of these losses, but could require up to 40 percent more water for irrigation.

III. Europe and Central Asia

Large areas of Central Asia are vulnerable to recurrent drought due to their continental location and the disruption of the region's water balance caused by degradation in the Aral Sea Basin. The region is experiencing a warming trend of in excess of 1°C per century, and, while no discernable change in regional precipitation trends has occurred, areas of Kazakhstan and Uzbekistan bordering the Aral Sea have experienced declining precipitation due to changes in the hydrologic cycle driven by the sea's contraction (Lioubimtseva et al. 2005). In addition, glaciers in the northern Tien Shan mountain range have retreated over the past four decades (Niederer et al. 2008). Central Asia experienced a record drought in 2000–2001, with precipitation less than

55 percent of the long-term average, which severely affected the agricultural sector. Uzbekistan alone suffered US$130 million in lost agricultural output (World Bank 2006a). The Caucasus region is also vulnerable to drought and has experienced a drying trend over the last century. Some countries, such as Armenia, are particularly vulnerable to desertification.

Climate Change

Temperatures in Central Asia are projected to rise an additional 3°C to 4°C by the end of this century. However, while long-term precipitation trends are less clear, fairly strong agreement exists in global climate models that the region could experience reduced precipitation during the spring and summer (Christensen et al. 2007), with estimates of yield reductions in Central Asia as great as 30 percent (Cruz et al., 2007). One of the critical factors for the region's agriculture concerns how climate change will affect water resources in the Tien Shan mountain range, an area that supplies a significant portion of water to Central Asia's arid plains in the form of spring/summer runoff from snow and ice storage. Runoff scenarios under a doubling of CO_2 concentrations suggest an initial increase in flood risk as glaciers melt, with a post-glacier situation of higher and earlier discharge during the spring snow melt followed by a water deficit during the hot summer months when irrigation demand is greatest (Haag et al. 2007).

The potential loss of this well-regulated runoff source, coupled with a temperature rise during the summer cropping season, could have a substantially negative effect on the region's agricultural production. Irrigated crop production occurs on almost 20 million hectares in Central Asia, with agriculture accounting for 90 percent of water withdrawals.

A large portion of Central Asia's irrigated land occurs in the Aral Sea Basin, which has become highly degraded from waterlogging and salinization. For example, some areas of Kazakhstan lose 10 to 15 percent of their agricultural land per year to salinization. Desertification risk is high throughout much of Central Asia due to the predominantly arid/semi-arid climate, extensive land degradation in rainfed cropping areas and rangelands, and salinization of irrigated areas (World Bank 2006a). Drought is a major cause of entrenched poverty in rural areas, although recent diversification of Central Asian economies away from agriculture has somewhat reduced the effect of drought. Similar climate change effects are expected in the Caucasus region, including reduced water for irrigated agriculture; shrinkage of forest vegetative zones and expansion of steppe, semi-desert, and desert areas; and reduced discharge into rivers from drought in some areas and increased discharge from glacier melt in others.

In Europe, climate change is expected to generate a mixture of positive and negative effects, with overall crop productivity predicted to increase from temperature rise and potentially from crop growth stimulation with increased CO_2

concentrations (Alcamo et al. 2007). In Russia, cereal yields and the overall land area suitable for agriculture could increase. However, crop-growing regions in southwestern Russia could face significant production shortfalls due to increased drought prevalence and reduced runoff, while northern Russia may experience more flooding. Southern Europe is likely to experience reduced productivity of summer crops as a result of increased heat stress, higher rainfall intensity, and longer dry spells. Production zones could shift northward for crops that are currently predominant in southern Europe, such as maize, sunflower and soybeans.

IV. South Asia

South Asia's agriculture is critically dependent upon the June–September southwest monsoon, which generates 70 percent of the Indian subcontinent's total annual precipitation. However, the distribution and timing of monsoon precipitation can be highly variable. For example, under extreme cases, up to 60 percent of annual rainfall can occur within a period of several days, resulting in severe flooding, high crop and livestock loss, and reduced groundwater recharge (Mall et al. 2006a). At the other extreme, severe failures of the Indian monsoon, which have historically had a strong positive relationship with El Niño events, create widespread drought. For example, the 2002 drought in India, caused by a mid-summer break in the monsoon, reduced national cereal output by 18 percent and India's gross domestic product (GDP) by 3 percent (Mall et al. 2006b). Drought has had a more negative impact on the Indian economy than floods, and the impacts of severe drought on India's total GDP have remained constant (between a 2 and 5 percent decline in total GDP), despite substantial economic diversification away from agriculture (Gadgil and Gadgil 2006).

Climate Change

The Indian monsoon is expected to intensify with climate change, producing a slight increase in precipitation for the Indian subcontinent by the end of this century (Christensen et al. 2007). However, greater regional variations in rainfall are also expected, with dry regions potentially becoming drier and wet regions wetter, and the number of additional years of record or near-record precipitation potentially increasing (Baettig, Wild, and Imboden 2007) (see **Box 2.1**). Intra-annual variability of precipitation could increase as well, resulting in a greater number of heavy rainfall days but a decrease in the overall number of days receiving rain, as has been the case with recent precipitation trends in northwestern India (Sivakumar, Das, and Brunini 2005). These hydrologic changes will occur against a backdrop of rising temperatures, with the region projected to experience a median temperature rise of 3.3°C by the end of this century (Christensen et al. 2007). A temperature increase of this magnitude is likely to exacerbate drought conditions during below-normal rainfall years. Temperature rise will also produce fundamental changes in the dry-season supply of glacial meltwater, an important water source

Box 2.1
CLIMATE VARIABILITY AND CHANGE IN THE INDO-GANGETIC PLAINS

The Indo-Gangetic Plains (IGP) contain some of the most productive agricultural land in South Asia, providing staple grain for 400 million people, primarily through a rice-wheat rotation system practiced on 13.5 million hectares. Yields of rice and wheat in this highly intensive system have stagnated and, in some cases, declined over the past few decades (Ladha et al. 2003). This trend will need to be reversed if the region is to meet future food demand. The UN Food and Agriculture Organization (FAO) estimates that South Asia will need to increase its cereal output by almost 50 percent over the next three decades to meet increasing demand; yet, given current projections of agricultural output and regional population growth, the region will have an estimated 22-million-ton cereal deficit by 2030.

Deterioration of the natural resource base, loss of soil fertility and soil nutrient imbalances, and a buildup of pests and pathogens are important factors contributing to diminished productivity of the rice-wheat system. Demand for irrigation water has led to the unsustainable extraction of groundwater, with several areas experiencing declining water tables. The introduction of canal irrigation in semi-arid parts of India and Pakistan has resulted in widespread salinity and water logging affecting nearly 7 million hectares of cultivated land.

Future climate change is expected to magnify the adverse effects of these existing pressures. Wheat is currently near its maximum temperature range, with high temperatures during reproductive growth and grain filling, representing a critical yield-limiting factor for wheat in much of the IGP. Incremental increases in temperature could thus have a large impact. For example, Ortiz and others (2008) estimate that by 2050 approximately half of the highly productive wheat areas of the IGP could be reclassified as a heat-stressed short-season production mega-environment. Rice yields are also expected to be affected, with an estimated decrease of 10 percent for every 1°C rise in nighttime temperatures (Peng et al. 2004). Given that South Asia is projected to experience a median temperature increase of 3.3°C by the 2080s, these yield loss estimates are well within the range of likely temperature rise over the next several decades. Furthermore, higher temperatures and evapotranspiration increase seasonal rainfall variability, and eventual loss of seasonal glacial meltwater will create greater pressure on existing irrigation water supplies, thereby further exacerbating soil salinization risk. Climate change may already be contributing to productivity decline in the IGP due to decreased solar radiation and increased minimum temperatures (Pathak et al. 2003). These factors suppress rice yields by decreasing photosynthesis and increasing respiration losses.

for irrigated agriculture. For example, the Himalayan glacial belt is expected to reduce its contribution to the region's water budget by 70 percent over the next 50 years, after an initial increase in flood risk from the release of glacial meltwater (Cruz et al. 2007).

V. East Asia and Pacific

The East Asian monsoon provides the majority of East and Southeast Asia's precipitation, with some areas receiving 50 to 80 percent of their annual rainfall during the monsoon. However, the monsoon weakened over the latter half of the 20th century, coinciding with more pronounced ENSO activity in East and Southeast Asia (as reviewed by Trenberth et al. 2007). Many areas of China have become drier with precipitation declining the most in late summer. Rainfall in semi-arid areas of eastern China has been particularly affected by a southward shift in the summer rain belt, while increased ENSO activity has produced drought in the Yellow River Basin and severe flooding in southern China (Xu et al. 2007; Yang et al. 2005). These changes in regional precipitation patterns have led to an increase in the rate of crop loss from both droughts and floods over the past several decades compared with crop losses in the mid-20th century. Also, a warming trend in China over the past two decades has shifted crop phenology, creating both positive and negative effects on cereal production (Tao et al. 2006).

In Indonesia, the ENSO has been observed to exert a strong influence on rainfall patterns, with 93 percent of the drought years over the past century linked to an eastward shift in rainfall distribution during El Niño events (Naylor et al. 2001, and references therein). El Niño years in Indonesia are characterized by a delayed onset of the monsoon, which delays rice planting and reduces the total area planted, resulting in production shortfalls (Naylor et al. 2007). These El Niño effects also impede timely planting of the subsequent dry-season rice crop, leading to reduced yields. Shortfalls in rice production from ENSO events can be severe, such as during the 1997–1998 ENSO when the overall decline in national rice production was nearly 4 percent, with losses approaching as much as 40 percent in some provinces (Fox 2000).

Climate Change

In China, the outlook for agricultural production under climate change is mixed. The rice belt is expected to expand northward as a result of temperature rise, with potential benefits being greatest where water is not limiting (Hijmans 2007). On the other hand, major grain producing areas, such as the Huang-Huai-Hai (3H) River Basin in eastern China, which is responsible for roughly half of the country's grain output, could experience decreased wheat and maize yields. Similar findings, but averaged across all of China, were reported by Xiong and others (2007). In both studies, CO_2 fertilization mitigated or, in some simulations, reversed this yield trend, although significant uncertainties remain as to the strength of the CO_2 fertilization effect, as discussed in Chapter 1. Warmer temperatures throughout China will increase demand for irrigation water, which, in many areas of the country, is already being withdrawn at unsustainable rates. China will be confronted with having to produce more food from less land in the future, with urbanization, land degradation, and desertification expected to decrease the per capita cultivated land from 0.09 hectare to 0.06 hectare by 2050 (Smit and Yunlong 1996). Climate change is expected to aggravate these threats.

In Indonesia, a projected increase in the ENSO's strength over the country could increase the likelihood of more prolonged drought conditions in the future (Overpeck and Cole 2007). Naylor and others (2007) estimated that the probability of a delayed start of the monsoon could increase, from the current 9 to 18 percent to 30 to 40 percent by 2050, thus significantly increasing the risk of crop failure. As the fourth most populous country in the world and third largest in rice production, Indonesia has a significant presence in the global rice economy. Rice production shortfalls in a country like Indonesia can exert upward pressure on global rice prices, as occurred following recent El Niño years, when Indonesia increased its rice imports by an average of 340 percent (Naylor et al. 2001).

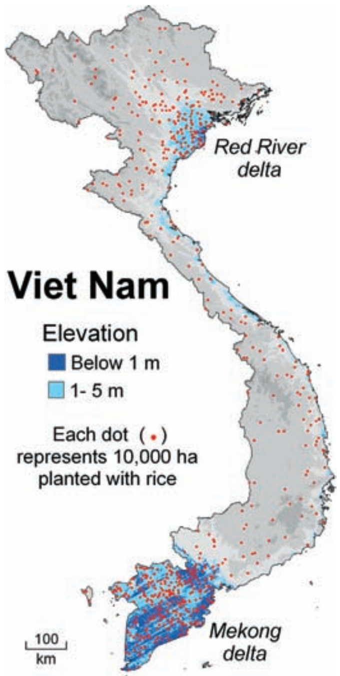
Asian rice production also faces a long-term threat from sea-level rise. The major river deltas of South and Southeast Asia, along with the Nile, are among the most vulnerable in terms of lost agricultural lands (Dasgupta et al. 2007). Sea-level rise poses a threat to rice production through increased risk of storm surges, submergence, saline intrusion of aquifers that reduce the amount and quality of freshwater for irrigation, prolonged waterlogging, and soil salinization. Agricultural lands vulnerable to a 1- to 2-meter sea-level rise, such as those in the Mekong and the Nile deltas, represent the greatest immediate concern. For example, a 1-meter sea level rise would threaten highly productive rice cultivation in the Mekong Delta (**Figure 2.2**), resulting in a 10 percent loss of GDP (Dasgupta et al. 2007). GDP loss would approximately triple in the event of a 5-meter rise. The 4th Assessment Report of the IPCC (IPCC 2007) estimated that global sea levels could rise between 18 and 59 centimeters by the end of this century, while other estimates place the range between 50 and 140 centimeters (Rahmstorf 2007). These models do not account for the possibility of rapid collapse of Arctic ice sheets, which would significantly accelerate this process.

VI. Latin America and the Caribbean

Latin America has recently witnessed several extreme climate events, including an increase in heavy rainfall in northern South America, severe drought in the Amazon Basin, and intense hurricane seasons in the Caribbean (as reviewed by Magrin et al. 2007). The region has experienced a warming trend, though less strongly than other low-latitude regions. Precipitation patterns have changed in some areas, with positive trends observed in southeastern South America and negative trends in southwestern South America, the southern Andean region, and western Central America. The ENSO, which exerts a dominant influence on regional climate variability, has increased in activity over the past few decades resulting in significant economic losses from floods, drought, and landslides. This intensification of the hydrologic cycle has accelerated land degradation, increasing soil erosion risk from heavy rainfall and enhanced wildfire risk from drought.

The most severe impacts from drought have occurred in the semi-arid zone of northeast Brazil, where long-term drying

FIGURE 2.2 Potential inundation of rice-producing areas from sea-level rise



Source: Robert Hijmans, International Rice Research Institute, Los Baños, Philippines.

trends, punctuated by ENSO events and increased temperatures, have significantly increased the risk to agriculture. Agricultural failures over the past several decades have intensified poverty in the region, and led to out-migration of rural populations. The ENSO has also been responsible for episodic drought in the Amazon and Central America, with significant reductions in crop and livestock production.

Climate Change

On an overall regional basis, climate change impacts in Latin America are not expected to have as strong an effect on agricultural GDP when compared with that in Africa and parts of Asia (Fischer et al. 2005). Nevertheless, climate change is projected to negatively influence agricultural production in several sub-regional areas, including the Amazon Basin and northeast Brazil, as well as parts of Central America and the Andes (Baettig, Wild, and Imboden 2007; Christensen et al. 2007). The primary impacts in these areas include intensification of moisture-deficit conditions in northeastern Brazil and parts of the Amazon and Central America, increased flood risk in southern Central America and southeastern South America, and increased risk of desertification in dryland areas subjected to high rates of land degradation. Climate change impacts on the Amazon Basin are of particular concern because of the Basin's role in regulating regional precipitation and its influence on hydrology further afield. Intensification of the dry season is likely in the east and southeast parts of the Basin, and, when combined with temperature rise, could result in drying in the east (Malhi et al. 2008). Forest dieback and conversion to savannah vegetation could exacerbate these drying trends.

Temperature rise is projected to be more pronounced in high-elevation mountain ranges compared with adjacent low-elevation areas, which will have profound effects on water budgets in the Andes as glaciers retreat over the next several decades. Agriculture will be affected both in the highlands, where dry valleys are critically dependent on the water supply from glaciers, and in lowland basins downstream that depend on water from Andean tributary streams (see **Box 2.2**).

Box 2.2
RESPONDING TO GLACIER RETREAT IN THE ANDES

Hydrology in the Andes region is likely to be profoundly altered during the course of this century as glaciers retreat under warming conditions. Springtime flooding could become more intense as higher volumes of meltwater enter surface water bodies. Eventually this water source will diminish and may, in some cases, disappear altogether. Glaciers play a critical role in regulating local climate and weather conditions and maintaining ecosystem integrity, as well as providing water for agriculture, human consumption, and hydropower generation. Thus, the impact caused by the diminution or loss of glacier runoff will be much greater than that incurred solely by a net change in water resource quantity.

The World Bank is helping the region respond to this threat through its *Adaptation to the Impact of Rapid Glacier Retreat in the Tropical Andes* project that examines the potential impacts of glacier melt on water resources and the subsequent risk to rural livelihoods and agriculture and identifies possible adaptation options. The project supports the design of a glacierized basin impacts map, which can be overlaid onto a set of detailed adaptation measures developed through stakeholder consultation.

Under this project, specific pilot adaptation measures in Bolivia and Peru are targeted at water management for crop production and livestock. Activities under the Bolivia pilot adaptation project include the construction of small ponds to compensate for the expected loss of water resources, implementation of reforestation and revegetation programs to lessen soil erosion risk, application of water conservation programs for crop and livestock production, and implementation of a water management plan to more efficiently use dwindling water resources in rural communities. The Peru adaptation pilot aims to improve water use efficiency in agriculture, improve water storage infrastructure to lessen overflow impacts caused by accelerated glacier melting, and implement a reforestation program. The Peru project also identifies drought-resistant crops and cultivars, improve input markets for their use, and promote changes in agricultural exports to adapt to diminished water resources.

Elsewhere in Latin America, temperature rise could affect economically important mid-altitude crops such as coffee. For example, projected changes in climatic conditions (temperature rise and changes in spring rainfall patterns) by 2020 are estimated to reduce Mexico's coffee production by one-third (Gay et al. 2006). Brazil's coffee production is likely to be similarly affected by temperature rise. Positive benefits to agriculture from temperature rise are expected in the southern cone region of South America due to an increase in the number of frost-free days. Median temperature rise for the region is projected to be between 2.5°C and 3.3°C by 2080.

In the Caribbean, losses to agricultural production caused by increased wind and flood damage from hurricanes are the primary concern, with temperature rise and drought also expected to negatively affect food production.

Conclusions

- Sub-Saharan Africa is highly vulnerable to negative impacts from climate variability and change, given its exposure to droughts and floods, high reliance on rainfed crops, and widespread degradation of its agricultural resource base. These vulnerabilities are very likely to increase with climate change.
- The Middle East and North Africa region is highly vulnerable to climate change, given the severe constraints imposed by high temperatures, low and erratic precipitation, prolonged drought, land degradation, and the future likelihood of increased warming and aridity.
- In Central Asia, a strong warming trend, loss of glacial meltwater, and a reduction in spring and summer precipitation are expected, which could significantly reduce crop yields.
- Climate change is expected to generate both positive and negative impacts in Europe. Northern Europen could benefit from a longer growing season, while southeastern Europe could be negatively affected by temperature rise and increased moisture deficits.

TABLE 2.2 Projected temperature increase relative to a 1990 baseline under an A1B scenario[2] according to the IPCC Fourth Assessment Report

Region	Projected Median Temperature Rise (annual °C from 2080–2100)
Sub-Saharan Africa	3.2–3.6
Middle East/North Africa	3.5
Central, South, and East Asia	2.5–3.7
Latin America	2.5–3.3

Source: Christensen et al. 2007

2 The A1B scenario is one of the scenarios developed by the Special Report on Emissions Scenarios (SRES) used in the IPCC Fourth Assessment Report. It assumes a balanced use of fossil fuel and nonfossil fuel energy sources.

TABLE 2.3 Projected mean precipitation trends for 2080–2100 by season under an A1B scenario, according to the IPCC Fourth Assessment Report

	DJF	MAM	JJA	SON
Region				
West Africa				
East Africa				
Southern Africa				
Mediterranean				
North Asia				
Central Asia				
East and Southeast Asia				
South Asia				
Central America				
Amazon				
Southern South America				

Colored cells represent where general model agreement exists on the sign of precipitation trends; white cells = lack of agreement between models; green cells = slight precipitation increase; blue cells = strong precipitation increase; orange cells = slight precipitation decrease; red cells = strong precipitation decrease.

Source: Christensen et al. 2007

- Mean precipitation across the South Asian region is expected to increase. However, the monsoon is expected to intensify which could increase flooding risks. Also, greater regional variations in rainfall are expected, with dry areas potentially becoming drier and wet areas wetter. The region's major cereal crops, rice and wheat, are vulnerable to temperature rise.
- East and southeast Asian agriculture, particularly rice production, faces climate change threats from rising temperatures, potentially increase ENSO activity, and sea-level rise, the latter of which could increase risks of storm surges, submergence, saline intrusion of aquifers, and soil salinization.
- Climate change impacts in Latin America are expected to be greatest in the Amazon Basin and northeastern Brazil, as well as parts of Central America and the Andes, due to a combination of potentially increased ENSO effects and temperature rise, and in the case of the Andean region, glacier retreat.

CHAPTER 3: VULNERABILITY, ADAPTATION, AND DEVELOPMENT

SUMMARY: This chapter examines the causes of vulnerability in the agricultural sector, discusses different approaches for integrating climate change concerns into vulnerability assessments and adaptation planning, and examines how technology delivery can be improved to support adaptation. The chapter also explores how adaptation considerations can be integrated into rural development in a manner that addresses gender equity issues, strengthens collective action to support adaptation, integrates adaptation priorities into decentralization and property rights policies, and enhances information and knowledge flows.

I. Vulnerability

Agriculture is one of the most vulnerable sectors to climate change because of its seasonality, the narrow range of weather conditions over which crop and livestock production can occur, the presence of significant nonclimatic stressors that influence sensitivity to changes in climatic conditions, and the endemic poverty often associated with food production in the developing world, which compounds vulnerability. Vulnerable agricultural systems are most prevalent in arid, semi-arid, and dry subhumid regions of the developing world, home to half of the world's currently malnourished populations. High rainfall variability and recurrent drought/flood cycles disrupt food production, particularly where crops are grown in marginal lands with low inputs.

Vulnerability to drought in these systems often results from the convergence of multiple climate and non-climate risk factors. Speranza, Kiteme, and Wiesmann (2008) identified a number of such factors for a semi-arid agropastoral setting, including unpredictable onset of rainy season, low and declining soil fertility and soil water-holding capacity, crop pests, and delayed planting or a reduction in the area under cultivation due to lack of access to agricultural implements for timely land preparation or inability to acquire seeds during planting time. Prolonged exposure to these risks erodes household resources, creating situations in which chronic stress predisposes producers to agronomic drought even in the absence of meteorological drought, and sensitivity to "shocks" from extreme events increases. The risk-prone nature of these agricultural systems creates significant disincentives to invest in yield-enhancing technologies.

Situations of uneven development can also increase vulnerability to climate shocks. For example, while trade liberalization can stimulate overall economic activity, it generally increases sensitivity to climate shocks in rural communities engaged in global commodity markets. The most visible example of this is the "double jeopardy" that arises when unfavorable economic conditions (output price volatility, spikes in agricultural input costs, or high import competition) coincide with extreme climate events (Eakin 2005; O'Brien et al. 2004). Unfavorable market signals can also lead to poor maintenance or abandonment of agricultural infrastructure, further compounding vulnerability to climate variability and change.

Rural communities face multiple hazards that undermine livelihood security and exacerbate vulnerability to extreme events. Key determinants of vulnerability (and, inversely, of capability) include:

- Ownership of land and livestock.
- Land size and productivity.
- Extent of abiotic and biotic stresses in the production system.
- Access to credit and markets.
- Availability and affordability of agricultural inputs.
- Access to cash income from off-farm livelihood activities.
- State of village infrastructure, including health services.
- Gender of household head.
- Connection to family and social networks.

[For detailed descriptions of hazards and rural livelihoods in the context of climate change, see Reid and Vogel (2006) and Tschakert (2007b)]. **Table 3.1** describes a range of climate and nonclimate drivers that contribute to rural economic vulnerability, as identified in adaptation projects that were conducted under the Global Environment Facility (GEF)-funded Assessments of Impacts and Adaptation to Climate Change program.

Vulnerability and the "Adaptation Deficit"

The negative impacts of high climate variability on agriculture reverberate through economies where agriculture is a major contributor to total gross domestic product (GDP), such as those in Sub-Saharan Africa that are dominated by rainfed production in semi-arid and dry subhumid zones. In these areas, seasonal rainfall, agricultural GDP, and national GDP are intricately linked. For example, Grey and Sadoff (2006) estimated that extreme climate events, like the widespread flooding and drought produced by back-to-back La Niña/El Niño events from 1997 through 2000 in East Africa, caused declines in GDP in excess of 10 percent. This effect has even been measured in relatively diversified economies, such as in India, where extreme climate events such as the mid-season break in the 2002 monsoon rains resulted in a 3 percent decline in total GDP following significant yield reductions from drought (Gadgil and Gadgil 2006).

These chronically vulnerable systems are characterized by low productivity and high yield volatility, a situation that creates an "adaptation deficit," where an inability to

TABLE 3.1 Climatic and nonclimatic determinants of vulnerability to climate change across varying vulnerability levels

Level of Vulnerability	Manifestations of Vulnerability	Climate Drivers	Nonclimate Drivers
High Countries: Sudan, Nigeria	Violent conflict Famine and chronic hunger Multiyear collapse of rural production systems Persistent and permanent rural out-migration	Persistent moisture deficit. Widespread drought Increased aridity Floods	Civil tension and conflict Governance failures Land degradation Lack of or insecure water rights and land tenure Limited off-farm livelihood options Lack of social safety nets Poor rural infrastructure
Medium Countries: Vietnam, Egypt	Loss of export earnings, national income and jobs Increased rural poverty rates Declining or more variable net farm incomes Failures of small farms Accelerated rural-to-urban migration	Increased frequency and extent of extreme climate events Changes in average climate and shifts in the rainy season that stress both export and traditional crop and livestock systems	High dependency on a small number of agricultural commodities Declining or volatile prices for export crops and rising input prices Insufficient agricultural research and development Lack of access to credit Poor rural infrastructure
Low Countries: Argentina, Mexico	Declining or more variable net farm incomes Decreased or more variable crop and livestock quality Temporary out-migration	Increased frequency and extent of extreme climate events Changes in average climate and shifts in the rainy season.	Nonclimate drivers buffered by: Robust and diversified rural development Equitable access to resources, credit, and insurance Maintenance of social safety nets and rural infrastructure Political stability

Source: Adapted from Leary et al. 2008

adequately cope with existing risks from climate variability and extreme events reinforces poverty and low levels of development. Failure to address this adaptation deficit is certain to hamper future efforts to adapt to long-term climate change. As Cooper and others (2008) note, "The ability of agricultural communities and stakeholders in Sub-Saharan Africa to better cope with the constraints and opportunities of current climate variability must first be enhanced for them to be able to adapt to climate change and the predicted future increase in climate variability." Section 2 describes approaches for reducing the adaptation deficit.

Hazards-Based versus Vulnerability-Based Approaches for Assessing Vulnerability

Assessing vulnerability and determining appropriate adaptation actions generally involves using a hazards-based or a vulnerability-based approach, or some combination therein. Both of these approaches seek to integrate adaptation into development, but they assume different pathways, with the former viewing sustainable development as best achieved by adapting to climate change and the latter viewing "climate-aware" development as a key antecedent to adaptation. These approaches are illustrated in the following diagram and described in **Table 3.2.**

The *hazards-based* approach is critical for identifying key impacts that can inform adaptation-planning processes and serve to mobilize resources at the national level. In the context of the agriculture sector, a hazards-based approach would be most applicable in situations where:

- Major investments in irrigation infrastructure are planned.
- Long-term projections of future land suitability for agriculture are needed.

Hazards-based adaptation approach

Adaptation to climate change impacts → Vulnerability reduction → Development

Vulnerability reduction-based adaptation approach

Climate-aware development → Vulnerability reduction → Impact reduction → Adaptation

Source: Schipper 2007.

TABLE 3.2 Comparison of hazards- and vulnerability-based approaches for assessing vulnerability and adaptation to climate change.

	Hazards-Based Approach (Top-Down)	Vulnerability-Based Approach (Bottom-Up)
Method for assessing climate change impacts	Incremental impacts from climate change using model-based projections	Impacts viewed in the context of current climate risks and the social factors that shape coping capacity for climate change
Consideration of nonclimate factors	Limited	Extensive
Advantages for adaptation assessment	Crucial for identifying climate change risks and long-term adaptation priorities	Crucial for identifying low- or no-regrets adaptation options that are robust against a wide range of plausible climate change outcomes
Disadvantages	High probability of error in model-based climate projections at fine spatial scales Insufficient consideration of current risks from climate variability and nonclimate stressors	High reliance on expert judgment Qualitative nature of results limits comparability across regions Lack of clear methodology

Source: Adapted from Füssel 2007

- Rural economic growth strategies seek to reconfigure/diversify food production systems.

The *vulnerability-based* approach, also referred to as "second-generation vulnerability assessments" or "sustainable livelihood frameworks," gives explicit consideration to various nonclimatic determinants of vulnerability and adaptive capacity, including poverty, economic inequality, health, effectiveness of government institutions, literacy, and education levels. The primary advantage of this approach is that it allows for incorporating a range of both climatic and nonclimatic vulnerability factors into adaptation planning, and, in doing so:

- Can present a wide range of potential entry points for adaptation.
- Perceives the needs of vulnerable communities in the context of adapting to multiple stressors, not just to those generated by hydrometeorological hazards.[1]
- Depends less on uncertainties about future climate projections.
- Tends to be more consistent with national and local development priorities, thus ensuring a greater chance of "buy-in" for implementing adaptation measures.

The hazards-based and vulnerability-based approaches need not occur in isolation. Integrating them is desirable and can lead to the discovery of synergies and complementarities between top-down and bottom-up planning processes. **Figure 3.1**, derived from a vulnerability and adaptation assessment recently conducted in Uganda (Orindi and Eriksen 2005), illustrates the challenges (differing perceptions of adaptation needs at the national and local levels) and opportunities (improving the outcome of planned adaptation measures by taking local priorities and concerns into account) in marrying the two approaches.

Vulnerability Mapping

Identifying and describing vulnerability can be difficult because of its complex and multifaceted nature. The process of vulnerability mapping (or vulnerability profiling) can help determine vulnerability by identifying where current vulnerabilities to climate change exist, where vulnerability hotspots could emerge as a result of climate change, and how present and future vulnerability are linked. Vulnerability mapping seeks to determine:

- Who the vulnerable are and what current and future stresses and risks they are facing.
- What the important climate-related hazards are, where they are likely to have an impact, and how they would change with climate change.

Although several methodological variations exist, most vulnerability mapping procedures utilize current and historical climate

1 Recent adaptation needs assessments for rural communities in developing regions (e.g., Leary et al., 2008) found that the impetus for adaptation planning occurred in response to multiple risks and not to climate change alone.

FIGURE 3.1 National and local adaptation measures from Uganda

Anticipated impacts:

- Water shortages from decreased rainfall, increased drought spells, and temperature rise
- Increased risk of food shortages and famine from agricultural failures
- Increased potential for malaria transmission
- Reduction in ecosystem integrity and resilience, and loss of biodiversity

Adaptation measures from Uganda's National Communication:

- Modernize agriculture through introduction of drought-resistant crops, use of pesticides, and changes in cropping configurations
- Develop capacity to increase ground and surface water supply
- Initiate water conservation practices
- Reduce livestock populations
- Reduce pressure on wood harvesting

Adaptation measures from community vulnerability assessments:

- Strengthen existing coping strategies and indigenous knowledge
- Improve access by the poor to new farming technologies
- Strengthen and formalize traditional laws and institutions for natural resource use
- Address causes of local conflicts
- Address factors that lead to infectious diseases
- Strengthen access to clean water and hygiene
- Bolster food reserves for emergencies

Source: Orindi and Eriksen 2005

data and projections of future climate change to map the potential distribution of populations at risk from droughts, floods, or other climate-related disturbances. They assess climatic and nonclimatic factors that contribute to vulnerability and identify where additional knowledge of sectors and livelihoods is needed. Climate hazards can be quite variable in space and time, and the degree of exposure and sensitivity to them is heavily influenced by socioeconomic factors; thus multiple types of information and data are needed to determine and map vulnerability. Nonclimatic data and information can originate from such sources as national development plans, census data, poverty reduction strategy papers, environmental management plans, millennium development targets, and human development indexes. **Box 3.1** describes a process of vulnerability mapping conducted in the context of adaptation in agriculture.

II. Adaptation

Vulnerability and development are intricately linked, as demonstrated in the preceding section. Adaptation thus should be well integrated with livelihood priorities and development goals if it is to succeed. This section examines linkages between agricultural development and adaptation, identifies where priorities for adaptation are greatest, and discusses the importance of ensuring that the research and development of agricultural technologies are relevant to the livelihood needs of vulnerable farmers.

Box 3.1
MAPPING VULNERABILITY: AN EXAMPLE FROM INDIA

Work by O'Brien et al. (2004) on mapping agricultural vulnerability to climate change and globalization in India illustrates the process through which vulnerability profiles can be developed for multiple stressors and for regions with fairly disparate development levels. In this study, the authors combined multiple indices for adaptive capacity with sensitivity indices that account for climate change.

- *Adaptive capacity* was determined using biophysical (soil quality and depth and groundwater availability), socioeconomic (literacy rates, degree of gender equity, and presence of alternative economic activities), and technological (availability of irrigation and quality of infrastructure) factors.
- *Sensitivity* to climate change effects was determined by applying the results from a downscaled regional climate model to a climate sensitivity index that mapped recent trends in dryness and monsoon dependency at the district level based on historic climate data.
- Climate change vulnerability was determined by combining the adaptive capacity and climate sensitivity indices, which were then mapped at the district level.

Through this analysis, the authors determined that climate sensitivity did not necessarily coincide with vulnerability. For example, districts in southern Bihar had only medium sensitivity to climate change yet were highly vulnerable because of their low adaptive capacity, whereas districts in northern Punjab that were highly sensitive to climate change had only moderate vulnerability due to their high adaptive capacity.

Synergies between Agricultural Development and Adaptation

The needs and challenges that agriculture will face as it adapts to climate change coincide well with the agenda for reasserting agriculture's role in economic growth and poverty reduction, as articulated in the 2008 World Development Report (WDR) on agriculture. Both processes—adapting to climate change and stimulating agriculture to drive development—require greater agricultural research and development expenditures, tighter integration of natural resource management into agricultural production, increased household access to production assets, education and skill development for rural diversification, and use of collective action to increase the economic and political clout of rural communities. Placing climate change impacts and the necessary adaptation responses squarely on the rural development agenda can draw attention to the rising opportunity costs of failing to confront the problems of entrenched resource degradation and poverty associated with underinvestment and misinvestment in agriculture.

Attention to adaptation needs can help sustain the development goals in each of the WDR's three agriculture worlds—agriculture-based, transforming, and urbanized—by providing a means for anticipating and prudently preparing for the potential negative impacts that climate change could have on the viability of investments in rural development. In some situations, this may mean developing a different set of investment priorities. In others, adaptation may be best achieved by undertaking more of a particular activity or identifying priority areas in which current activities should receive additional support to accelerate the adoption and dissemination of yield-enhancing technologies, natural resource protection practices, or livelihood diversification. Several potential entry points exist through which adaptation can be mainstreamed into the WDR's agenda for agriculture's three worlds, as described in **Table 3.3.**[2]

Priorities for Adaptation in the Agricultural Sector

Agriculture sector strategies, and national development priorities more generally, should be examined through a "climate lens" to determine where climate risks to these strategies and priorities currently exist; how they may change in the future; and which production technologies, policies, and institutions need to be strengthened to enhance climate risk management and build adaptive capacity. Bringing a climate-aware perspective to agricultural development is particularly important for investments with a long life span—such as irrigation systems, rural roads, and other physical infrastructure—and for economic growth strategies aimed at farming system diversification to ensure that these efforts are not maladaptive with respect to climate change.

Integrating climate concerns into agricultural development is especially critical in areas where fundamental shifts in agricultural land use could arise from temperature rise and regional changes in precipitation or from sea-level rise and glacier retreat. These changes could potentially affect land use in the following ways:

- Loss of rangeland or increased marginalization of livestock production in extensive arid grazing zones, such as the Maghreb.
- Increased prominence of livestock, including a shift from arable land to rangeland, in marginal cereal producing areas, such as the Maghreb, the Sahel, northeastern Brazil, and Rajasthan in India.
- Rainfed maize production potentially shifting to millet and sorghum in what are currently dry subhumid areas, such as Sub-Saharan Africa.
- Rice production in irrigation-intensive, dry subhumid areas, such as South Asia, transitioning to upland rice or to other nonrice crops.
- Severe restrictions in water availability from glacier retreat causing a shift toward alternative land uses in glacier meltwater–dependent regions, such as the Andes and parts of Central and South Asia.

2 The agenda and agenda-supporting activities listed in Tables 3.3 are derived from the World Development Report 2008, chap 10 (World Bank, 2008).

TABLE 3.3a Agriculture-based countries

Agenda	Agenda-Supporting Activities	Implications for Adaptation
Building markets and value chains	Diversification of production systems toward a mix of products	Diversification efforts can be directed to reducing reliance on climate-sensitive farming practices in high-risk environments.
	Improved functioning of markets through public–private partnerships, and physical and institutional investments	Markets provide an incentive to invest in soil and water conservation and land improvements that broaden the farmer's coping range to increased climate variability and extreme climate events. Road and communication infrastructure investments better channel adaptation-relevant knowledge to rural communities; weather-proofed roads facilitate seasonal migration, nonfarm livelihood pursuits, and movement of food aid.
Smallholder-based productivity revolution	Agricultural research and extension systems	Research to develop stress-tolerant crop varieties, introduce new crops, and manage pests directly ties in with adaptation needs; stronger formal extension services and new community extension models enhance the adoption process.
	Access to financial services	Lack of timely access to credit has been identified as a key contributor to vulnerability and an important bottleneck to technology adoption in numerous disaster management and adaptation assessments. Rural finance should be a priority issue, given the need to accelerate technology adoption and infrastructure improvement for adaptation.
	Subsidies to stimulate input markets	Improving the performance of seed systems and other input markets (access to fertilizers, conservation tillage equipment, etc.) is important for reducing vulnerability to climate variability and extreme events.
	Decentralized approach to technology development and service delivery	Participatory approaches, such as community-based extension, lead to better-suited technologies and more sustained and wider adoption.
Securing livelihoods and food security	Water harvesting, soil and water conservation, and agroforestry Weather-based index insurance	All of these factors are critical for adapting to increased storm intensity, greater seasonal climate variability, and increased frequency and severity of extreme events.
Facilitating labor mobility and rural nonfarm development	Facilitating growth in the rural nonfarm economy and inducing private investment through greater investment in health and education and increased donor funding and public spending on agriculture.	Investment in rural health systems is important, given the risks that climate change will increase the human disease burden through increased range and activity of vector-borne diseases, flood damage to the health infrastructure, spread of waterborne diseases, and malnutrition from crop failure. Education is critical for new skills that allow vulnerable communities to broaden livelihood options and reduce reliance on climate-sensitive activities.

TABLE 3.3b Transforming countries

Agenda	Agenda-Supporting Activities	Implications for Adaptation
Infrastructure to support diversification	Provide infrastructure to support agricultural and rural economic diversification	Rural infrastructure investments that enhance access to markets and information can aid adaptation planning through providing economic incentives for adopting sustainable practices and better channeling adaptation-relevant knowledge to rural communities.
High-value activities	Diversify smallholder farming away from staple crops and toward high-value agricultural products for urban markets	Carefully planned diversification reduces reliance on climate-sensitive crops and gives farmers more fungible assets. Access to rural financial services and other resources through engagement with the private sector can reduce household vulnerability.
Food staples, livestock, and safety nets	Bring "doubly green revolution" to marginal rural areas	Reduced land and water degradation and improved water productivity reduces vulnerability to increases in storm intensity, seasonal climate variability, and extreme climate events. Increased research and extension could be prioritized to address the severe land management challenges that will result from an increase in extreme events.
	Promote livestock activities among landless and smallholder farmers	Diminished quality of the resource base for economically marginal populations requires livelihood diversification. Potential expansion of rangeland at the cost of cropland, with climate change, will necessitate greater investment in livestock.
Rural nonfarm economy	Address rural unemployment through nonfarm economic development	The nonfarm economy could become more important in areas adversely affected by climate change.

- Saltwater intrusion in highly productive delta areas, such as the Mekong Delta, leading to restriction or abandonment of production of rice and other crops, and a shift toward alternative land uses such as aquaculture.
- Improved agricultural potential at high latitudes, which is expected to include northward movement of the rice belt in northern Asia and shifting of breadbasket regions toward northern Europe, the northern regions of North America, and the South American cone.
- Additional land conversion pressures on natural systems of highland areas as temperature rise improves agricultural potential at high altitudes, such as in the East African highlands.

Although there are significant challenges in adapting to the kinds of land use and climate changes described here, it is important to bear in mind that adaptation is a

TABLE 3.3c Urbanized countries

Agenda	Agenda-Supporting Activities	Implications for Adaptation
Inclusion in new food markets	Promote inclusion of smallholders in new food markets through greater access to land and skills for new agriculture	Reducing inequalities of smallholders to assets and access to public services improves their ability to diversify away from climate-sensitive activities; however, an overreliance on markets can reduce risk-buffering activities. Collective action gained through the promotion of producer organizations can improve efficiency of transmitting climate impacts and adaptation knowledge.
Subsistence agriculture, social assistance, and environmental services	Improve productivity and provide social assistance along with payments for environmental services	Increased research and extension investments improve smallholder access to technologies (e.g. improved varieties that help promote climate risk management and adaptation). Payments for environmental service programs can reduce risk of increased land degradation and secure water supplies for upstream and downstream communities affected by climate change.
Territorial development and skills for the rural nonfarm economy	Promoting clusters of complementary nonfarm employment opportunities among countries	Nonfarm employment would reduce reliance on climate-sensitive agricultural activities.

reiterative process that involves adapting and readapting as impacts, socioeconomic conditions, and knowledge change. Narrowing the adaptation deficit with respect to current climate variability and extreme events is an important first step toward building the capacity for instituting longer-term adaptation measures in many developing world agricultural systems. Appropriate actions for reducing the adaptation deficit through "no regrets" measures (many of which are described in Table 3.3) can also help agriculture begin to adapt to long-term impacts, given the expectation that climate change could manifest itself, in part, as increased frequency and intensity of what is currently experienced as climate variability (Washington et al. 2006).

The following two sections discuss the potential to enhance climate risk management through better utilizing existing technologies, and the importance of paying greater attention to technology dissemination and adoption processes in agricultural development.

Improving Agricultural Development Outcomes to Support Adaptation

Despite a recent trend toward increased climate variability over land masses, significant scope remains for improving the productive potential of agriculture, even in high-risk, rainfed environments, as evidenced by the large yield gap under optimal versus suboptimal input levels. The existence of this yield gap does not mean that adaptation in agriculture can be achieved simply by adopting a particular set of technologies and production practices; rather, it points to where multiple areas for potential improvement exist (i.e., water productivity, soil fertility and quality, suitable genotypes, crop diversification, etc.) that could enhance the near- and medium-term adaptive capacity of agriculture to climate change—and thus better position it to adapt to long-term impacts. Actions taken now and over the next few decades will be critical. As Prowse and Braunholtz-Speight (2007) state: "There might be a limited window of opportunity for current strategies to trigger rural growth processes and wider multipliers. . . . It may only be a matter of two or three decades before current strategies to foster smallholder-driven rural growth become much harder to achieve."

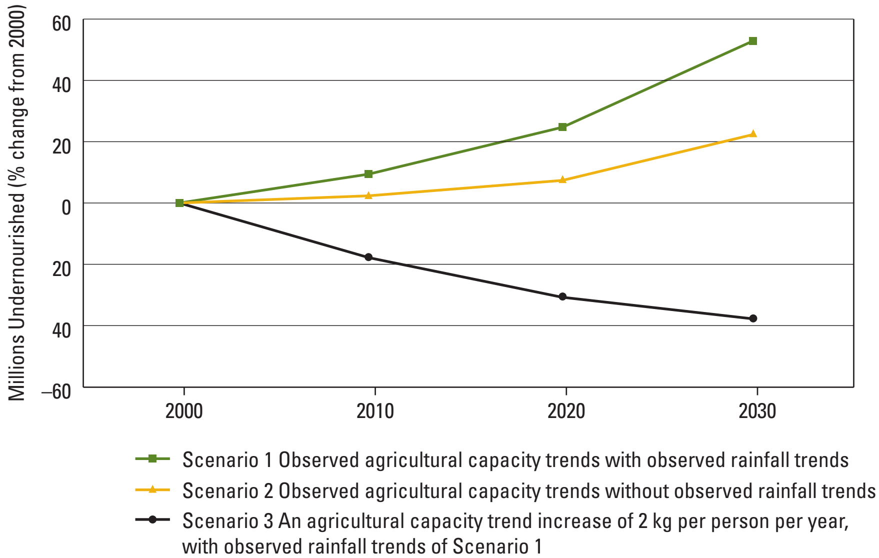
In this context, current agricultural development policies that mitigate seasonal climate risk through increasing agricultural productivity in an environmentally sustainable manner, diversifying rural livelihoods, and increasing local control over resources and resource-use decision making serve to both better enable current development needs and support the emergence of a strong foundation for future adaptive capacity. For example, in a recent modeling analysis of agricultural capacity and rainfall in Africa, Funk and others (2008) demonstrated that modest increases in per capita agricultural productivity could be sufficient to more than offset declines in rainfall over a one- to three-decade planning horizon (**Figure 3.2**).

Technologies, Adaptation, and Livelihoods

While technologies and knowledge systems are available to achieve higher and more stable yields and better manage natural resources, both of which are important for managing climate risks, their adoption and sustained use has generally been limited to locations with favorable production environments and strong supportive rural institutions. In more environmentally or economically marginal areas, which generally coincide with dryland areas, the uptake of agricultural innovations that could support better climate risk management and adaptation has been lacking. This is due, in part, to the failure of the technology (or agricultural innovation) and the technology dissemination effort to consider the myriad social dimensions of rural livelihoods that ultimately determine whether a particular technology is appropriate and whether it is adopted. Important reasons technologies have not been self-sustaining include:

- Lack of consideration of the range of constraints faced by smallholder producers in using the technologies.
- Lack of immediate and tangible economic benefits due to the nature of the technology itself or because of an absence of market incentives for adopting the technology.
- Poorly developed dissemination pathways that prevent technology spillover effects.

FIGURE 3.2 Food balance model describing three scenarios for changes in undernourishment in eastern and southern Africa



The observed trends of reduced rainfall in southern and eastern Africa in Scenario 1 attributed to warming in the south-central Indian Ocean

Source: Funk et al. 2008

- Insufficiently transferable knowledge and use of the technology to the local context or lack of congruence with broader livelihood needs.

Addressing the underlying causes of poor adoption or disadoption of technologies and innovations such as soil and water conservation measures, improved crop varieties, integrated pest management, and related development efforts is critical in order to achieve more sustainable production systems that are better able to cope with climate change. As Kandlikar and Risbey (2000) note in a review of adaptation challenges for agriculture, "[F]armers in low income countries face high downside risks from failure of new technologies, especially if information and government support is limited or lacking. In such cases, they are likely to choose options that have been well tested in the past. Studies of [climate change] adaptation need to pay greater attention to these issues to be truly relevant in a global sense."

Understanding how technologies affect livelihoods, resource access and exclusion, and agroecosystem resilience—rather than simply how a particular technology improves a targeted production factor—will become increasingly important as risks to agriculture increase with climate change. The recent development of "impact pathway" approaches for monitoring and evaluating technology adoption provides a means for rectifying problems associated with poor social sustainability of technology development. These approaches emphasize closer tracking of the fate and impact of agricultural technologies in order to identify and anticipate the various bottlenecks that constrain adoption, and to understand the means through which technologies are adjusted and reconfigured to be more responsive to local needs. (For a discussion of these issues, see Douthwaite et al. 2007; German, Mowo, and Kingamkono 2006; and Nederlof and Dangbénon 2007.)

Insights gained from paying more attention to *ex-post facto* tracking of technologies can bring greater efficiency to the research and development process by identifying critical leverage points and social networks that either hinder or enhance widespread access to the technology's benefits. They can subsequently inform strategies for improving the technology spillover effect that ideally leads to dissemination in the absence or reduced presence of external project intervention. This approach has important implications for adaptation in that:

- More rapid and sustained adoption of yield-boosting technologies and natural resource management practices is needed to both improve food security in the near term and bolster resilience to climate variability and change in the longer term. Identifying where critical bottlenecks or distortions exist in the technology rollout process can improve the effectiveness of this effort.
- Agricultural development strategies will need to reflect the likelihood that climate change impacts on precipitation will not be unidirectional. Regions projected to become drier in the long run are still likely to face risks from excessive rainfall, and the inverse would apply to regions projected to become wetter. Understanding pathways through which communities use and transform technologies will be important for developing broad and flexible approaches.
- Flexible approaches are needed given that adaptation need are often quite place based and context specific, as **Box 3.2** demonstrates. Thus agricultural development policies need to more fully consider the array of physical, cultural, and socioeconomic factors that determine how adaptation priorities are derived at the local level.

III. Rural Development Policies and Adaptation

Achieving effective and equitable adaptation outcomes will require coupling innovations in agricultural production with strong policy support aimed at encouraging or reinforcing social processes that reduce risk and exposure and enhance knowledge and information flows. Interventions to facilitate this process include those that:

- Tailor adaptation policies to vulnerable groups, particularly women.
- Strengthen processes that support collective action.
- Integrate climate risk considerations into decentralization and property rights policies.
- Enhance data access and knowledge dissemination.

Box 3.2

CLIMATE RISK MANAGEMENT AND ADAPTATION IN THE LOWER MEKONG RIVER BASIN

The Assessments of Impacts and Adaptation to Climate Change (AIACC) project examined the issue of sustainable livelihoods in relation to lowland rainfed and upland rice systems in Southeast Asia. These systems generally occur in high-risk farming environments where poverty is widespread, rural infrastructure is poor, and flood and drought occurrence is common. These low-input systems often face different kinds of adaptation issues than those of input-intensive irrigated rice.

The AIACC project examined rainfed lowland rice farming communities in Lao People's Democratic Republic, Thailand, and Vietnam to determine the adequacy of existing local-level adaptation practices for current climate variability and climate change. Farmers employed a wide range of coping strategies. In Lao PDR, these included changes in production practices and varieties based on indigenous weather prediction, livestock rearing, and gathered foods. In Thailand, remittances from urban dwellers were important for coping, while in Vietnam farmers relied on physical improvements to the farm, such as maintaining irrigation systems and building embankments against floods. Structural changes for better water control in Vietnam have become increasingly necessary because of heightened flood risk, and farmers have had to shift practices in order to live with the floods rather than trying to control them. Seasonal or permanent migration was seen as having high potential in Thailand but limited potential in the other two countries, whereas shared resources such as rice reserves and community fishponds had high potential in Lao PDR but low potential in Thailand, where market forces were strong. Lack of market infrastructure was seen as a major impediment for many adaptation options, and the absence of seasonal or inter-annual climate forecasts limited farm-level planning for risk reduction. This study clearly demonstrates that contextual nature of adaptation.

Source: Chinvanno et al. 2008

Tailoring Adaptation Measures to Vulnerable Groups—Factoring Gender into Adaptation Policies

Women are generally more vulnerable to extreme climate events than men, and poor women more than rich. This is due to their disproportionate involvement in climate-sensitive natural resource activities, combined with their limited access to new agricultural technologies, secure land tenure rights, decision making over natural resource use, and limited opportunities for off-farm income generation (Denton, 2002; Lambrou and Piana, 2006). Gender exclusion is often exacerbated by the introduction of new technologies, with men capturing their benefits at much higher rates than women. For example, in a cross-technology survey of adoption rates for germplasm improvement, soil fertility management, soil and water conservation, and cash crop introduction, German, Mowo, and Kingamkono (2006) found that rates were 95 percent for men compared with only 5 percent for women and that information exchange tended to occur along gender lines. [However, there are instances of successful "gender-neutral" natural resource management (NRM) innovations such as the case of improved fallow management in Zambia.] The burden on women's labor in rural communities is certain to increase given the expected climate change impacts on water and land resources, which could further impinge women's abilities to collect household fuelwood and water.

Adaptation strategies need to recognize the unique vulnerabilities of women, their role in household food security, and the networks they use to access social capital. Addressing vulnerabilities along gender lines therefore requires developing policies specifically aimed at women's resource needs and capabilities, such as empowering women in NRM decision-making processes; enhancing knowledge transfer along gender lines, such as through building capacity of women extension agents; and targeting technologies and diversification activities directly at women's capabilities. The microfinance revolution has ushered in significant progress toward empowering women through rural microenterprise. Sustaining and expanding this effort to include targeted microfinance for vulnerable groups in flood- and drought-prone areas would help them diversify away from climate-sensitive activities.

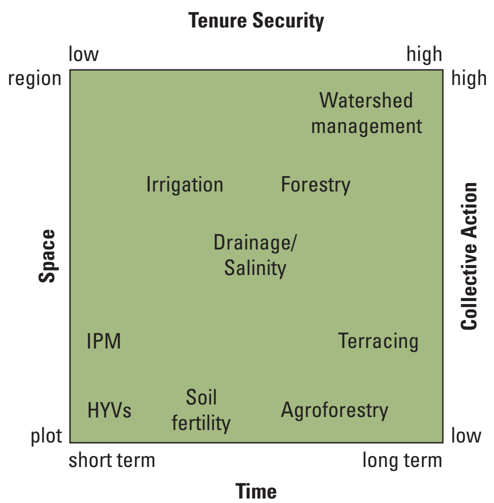
Strengthening Processes That Enhance Collective Action

Well-functioning social networks and modes of collective action are essential for enabling communities in hazard-prone environments to proactively manage and more completely recover from climate-related risks, such as drought, wildfires, landslides, pest outbreaks, and floods. For example, in a recent adaptation assessment of rural communities in southern Africa, reciprocity of actions between households and individuals, along with collective community actions, were seen as vital to broadening the individual's ability to cope effectively during times of stress and to secure new agriculturally based opportunities that facilitate further adaptation to climate change (Thomas et al. 2005). Collective action, along with high levels of property rights, are essential for adaptation responses that require a significant degree of coordination, such as large-scale irrigation and salinity management, or that have long payback periods and require coordination, such as terracing, forestry, and watershed management (**Figure 3.3**). The benefits and potential pitfalls of well-defined property rights in the context of managing climate risks are discussed below.

Integrating Adaptation Priorities into Decentralization and Property Rights Policies

Issues of property rights and decentralization have reemerged as development priorities over the last several years. This has led to the acknowledgment of the essential links between property rights security and long-term investments in land improvement and the recognition of failures in NRM created by centrally managed natural resource

FIGURE 3.3 Relationship among property rights, collective action, and land management



Source: Meinzen-Dick, DiGregorio, and McCarthy 2004

decisions that impose "uniform rules for socially and environmentally diverse landscapes" (Meinzen-Dick, DiGregorio, and McCarthy 2004).

Devolution of property rights to local communities, where successful, has led to genuinely transformative change, such as in Niger, where the transfer of tree ownership from the government to the individual catalyzed farmer-managed natural regeneration of field trees (see Chapter 6, Box 6.2). Also, in India and Nepal, granting forest products access and concession rights to local communities by governments has led to the creation of 20,000 new user groups (Pretty and Ward 2001). These kinds of transformations clearly have positive implications for adaptation in situations where newly obtained resource ownership leads to better resource protection or fosters new forms of social organization that strengthen social capital. However, decentralization does not automatically trigger positive change, particularly when increased resource management responsibilities at the local level do not coincide with a transfer of resource ownership rights from the state. Careful attention must be paid to how decentralization plays out at the local level in order to ensure that local communities have sufficient autonomy over resource-use decisions, which will allow them to better adapt to climate change.

Equity issues in connection with land tenure reform policies are another area in which potential pitfalls exist and where careful policy considerations are needed to avoid increasing the vulnerability of marginal groups. Meinzen-Dick and Mwangi (2008) caution against a one-size-fits-all approach to formalizing land ownership because of the effect that consolidating rights with individuals can have on negating claims by marginal groups for access to livelihood resources. Situations of resource exclusion can arise where land tenure security policies focused solely on individual titling potentially prohibit women, seasonal pastoralists, and others from using water and other natural resources and grazing land.

The negative effects resulting from resource exclusion could become more acute with climate change in regions projected to experience increased drought and a subsequent dwindling of water and related resources. Thus, in the context of adaptation, strategies and policies should be developed that support land tenure and local resource ownership, while articulating where additional burdens imposed by climate change could require stronger state–society linkages or other remedial actions. Policy support and dialogue for understanding the local dynamics of resource ownership arrangements—who wins, who loses and how, and where potential shifts could occur with climate change—would be a good starting point. Also, to the extent possible, land tenure security policies should be integrated with efforts to address nontenurial factors that constrain production and magnify vulnerability. For example, Bugri (2008) found that stable tenure security in northeast Ghana did not necessarily lessen farmer vulnerability to climate and other livelihood shocks caused by lack of access to credit, poor market conditions, and high levels of biotic and abiotic crop stresses.

Enhancing Data Access and Knowledge Dissemination

The means through which knowledge and information are generated, managed, and disseminated are critical to improving development outcomes that support adaptation. Lack of knowledge and information can constrain adaptation in situations where recognition of climate trends is lagging, where knowledge about new techniques is lacking, or where avenues for transmitting knowledge upward from communities to policy makers is ineffective or absent. An assessment of recent adaptation efforts across the Assessments of Impacts and Adaptations to Climate Change (AIACC) program found that poorly developed or poorly coordinated knowledge networks were an important hindrance to adaptation (Leary et al. 2008).

Because of its context and location-specific nature, adaptation is very knowledge intensive; areas facing the same type of climate risk will have very different knowledge gaps and needs, depending on the strength of institutions and governance, level of education, infrastructure, and resiliency of social networks, to name a few factors. Access to data of all sorts (socioeconomic, environmental, and climatic) by adaptation planners in government institutions is crucial for reducing the uncertainty costs around adaptation.[3]

Top-down dissemination pathways are important for relaying information about future climate change impacts and developing macro-level policies. They are limited, however, in their ability to provide climate information, which is relevant to the processes through which many vulnerable communities prioritize livelihood threats, manage risk, or extend development goals (Vogel et al. 2007). The extent to which knowledge and information are acted upon at the local level depends on perceptions of risk from current and future hydrometeorological hazards, as well as the influence

3 World Bank Task Team Leaders (TTLs) interviewed in conjunction with this study stressed the importance of data and information to adaptation planning, and, in some situations, data gaps were seen as a key bottleneck to implementing adaptation measures.

that the array of nonclimate factors brings to bear on the risk calculus. Grothmann and Patt (2005) describe how farmers in Zimbabwe, given a forecast of below-normal rainfall, still chose to grow maize over millet when the potential crop loss risks from drought were weighed against the substantial risks that might ensue from not growing maize, given the extent to which institutional, societal, and market forces were aligned in favor of maize production. Similarly, policies to promote adaptation measures in Mozambique have been stymied by differences in policy-maker and farmer perceptions of flood risks in resettlement programs (Patt and Schröter 2007).

The departure in how formal institutions and vulnerable communities prioritize risk, provided by the preceding two examples, points to the importance of embedding climate knowledge and information for risk management and adaptation within the larger socioeconomic context of the agricultural system and combining local-level access to climate information with an active dialogue process in developing implementable policies. Ethnographic studies can be a useful tool for informing policy makers engaged in adaptation planning of how communities process and transform information and how local and indigenous knowledge systems and practices provide a cultural context for decision making (Nyong, Adesina, and Elasha 2007; Roncoli 2006).

Options for Improving Knowledge and Information Flows New tools and models are emerging that can facilitate the flow of adaptation-relevant knowledge and information, as illustrated in **Box 3.3**. These include fortifying and expanding information and communication technology (ICT) and participatory extension systems, as well as approaches created specifically for adaptation, such as shared learning dialogues (SLDs).

ICT can be deployed to better enable information gathering and storage and dissemination to rural communities. Balaji, Meera, and Dixit (2007) described how information service provisions through ICT can improve drought preparedness and recovery in semi-arid regions in India through:

- Establishing communication centers for drought mitigation.
- Filling community information gaps with respect to markets, climate, employment, and wages, as well as livelihood aspects not normally covered by conventional rural development information systems.
- Micro-level drought vulnerability assessments linked to village information formats.

Scaling up ICT would entail intensive training of village facilitators, integration of agricultural information services for ICT into the wider range of general information services, and investments in ICT hardware. Piggybacking seasonal climate forecasts onto ICT would further enable climate risk management and adaptation.

Participatory extension efforts have begun to take hold in the developing world over

Box 3.3

ENHANCING KNOWLEDGE FLOWS FOR ADAPTATION TO CLIMATE CHANGE IN ARID LANDS IN KENYA

Agriculture in Kenya's extensive arid and semi-arid lands is exposed to significant risk from high inter-annual climate variability; rainy seasons can vary from being extremely wet and associated with floods and landslides to situations of drought caused by delayed or failed rains. Climate change is likely to introduce an additional burden to these systems, because the variability between extremely dry and wet years is expected to intensify, and temperatures in the region are projected to increase by more than 3°C by the end of this century. The World Bank is helping Kenya enhance the adaptive capacity of its dryland areas, through the recently initiated KACCAL (Adaptation to Climate Change in Arid Lands in Kenya) project, which aims to help communities better manage climate risk through such measures as:

- Building the capacity of mobile extension systems to provide guidance on climate risk in relation to land-use and natural resource management issues.
- Strengthening current early warning systems by coupling household-level surveys with weather and climate forecasts.
- Incorporating information about medium- and long-term climate projections into local-level (district and community) planning processes.
- Enhancing information sharing mechanisms, which bring together technical, development, and policy perspectives.

the past several years and have led to more responsive service delivery by introducing new technologies and the means to empower technology uptake and innovation by farmers. Supporting expansion of the participatory extension model could aid adaptation efforts in the following ways:

- Extension geared toward joint learning and the communication and sharing of knowledge among farmers provide a platform for exchanging information about climate impacts and appropriate measures for adaptation. In addition, the intersection point between formal extension services and participatory extension approaches could serve as a hub for bottom-up transmission of knowledge related to coping strategies and adaptation needs of local communities. Thomas and others (2005) found that support for group visits and farmer-to-farmer exchange networks were an effective and low-cost means for relaying adaptation-relevant knowledge and information.
- The process of diversifying production systems away from reliance on climate-sensitive crops or practices is very knowledge intensive, and formal extension services by themselves will not be able to meet the substantial knowledge and information demands. Rural microenterprises

being promoted for adaptation—such as bee keeping, small livestock rearing, and irrigated horticulture—are beyond the usual mandate of formal extension linked to national agriculture research services.

- Formal extension services must effectively reach women and other marginal groups that are most vulnerable to extreme climate events.

  Although a potentially powerful tool, the establishment of effective participatory extension systems requires substantial capacity building to ensure community ownership over the process, inclusion of marginal groups, and mechanisms for conflict resolution (Hagmann et al. 1999).

  Shared learning dialogues (SDLs) are another means of improving knowledge and information flows for adaptation. This method has been used to inform vulnerability and adaptation assessments for flood risks in South Asia (Moench and Dixit 2007, and references therein). SLDs refer to mediated discussions among stakeholders at a particular level, the information of which is vertically integrated across SLDs to identify adaptation priorities and determine implementable options. In the South Asia flood adaptation example, the SLDs assisted in revealing practical measures that could be taken to help communities simultaneously address current problems and better prepare for climate change. An advantage of this method was illustrated when key issues emerging from local-level SLDs were conveyed to policy makers in state-level SLDs, thus enhancing the potential for better vertical coordination.

Conclusions

- Agriculture is one of the most vulnerable sectors to climate variability and change, particularly in dryland, rainfed areas. Rural communities, in particular, face multiple pressures to sustainable livelihoods that exacerbate vulnerability to climate change.
- Multiple approaches exist for assessing vulnerability. These range from approaches that are hazards based (sustainable development best achieved by adaptation) to those that are vulnerability based (development to reduce vulnerability leads to adaptation).
- Addressing the inability to cope with current climate risks, or the "adaptation deficit," is an essential starting point for adaptation throughout much of the developing world. Given that adaptation is a reiterative process, building the capacity to better manage near- and medium-term climate risks (one to two decades) is essential for creating the foundation upon which long-term adaptation can occur.
- Better use of existing production technologies and the development of new technologies are important for adaptation in agriculture. Optimal use of these technologies depends on

enhancing adoption and dissemination processes such that they are relevant to the livelihood needs of farmers in vulnerable areas. This will require that technologies and technology-dissemination processes are flexible, allow for farmer innovation, and are pro-poor.

- For adaptation to be equitable, its strategies must take into account the unique adaptation needs and capacities of women and other marginalized groups.
- Strong social networks and collective action can enhance the ability of communities to cope with extreme climate events, sustainably manage natural resources, and influence policy outcomes in the face of climate change.
- High levels of collective action and property rights are necessary for NRM strategies that are large scale and require long-term investments, such as with watershed management.
- Climate knowledge and information for risk management and adaptation needs to be embedded within the larger socioeconomic context of the agricultural system, and local-level access to climate information needs to be accompanied by an active dialogue process for developing implementable policies.

CHAPTER 4: CLIMATE INFORMATION

SUMMARY: This chapter discusses sources of uncertainty with respect to projections of future climate change, as well as advantages and disadvantages of using downscaled regional climate models. It also describes a range of tools used to generate scenarios for estimating future impacts, which can then inform adaptation planning. Finally, it examines technical progress in, and capacity building needs for, advancing climate-crop modeling, seasonal climate forecasting, and early warning systems (EWSs).

I. Understanding and Managing Uncertainty

Global Climate Models

Adaptation planning is occurring, and will continue to occur, in an environment of uncertainty concerning trajectories of future greenhouse gas emissions; the direction of climate change; and influence of feedbacks in the climate system, including those from land-use/land-cover change. This will significantly affect the magnitude of future impacts and the ability of societies to adapt. However, recent advances in climate modeling have begun to address some of this uncertainty, as described in the IPCC's Fourth Assessment Report (Randall et al. 2007). Good agreement exists among the various atmospheric-ocean general circulation climate models (AOGCMs) with respect to:

- The magnitude of temperature rise at the end of this century across different emissions scenarios.
- Changes in mean precipitation in some areas of the subtropics, such as southern Africa and the Mediterranean basin.
- Qualitative shifts in precipitation that will likely lead to an increase in the intensity and decrease in the frequency of storms.

Significant disagreement regarding the long-term direction of precipitation still remains among climate models for large areas of tropical South America, Africa, and Asia, reflecting knowledge gaps about convective precipitation in the tropics. The magnitude of regional-scale temperature rise over the 2020–2030 period is also not well estimated due to the predominance of natural internal variability in the climate system and land degradation processes relative to the comparatively weak signal originating from anthropogenic climate forcing (Paeth and Thamm 2007; Smith et al. 2007a).

A climate envelope analysis, in which multiple-model runs (ensembles) are done using both different input conditions and multiple models, can help identify potential sources of uncertainty and the range of uncertainty by providing a distribution of results. Understanding the range of uncertainty from multiple models provides a more robust analysis for adaptation planning than uncertainty generated by one or two models. An envelope analysis can show where agreement exists across the model runs for some of the expected changes (such as temperature rise), where models disagree (such as with the direction of precipitation), and the distribution and range of model outcomes. This method provides the user with a "complete envelope" of possibilities and an understanding that the future climate will lie somewhere within that range. Using a climate envelope approach can help avoid the risks associated with relying on a single outcome, although it cannot avoid problems associated with missing or misrepresented processes.

Scenario Generation for Decadal Climate Projections

A range of scenario-generation methods for future climate is available for adaptation planning, from relatively simple sensitivity analysis to more complex downscaling methods (**Table 4.1**). Wilby (2007a) proposes grouping the various scenario-generating methods into entry-, intermediate-, and advanced-level methods, considering that:

- Entry-level methods provide site- or area-specific climate risk information, which can support scoping assessments and awareness-raising activities, with modest data needs and low demands on technical resources.
- Intermediate-level scenario methods are comparatively more information-rich and have greater data and resource needs than entry-level methods.
- Advanced-level methods are capable of capturing the full range of climate forcings but require extensive specialist knowledge and computing resources.

The entry- and intermediate-level methods are appropriate for many adaptation applications in agriculture that will be used over the next few decades (up to a 2030 timeframe), depending on physical location, access to reliable data sources and relevant biophysical and economic models, and internal technical capacity. Regional downscaling of global climate models (GCMs) showing projections of long-term impacts can complement the information generated by entry- and intermediate-level methods, and help ensure some consistency between near- and medium-term adaptation planning and long-term climate hazards. While scenarios of future climate are critical, their absence need not preclude adaptation, as Osman-Elasha and others (2008) demonstrated in an adaptation project targeted at the livelihood sustainability of highly drought-vulnerable populations in Sudan. In that situation, the adaption deficit with respect to current climate hazards was quite high; thus efforts to mitigate current hazards were viewed as essential to providing a basis for future adaptation actions.

TABLE 4.1 Description of methods for generating climate scenarios for use in adaptation planning at decadal time scales

Method/Application	Description of Methodology	Advantages	Disadvantages
ENTRY LEVEL:			
Sensitivity analysis *Resource management, sectoral*	Climate observations fed into a validated resource model to obtain baseline conditions, followed by data perturbed by a fixed amount to reflect changes in climate parameters, and subsequently to discern resource sensitivity.	1. Easy to apply. 2. Requires no future climate change information. 3. Shows most important variables/system thresholds. 4. Allows comparison between studies.	1. Provides no insight into the likelihood of associated impacts unless benchmarked to other scenarios. 2. Impact model uncertainty seldom reported or unknown.
Change factors	Change factors represent ratios or absolute differences in precipitation and temperature baseline and future climate models, based on sampling distributions from one or several GCMs and/or RCMs.	1. Easy to apply. 2. Can handle probabilistic climate model output.	1. Perturbs only baseline mean and variance. 2. Limited availability of scenarios for 2020s.
Climate analogues	Analogue scenarios are constructed from paleo- or recent instrumental records to give plausible representation of future climate. Temporal analogues are taken from previous climates of the region, and spatial analogues from another region where present conditions could represent future climate of the study area.	1. Easy to apply. 2. Requires no future climate change information. 3. Reveals multi-sector impacts/vulnerability to past climate conditions or extreme events, such as a flood or drought episodes.	1. Assumes that the same socioeconomic or environmental responses recur under similar climate conditions. 2. Requires data on confounding factors such as population growth, technological advance and conflict.
Trend extrapolation	Current trends are extrapolated into a near-term future.	1. Easy to apply. 2. Reflects local conditions. 3. Uses recent patterns of climate variability and change. 4. Instrumented series can be extended through environmental reconstruction. 5. Tools freely available.	1. Typically assumes linear change. 2. Trends (sign and magnitude) are sensitive to the choice/length of record. 3. Assumes underlying climatology of a region is unchanged. 4. Needs high-quality observational data for calibration. 5. Confounding factors can cause false trends.

(*Continued*)

TABLE 4.1 (*Continued*)

Method/Application	Description of Methodology	Advantages	Disadvantages
INTERMEDIATE LEVEL:			
Pattern-scaling	Factoring backward from long-term projections in RCM or GCM outputs to derive rate of climate change and to scale quantities for intervening periods.	1. Modest computational demand. 2. Allows analysis of GCM and emissions uncertainty. 3. Shows regional and transient patterns of climate change. 4. Tools freely available.	1. Assumes climate change pattern for 2080s maps to earlier periods. 2. Assumes linear relationship with global mean temperatures. 3. Coarse spatial resolution.
Weather generators	Models that replicate statistical attributes of meteorological station records, used to simulate long series of weather sequences such as wet and dry spells.	1. Modest computational demand. 2. Provides daily or sub-daily meteorological variables. 3. Preserves relationships among weather variables. 4. Already in widespread use for simulating present climate. 5. Tools freely available.	1. Needs high-quality observational data for calibration and verification. 2. Assumes a constant relationship between large-scale circulation patterns and local weather. 3. Scenarios are sensitive to choice of predictors and quality of GCM output. 4. Scenarios are typically time-slice rather than transient.
Statistical downscaling of GCMs	Spatial interpolation of gridded GCM or RCM output to required locations, or models of quantitative relationships between large-scale atmospheric variables (predictors) and local surface variables. (predictands).	1. Modest computational demand. 2. Provides transient daily variables. 3. Reflects local conditions. 4. Can provide scenarios for exotic variables (e.g., urban heat island, air quality). 5. Tools freely available.	1. Requires high-quality observational data for calibration and verification. 2. Assumes a constant relationship between large-scale circulation patterns and local weather. 3. Scenarios are sensitive to choice of forcing factors and host GCM. 4. Choice of host GCM constrained by archived outputs.
ADVANCED LEVEL:			
RCMs using dynamical downscaling of GCMs	Atmospheric fields simulated by a GCM are fed into the boundary of an RCM at different spatial resolutions. The RCM is nested within the GCM.	1. Maps regional climate scenarios at 20- to 50-km resolution. 2. Reflects underlying land-surface controls and feedbacks. 3. Preserves relationships among weather variables.	1. Computational and technical demand high. 2. Scenarios are sensitive to choice of host GCM. 3. Requires high-quality observational data for model verification.

Method/Application	Description of Methodology	Advantages	Disadvantages
		4. Ensemble experiments are becoming available for uncertainty analysis.	4. Scenarios are typically time-slice rather than transient. 5. Limited availability of scenarios for 2020s.
AOGCMs		1. Forecasts of global mean and regional temperature changes for the 2020s. 2. Reflects dominant earth system processes and feedbacks affecting global climate. 3. Ensemble experiments are becoming available for uncertainty analysis.	1. Computational and technical demand high (supercomputing). 2. Scenarios are sensitive to initial conditions (sea surface temperatures) and external factors (such as volcanic eruptions). 3. Scenarios are sensitive to choice of host GCM. 4. Coarse spatial resolution.

Source: Wilby 2007a

Regional Downscaling of GCMs

GCMs simulate the whole Earth but with a relatively coarse spatial resolution (e.g., they can capture features with scales of a few hundred kilometers and larger), while regional climate models (RCMs)—downscaled from GCMs—have a much higher resolution (simulating features with scales as small as a few kilometers). Downscaling can be accomplished through one of two techniques: "dynamical" or "statistical" downscaling. Dynamical downscaling refers to the process of nesting high-resolution RCMs within a global model, while statistical downscaling relies on using statistical relationships between large-scale atmospheric variables and regional climate to generate projections of future regional climatic conditions. The downscaling methodology is as follows:

- The GCM is run for the relevant time period—for example, 1990–2090—and output, in the form of temperatures, wind, humidity, etc., at each GCM grid cell, is collected.
- The RCM is then run for particular "time slices" of the longer GCM run, such as the decade of 1990–2000 and 2080–2090. This is accomplished by using the GCM output from these time slices as the boundary conditions at the edge of the RCM domain.
- Additional nestings, telescoping down to finer and finer scales, are also possible.
- The RCM output is then used for applications such as climate impact analysis.

RCM Advantages and Limitations

Downscaling of GCMs can provide a powerful alternative to using global-scale models for adaptation planning. The advantages of RCM downscaling are that climate can be simulated at much finer scales than is possible with a GCM, and the RCMs can realistically simulate regional features such as the influence of water bodies on climate, extreme climate events, seasonal and diurnal variations of precipitation, and regional scale climate anomalies. However, RCMs are prone to "error propagation" from the GCMs and require significant computational resources, and their results are sensitive to the selection of domain and resolution. Finally, an important caveat in using RCMs concerns the degree of uncertainty in the GCMs: if low confidence exists in the GCM (such as noted earlier for projections of precipitation trends over some tropical land masses), then acquiring credible downscaled results for fine-scale adaptation planning may be impossible.

RCMs are useful for identifying where general sensitivity to climate change exists, which can help to inform adaptation planning at broad scales, assuming the information from the RCM is reasonably robust. The analysis by Thornton and others (2006), which demonstrated potential negative impacts of climate change on growing-season length, number of growing seasons, and prevalence of failed seasons for African agriculture, is a good example of such an application. RCMs are also important in situations where information about future conditions is premium (as in the case of potential climate change impacts on transboundary resource sharing), where impacts will be predominately long term or where multiple, economically important sectors intersect.

In considering RCM use, it is important to bear in mind that the practical future planning horizon for agriculture is one to three decades, a period over which the signal from anthropogenic forcing—upon which climate models linked to emissions scenarios is based—is weak. Also, climate models fail to account for non-greenhouse gas drivers of regional climate change, an important omission in many developing regions where land-use/land-cover change and aerosol formation from wild fires and agricultural land preparation are significant drivers (see **Box 4.1**). The capacity to act on the information generated by RCMs is often low in many of the most vulnerable countries, and building capacity in this area may be an important initial task[1].

Capacity Building Needs for Scenario Generation

A recent analysis, commissioned by the U.K. Department for International Development (DFID), of decadal climate scenarios and impact assessment capacity in developing regions (Wilby 2007b), appraised options and entry points for improving capacity to generate the types of scenarios described in Table 4.1. The report covers the timeframe from the present to 2030 and identifies four principal areas—monitoring

1 Lack of data, and experience with using and interpreting dynamic simulation models, were identified as important gaps in the 14-country Netherlands Climate Assistance Program; time and resources spent improving capacity to use and interpret complex models were viewed as somewhat in competition with other objectives of adaptation projects.

Box 4.1

USING CLIMATE INFORMATION TO ESTIMATE IMPACTS ON AGRICULTURE

Land-use practices associated with agriculture exert a significant influence on regional climate through a myriad of radiation, temperature, and moisture interactions, while agriculture itself is subjected to numerous environmental forcings and feedbacks that determine its degree of vulnerability. Climate is one among several of these determinants, each of which exert direct pressure on agriculture, as well as indirectly on the system through influencing and being influenced by the other drivers, usually in a nonlinear fashion. (For an overview of this issue, see Pielke et al. 2007.)

Given the inherent complexities and uncertainties among agriculture, regional climate forcing, and various other drivers of environmental change, it is important to seek out multiple types of information and data to estimate how climate change will contribute to the future vulnerability of an agricultural system. Rather than having GCM data drive the determination of impacts and vulnerability, it may instead be preferable to identify where vulnerabilities or pressure points (both climatic and nonclimatic) exist in the current system—and what their respective thresholds may be—and then work upward to integrate this information with climate model data. This latter approach is more explicitly development focused in that it gives greater consideration and weight to other vulnerability factors, and in doing so can identify critical nonclimatic stressors that, if addressed, could reduce overall climate sensitivity in the agricultural system. Building the capacity to perform these types of assessments requires investments in developing climate modeling capacity at the national level, accompanied by efforts to strengthen overall capacity for environmental resource modeling and support for introducing tools and educational approaches that integrate local knowledge into climate change vulnerability assessments.

and data, basic science, decision support, and human capital—where capacity building is needed.

1. *Monitoring and data* opportunities include:
   a. Digitization of weather data that would benefit both local capacity building for data management, as well as climate model development efforts in data-sparse regions.
   b. Compiling and centralizing country-scale data on ancillary effects of climate on the range of co-stressors affecting socioeconomic systems.
   c. Support for meteorological and oceanographic field campaigns, which would fill knowledge gaps in observing networks and data collection.
2. *Basic science* support would help improve understanding of the physical processes driving regional climate variability and change and, in doing so, better characterize key sources of uncertainty affecting decadal climate forecasts. Opportunities in this area include building stronger research capacity for understanding climate teleconnection patterns and for enhanced modeling of regional feedbacks and extremes and improving capacity to assess decadal variability within climate models. All of these efforts should be aimed at translating

climate information into policy-relevant decadal forecast products.

3. *Decision support* is needed for improving access to and understanding of climate risk information for adaptation planning through online data portals for climate risk-screening tools, online scenario tools for regional climate change, and IPCC climate change scenarios.

4. Supporting *human capital* development could include building in-country climate science capacity, enhancing north–south and south–south institutional linkages, strengthening communication and coordination between suppliers and users of climate information, and improving general "climate literacy" through education initiatives (See **Box 4.2**).

II. Using Climate Information for Adaptation and Development in Agriculture

Crop Growth Simulation Modeling

Concern over the potential impacts of climate change on crop production has spawned interest in simulating future crop production for impacts assessment and adaptation planning. Coupled crop and climate models, in which future climate parameters from a climate model are used to parameterize weather inputs to a crop model, can provide an estimate of potential impacts on crop yields. Coupled models can also help aid adaptation planning by making it possible to simulate the effect of adaptation measures such as irrigation, new crop mixes and varieties, and increased fertility inputs on crop yields—using different climate change scenarios and varying the input parameters. The main strength of most crop models is their flexibility in that they can be readily linked to upstream or downstream models to generate outputs beyond what the original model can provide. Additional applications of coupled models include using yield outputs from a crop model to serve as inputs to economic models for calculating the economic value of future production assets, as well as linking irrigation management simulations from crop models to groundwater models to assess the future availability of water resources for agricultural uses.

Crop models can approximate broad changes in production under current and future climatic conditions provided that limitations and uncertainties in the models are understood, including uncertainties in GCM projections with respect to the direction and nature of precipitation trends. These limitations and uncertainties require that crop model simulations be interpreted in terms of the likely change in future yields, and less so in terms of the magnitude of that change. (For a comparison of different types of crop models, see **Table 4.2**.) Important limitations and uncertainties of crop models include:

- Inability to simulate the effects of extreme events like flooding or wind damage on crop yields.

Box 4.2

DATA GENERATION AND ACCESS FOR ADAPTATION: A WORLD BANK TASK TEAM LEADER (TTL) PERSPECTIVE

TTL interviews were conducted in conjunction with this report to identify gaps and bottlenecks in implementing World Bank adaptation projects. The interviews revealed that data generation and access, and the capacity to interpret and use data, were important obstacles to adaptation planning for World Bank projects in Kenya, Mozambique, the Philippines, and Yemen; adaptation projects in China and India did not encounter significant data gaps. These data and information gaps existed in agricultural, environmental, and socioeconomic realms, as well as with climate trends and projections. Poor access to data contributed to this gap in situations where data was scattered among ministries or not readily shared. Lastly, deficiencies were prevalent in national capacities to work with data and information to support adaptation planning, including in inadequate project interpretation and GIS/mapping capacity (Kenya), and low capacity to understand data sets (Yemen). Access to data and information is a critical bottleneck for adaptation planning in many low-income countries because data sets are scarce, not centralized, or not readily shared among government ministries. (Middle-income countries may also face some of these same challenges, but to a lesser degree.) Given the potentially immense information gaps in undertaking adaptation, greater support and investments are needed in computational and spatial analysis capacity, as well as in education and skill development for effective data generation, organization, and interpretation. Areas of potential capacity building and education include:

- Operating climate models and interpreting climate model output, and using a range of methods to generate climate change scenarios.
- Working with environmental data sets (and the attendant skills and hardware in GIS, remote sensing, land satellite imagery, etc.).
- Collecting, organizing, and analyzing environmental, socioeconomic, and climatic data, where information is currently scarce.

- Inability to simulate effects of changes in pest, disease, and weed pressure—or in soil and water quality—on crop yields that could occur with climate change, although a small number of specific pest-crop models parameterized for a few particular systems do exist.
- Inability to accurately simulate the effects of extreme climate events on crop yields, because GCMs do not adequately capture effects of climate variability.
- Widely divergent comparisons of yield change across models, even when using the same input data (e.g., Challinor and Wheeler 2008).[2]
- Significant uncertainties as to the strength of the CO_2 fertilization effect on future crop yields.
- Poor performance of regional/global soil, crop, and climate data at the local (project)

2 Probabilistic estimates of climate change impacts that rely on a range of plausible outcomes using an ensemble of models can help better evaluate sources of crop and climate uncertainty than those generated by scenario analysis, as described by Telbaldi and Lobell (2008).

TABLE 4.2 Description of widely used model types

Agronomic Model	Climate Change–Related Outputs	Consideration of Adaptation	Strengths	Limitations
GAEZ Global Agroecological Zone system utilizes land-type and land-use data to assess resources for a wide range of agricultural land-use options. Contact information: Günther Fischer International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria; Tel: +43.2236.807.0; Fax: +43.2236.71.313; e-mail: fisher@iiasa.ac.at	Climate change impacts on yields. Climate change impacts on areas suitable for crop cultivation. Optimal changes in crops and sequential multicropping due to climate change.	Optimal adaptations of crop calendars, switching of crop types, and changes in potential multi-cropping are embedded in the results. Changes in production potential as a result of irrigation and/or multi-cropping can be calculated.	Provides a comprehensive and standardized framework for characterizing land use suitability. Particularly relevant for comparative national and regional analyses. Agroecological zone (AEZ) evaluation procedures have been extended for grasslands and forest resources management.	Regional data, with low accuracy at the local level, and global data sets used as inputs to AEZ are of uneven quality. The benefits of irrigation are calculated under the assumptions that good-quality water resources are available and irrigation infrastructure is in place. Suitability for project-level economic analysis is poor. (Economic modeling is treated as a co-determinant of the biophysical potential of land.)
EPIC Erosion Productivity Input Calculator (and its extensions and applications, including APEX, CroPMan, and WinEPIC) is a process plant growth model that simulates daily crop growth. Contact information: EPIC programmers and user trainers, such as Dr. Susan Riha, Department of Earth and Atmospheric Sciences Cornell University 140 Emerson Hall, Ithaca, New York 14853 USA Tel: +1.607 .255. 6143; e-mail: sjr4@cornell.edu.	Climate change impacts on yields. Changes in production potential as a result of crop management practices.	EPIC can be used to determine the effect of agricultural adaptation strategies on yields and on soil and water conservation.	Continuous upgrades, extensions and applications make EPIC highly flexible. Suitability for project-level economic analysis is good. EPIC contains a broad range of environmental and production components.	Model is data intensive and detailed inputs are required. "The parameter files are extremely sensitive to local conditions. EPIC can give grossly misleading results . . . when relying on default settings." (Source: UN Framework Convention on Climate Change [UNFCCC], methodologies for adaptation: EPIC)

Agronomic Model	Climate Change–Related Outputs	Consideration of Adaptation	Strengths	Limitations
DSSAT Decision Support System for Agrotechnology Transfer is an integrative software shell under which are contained dynamic crop growth simulation models for cereals (CERES), grain legumes (CROPGRO), and roots and tubers (SUBSTOR). Contact information: International Consortium for Agricultural Systems Applications (ICASA) 2440 Campus Road, Box 527 Honolulu, Hawaii 96822 USA Tel: 808-956-2713; Fax: 808-956-2711; Internet: ICASA@icasa.net	Key outputs are the impact of climate change on crop production, resource use, and environmental pollution.	The user can simulate the performance of various adaptation management options on screen and ask "what if" questions regarding weather and other criteria for those options.	The model contains several modules (land, crop management, soil, weather, soil-plant-atmosphere, plant growth modules) that give it flexibility. Suitability for project-level economic analysis is good. DSSAT can be used at different spatial scales, from the farm up to the regional level, to determine climate change impacts on production, and potential adaptation practices.	Detailed inputs are required. Does not contain a hydrologic module.

scale, due to the fact that climate models operate on grid sizes several orders of magnitude greater than field-scale crop models.[3]

- The capacity to effectively use crop models in developing countries needs to be strengthened in order to encourage their broader uptake (**Box 4.3**).

Seasonal Climate Forecasting

Improved understanding of the interactions between sea surface temperature (SST) anomalies, El Niño teleconnections, and seasonal climate conditions has led to advances in the science of seasonal climate forecasting. This, in turn, has resulted in a proliferation of seasonal climate forecasting activities in many regions of the world. [For a detailed review of this issue, see Sivakumar and Hansen (2007) and authors within that volume.] Seasonal climate forecasts have the potential to significantly bolster climate risk management capabilities in agriculture, particularly in risk-prone rainfed environments where high climate variability at seasonal and inter-annual scales depresses crop productivity and constrains investments in soil fertility enhancement and other production innovations. These forecasts are viewed as being particularly

3 Recent success has been achieved in matching spatial scales in coupled crop-climate models through use of the process-based general large-area model (GLAM) specifically developed to operate at spatial scales equivalent to that of GCMs (Osborne et al. 2007).

Box 4.3

EDUCATION AND SKILL DEVELOPMENT FOR USING CROP-CLIMATE MODELS

The increasing availability of low-cost, module-based software systems has enhanced the reach of crop models into developing regions. However, availability does not necessarily translate into sustained use among national scientists and policy makers. Efforts of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to build national capacity in the use of the Agricultural Production Systems Simulator (APSIM) model among national agriculture research and extension services in Africa illustrate potential constraints to adopting crop models. These include lack of opportunities for technicians exposed to this model in training courses to use it on a sustained basis, as the short duration of the training course (normally four to five days) is often insufficient to gain enough experience to ensure operational problems are not encountered later.

The capacity of countries to more fully use crop-climate modeling as an adaptation-planning tool could be enhanced in the long term through educational initiatives that support university studies in the field of agroclimatology. An agroclimatology curriculum would offer the following advantages:

- Sufficient time to ensure comprehensive training, which could also be coupled with "practical modeling exercises" as part of the curriculum.
- Better preparation in agroclimatology qualifications to move into both the National Agricultural Research and Extension Services (NARES) and the National Meteorological Services (NMS).
- Greater opportunities for cross-fertilization between the NARES and the NMS, and greater potential for the NMS to offer "products" for agricultural research and extension rather than just act in the role of custodians of meteorological data.

Source: Peter Cooper, ICRISAT, personal communication

valuable during periods when the ENSO signal is strong, because this tends to coincide with anomalously wet or dry years, thus representing a risk (or opportunity) in relation to how societies manage water use, public health, food production and emergency food dispensation, and trade and commerce.

Prospects for further improving probabilistic forecasting over the next decade are good, given recent advances in dynamically coupling crop models within climate models and improvements in remote-sensing technologies and access to spatial environmental databases (Doblas-Reyes, Hagedorn, and Palmer 2006; Wheeler, Challinor, and Slingo 2007). These technological advances have the potential to enhance the resolution of climate-crop forecasting as well as improve the ability to assess uncertainties within climate-based crop forecasting. However, despite both realized and potential progress in seasonal climate forecasting skills, significant uncertainties remain in relation to intra-seasonal rainfall variability, namely, the onset and cessation of the rainy season and the seasonal distribution of rains, particularly as it pertains to the timing of dry periods in relation to sensitive crop growth stages (Archer et al. 2007; Traoré et al. 2007). In addition, ENSO-based forecasts have limited utility in regions where climate variability is influenced by a number of other large-scale climate factors, in addition to the ENSO. Box 4.3 contains a summary of scientific, policy and capacity building issues related to seasonal climate forecasting.

In recent years, forecasts have been applied in a number of different agricultural environments, ranging from resource-endowed systems, where the forecast can aid the effectiveness of well-established extension and commodity support programs, to high-risk marginal farming environments, where the potential benefits of forecasts are quite high but the capacity to utilize the information is low. Populations engaged in the latter are currently the focus of a concerted effort to bring climate information to bear on farmer decision making as a means of enhancing current climate risk management and building adaptive capacity to climate change. For example, the World Meteorological Organization (WMO) is pushing to build capacity for generating and disseminating seasonal climate forecasts in Sub-Saharan Africa. Similar, though smaller-scale, efforts are being pursued in South and Southeast Asia and Latin America (reviewed in Sivakumar and Hansen 2007).

Regional climate outlook forums (COFs) are an important means through which a seasonal climate forecast is developed in regions such as Africa. The process consists of achieving consensus on a single forecast among several individual ones and delivering this to forum participants, which may include representatives of national meteorological services and other agencies, and sector users of climate information, including agricultural producers. COFs are held on an annual or biannual basis in advance of the rainy season, with the seasonal forecast usually developed for a 90-day climate window and at national or regional scales. Forecasts are expressed in probabilistic terms, reflecting the likelihood of below-normal, normal, or above-normal rainfall. The first regional COF took place in southern Africa (the SARCOF) in 1997–1998, with the participation of 12 countries. Subsequent COFs have been developed for other subregions in Africa.

Advantages of Seasonal Climate Forecasts
The timely dissemination of a reasonably well-skilled seasonal climate forecast has the potential to improve climate risk management on a seasonal basis, through both mitigating risk during unfavorable seasons and capturing benefits during good seasons. Moreover, the process through which capacity is developed to use forecasts broadly across society could help prepare Africa and other at-risk regions to adapt to climate change, where priority management for adaptation to climate change emerges from better management of climate variability (Washington et al. 2006). Seasonal climate forecasts contribute to building a good foundation for adaptation through:

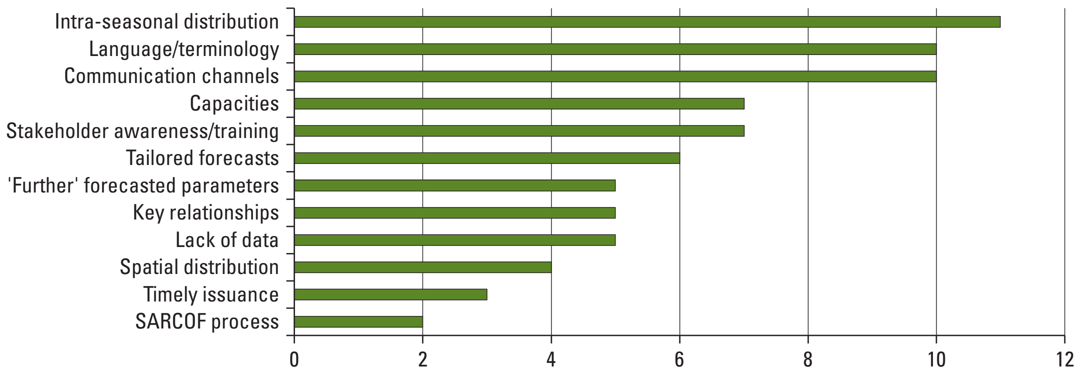
- Coordinating among formal institutions around a central task and increased potential for interactions between formal and informal institutions.
- Building communication infrastructure to support forecast dissemination.
- Educating and sensitizing the public about the probabilistic nature of seasonal climate, climate risks to society, and linkages between reducing risks and promoting development.
- Empowering rural communities and building their collective action through participation in forecast workshops.
- Better managing seasonal climate variability risk, which invites investments in soil fertility, improved varieties, and other production innovations that help production systems adapt to climate change.

Limitations of Seasonal Climate Forecasts[4]
Thus far, the science of generating seasonal climate forecasts is far ahead of its practical use, in that the capacity of end-users—such as agricultural extension, farmers, and rural nongovernmental organizations (NGOs)—to understand and respond to seasonal climate forecast information is low. However, evidence is emerging from semi-arid environments, including Zimbabwe (Patt, Suarez, and Gwata 2005), Mali (Hellmuth et al. 2007), and Burkina Faso (Roncoli et al. 2008), that efforts to translate and localize this information can positively influence farmers' decision-making processes regarding food production. While these few success stories indicate a potential benefit to smallholder producers of using seasonal climate information, the reliance on COFs as the predominant vehicle for seasonal forecast dissemination has thus far proven inadequate for reaching rural populations and being integrated into farm-level decision making (Patt, Ogallo, and Helmut 2007). The causes of lackluster dissemination and uptake include the following.

1. *Forecasts are not specific enough to the needs of end-users*. Lack of specificity in seasonal forecasts has multiple dimensions, including issues of poor spatial resolution of forecasts with respect to local-scale agricultural decision-making needs, and an absence of information about intra-seasonal rainfall distribution (the "quality" of the rainy season), as well as about climate parameters other than rainfall. Archer et al. (2007) identified these as major gaps in Southern Africa (see **Figure 4.1**). While rainfall is the chief concern for agriculture and related sectors, providing information about other climate parameters, such as relative humidity and temperature, would help countries monitor soil moisture conditions in cropping areas and protect particular commodities, such as livestock, if temperatures exceed critical thresholds. Future advances in climate downscaling using high-resolution RCMs and the development of downscaling forecast systems could help better link prediction with application at scales that decision makers need.

4 For a summary of the remedial actions and capacity building needs to address limitations, see Table 4.3.

FIGURE 4.1 Identified priority weaknesses/gaps in the climate information system of the Southern Africa Regional Climate Outlook Forum (SARCOF)



SARCOF is identified by representatives of the 12-member Southern African Development Community (SADC). The x-axis represents the response by SADC member representatives.
Source: Archer et al. 2007

Related to insufficient forecast specificity is the apparent or potential lack of relevance of seasonal climate forecasts in some situations. For example, contradictions can exist between climatologically and agronomically optimal windows for seeding crops in high-risk farming environments, with the former relying on evidence from large-scale weather and climate dynamics to determine the "safe" start of the growing season and the latter considering effects of nitrogen leaching, weed competition, pest pressure, and seedling damage from heavy precipitation in deciding when to begin cultivation (Traoré et al. 2007). Although farmers draw from multiple information sources when making production decisions related to climate forecasts, efforts to reconcile forecast recommendations with production considerations, such as through better coordination between hydromet services and NARES, could improve the utility of climate information.

2. *Coordination between forecasters and end-users is inadequate*. The top-down information flow that characterizes the COF process tends to preclude input from intended beneficiaries as to how forecasts can best be translated to address specific societal needs or how to develop knowledge packages that bundle climate predictions with information about appropriate remedial actions or other livelihood priorities (Archer et al. 2007; Patt, Ogallo, and Helmut 2007; Vogel and O'Brien 2006). Linking climate information with broader livelihood and development priorities and disseminating forecasts through multiple fora—such as where decisions are made on water, health, housing and disaster management—are proposed as an alternative to the COF model for climate information dissemination. Inadequate coordination also stems from poorly integrated government institutions, as

in situations where linkages between national meteorological/hydrological services and their putative partner institutions (extension services and national agricultural research institutions) are weak or absent, or where institutional capacity is simply inadequate to absorb forecast information.

3. *Poor interpretation and communication of forecasts lead to misunderstanding and mistrust and to low overall dissemination rates*. A poorly skilled forecast (getting the forecast wrong), while still a serious concern, is a relatively less pervasive problem than how forecasts are translated and disseminated. In southern Africa, for example, very few national meteorological/hydrological services translate their forecasts beyond English, potentially excluding important sectors of the target population from receiving and being able to use the forecasts (Archer et al. 2007). Also, the probabilistic nature of forecasting is prone to misinterpretation and confusion if probabilities are translated into deterministic statements and warnings or are otherwise manipulated, as has occurred on occasion in southern Africa.

4. *Inability to act on forecast exists*. The ability of farmers to ultimately act on climate information is circumscribed by the range of other nonclimatic factors and considerations that constitute livelihood sustainability. These include physical production factors—such as access to seeds, implements, fertilizer, labor, land, and credit, which allow farmers to make adjustments in relation to expected seasonal conditions—as well as institutional factors—such as favorable and unfavorable market signals and agricultural policies. Climate information must compete with other livelihood demands, and, while there may be sound climatological reasons for heeding a forecast, there are often equally compelling reasons not to. Bundling capacity-building efforts for seasonal climate forecast use with timely access to production inputs and nonclimate information can help lower the threshold for acting on climate forecast information.

5. *Efforts to enhance access to climate information can aggravate social inequalities*. Social tensions and inequalities lead to the exclusion of groups by gender, ethnicity, and social class from access to climate information, whether through formal forecast dissemination events or from poorly developed social networks that constrain information flows (Roncoli et al. 2008; Washington et al. 2006). To be sure, this dynamic, in which politically or economically elite groups in rural communities capture the benefits of technology, is not confined to seasonal climate information. Newly emerging methodologies for tracking the movement of technologies promoted for sustainable agriculture and the greater use of ethnographic studies could help develop creative ways for reaching marginal groups (see Chapter 3).

One way to enhance access to climate information is through the use of participatory farmer workshops designed to help farmers better understand and use seasonal climate forecasts. These workshops can improve trust and credibility of forecasts and provide an opportunity for farmers to experience repeated exposure to, and become familiar with, the concepts behind probabilistic forecasting, thus allowing better comprehension of what forecasts can and cannot do. Workshop participation has positively influenced the anticipatory behavior of participants, through broadening their perceived range of options for the coming cultivation season. The workshops also provide spillover effects to the larger community as participants share information with nonparticipants. Benefits from this participatory model can flow to researchers as well by providing them with insights into the cognitive processes through which risk is communicated and processed and the political economy of information transference in rural communities. Roncoli and others (2008) caution that the potential for a reverse learning process (farmer to researcher) to occur depends on the willingness of the latter to broaden the focus of forecast impacts beyond yield levels and the area under cultivation to include consideration of other livelihood needs that intersect with climate information.

Participatory farmer workshops on seasonal climate forecasts are at an early stage in their development. Repeated exposure to probabilistic climate information is needed to build trust in the forecast, and maintaining this trust and credibility depends on regularity of meetings with stakeholders and continuity in support of these local-level initiatives for researchers and extension and farmer organizations (Patt and Gwata 2002; Roncoli 2006). Instilling a sense of trust and credibility in forecasts is needed at policymaking levels as well and could be achieved by creating opportunities for better communication between national meteorological services (or other agencies well-versed in probabilistic forecasts) and other government institutions and market intermediaries (Archer et al. 2007).

Early Warning Systems

The reach of early warning systems (EWS) has progressed significantly over the past several years and has become an important element of disaster risk-reduction planning. Some EWS initiatives are well developed, such as the U.S. Agency for International Development's Famine Early Warning System Network, while separate systems for livestock, malaria, and locusts are fairly new or still operate mostly on a pilot-scale basis. National capacity for EWS in low-income countries is low, because these countries lack basic equipment, skills, and financial resources for developing technical capacity to generate early warnings. The effects of low technical capacity are further compounded by inadequate political commitment, weak coordination, and lack of public involvement in the development and operation of EWS, which is needed in warning dissemination and response preparedness (UNISDR, 2006).

The United Nations recently commissioned a survey of EWS capacity for building a globally comprehensive EWS, comprised of better coordinated networks of existing and envisioned systems (UNISDR, 2006). In the survey, a number of technical issues for EWS were identified, which could be considered in capacity-building activities for developing regions. They include:

- Surveys of gaps and needs with respect to weather-, climate-, and water-related hazards warning systems.
- Identifying key gaps in operational forecasting and warning systems within hydromet (hydrological and meteorological) services for severe storms, flash floods, storm surges, and dust and sand storms.
- Establishing, where needed, basic meteorological EWS in countries affected by tropical cyclones.
- Enhancing data sharing and early warning exchanges at river basin units for basins that span multiple countries or territories.
- Improving coordination of existing EWS in drought monitoring centers.
- Investigating potential for developing wildland-fire-monitoring EWS, as well as for landslide monitoring in vulnerable countries.
- Identifying and implementing capacity-building programs in telecommunications and observational infrastructure for reliable and efficient delivery of warnings.
- Building technical expertise for a multi-hazard approach, not single-hazard EWS.

The capacity to respond to early warnings of disasters ultimately determines the viability of the endeavor. Fostering people-centered EWS has a distinctly different set of challenges from that of building technically sound systems. Capacity needs for people-centered EWS identified in the UN 2006 survey include:

- Acknowledging that EWS policies must be people centered in addition to being technically sound.
- Supporting communication among key actors in early warning to ensure better coordination of action.
- Supporting mechanisms for clearer authority, political responsibility and chain of command in issuing early warnings.
- Performing systematic national surveys of EWS needs, covering hazards and vulnerabilities, institutional and social factors, and existing capacities and gaps.
- Stimulating community-based risk assessment, supporting local training and informational needs, incorporating local needs and traditional knowledge in warning system design, and considering gender needs and cultural diversity.
- Engaging the media.
- Supporting a multi-hazard approach.

TABLE 4.3 Considerations for policy and institutional capacity building to improve the generation and dissemination of seasonal climate forecasts for agriculture

Issue/Challenge	Remedial Actions	Capacity-Building Needs
Improve forecast skill/quality	Prioritize collections of data on poorly understood climate processes. Enhance integration of GCM output with environmental monitoring data sets. Develop capacity for modeling crop-livestock systems and whole-farm processes.	Promote efforts to collect field-level data that could improve modeling capacity, such as is done through the African Monsoon Multidisciplinary Analysis. Improve national-level education and training, and enhance north–south research linkages.
	Address the deterioration of infrastructure for meteorological data collection and reporting to observational networks. Promote data rescue.	Provide support for increasing the density of stations in poorly covered areas. Assess options for addressing routine failures in data transmission to the WMO. Provide support for digitizing historical climate data.
Forecasts lack sufficient specificity for end-user needs	Expand the range of climate parameters in seasonal forecasts. Expand the capacity of seasonal climate prediction to include intra-seasonal variability. Assess scope for improving downscaling and GCM uncertainty in developing regions.	Provide more land-surface data collection to improve accuracy of climate models. Provide education and training. Provide support for regional climate "nodes of excellence" that could provide downscaled data to countries in region.
	Enhance bottom-up communication of end-user climate information needs.	Encourage linkages between hydromet services and other government and rural institutions that serve rural communities.
Inadequate coordination and communication between climate forecast and end-users communities	Promote avenues for communicating end-user needs to climate modelers and national hydromet services. Improve functional linkages between hydromet services and agricultural research/extension institutions. Better engage nontraditional stakeholders (commodity boards, market intermediaries) in seasonal climate forecast communication. Expand scope for integrating climate information into other well-established information pathways.	Improve the capacity (skills and equipment) of national hydromet services to support the needs of both regional climate-forecasting networks and internal stakeholders. Investigate opportunities to better integrate forecast transference within efforts to improve general coordination among government agencies. Develop weather/climate capacity of agricultural extension through education efforts on probabilistic forecasts. Translate seasonal climate forecasts into local languages.

(*Continued*)

TABLE 4.3 (*Continued*)

Issue/Challenge	Remedial Actions	Capacity-Building Needs
Poor comprehension of forecasts by end-users	Expand number of languages in which forecast information broadcasted. Educate media about probabilistic forecasts. Expand opportunities for farmer participatory workshops on climate, and support the institutions that can maintain continuity with stakeholder communities. Provide other dissemination pathways to rural communities.	Promote better training of extension. Provide support for formal and informal institutional efforts to maintain continuity with stakeholder communities. Expand support for FM community radio initiatives to reach remote and resource poor communities.
Inability to act on forecasts	*For government level:* Improve coordination between meteorological and agriculture services. *For local level:* Bundle forecast information with management options for acting on the forecast, including timely access by rural communities to seeds, inputs, and credit.	Develop policies and measures that encourage opportunities for integrating climate forecast information into interagency coordination efforts. Improve ability of institutions to protect commodities from heat stress.

The skills and knowledge gained through developing better EWS for near-term climate risk management can bolster efforts to reduce vulnerability to medium- and long-term climate impacts. This can occur through the use of EWS in promoting and contributing to self-learning about hazard avoidance in affected areas, sensitization about future climate risk that can aid local-level decision making, and pointing to where wide-ranging structural and non-structural risk management measures are needed. Climate change projections can further assist long-term EWS planning by providing information about future risks that can be used to determine where to place additional resources. In some cases, the EWS themselves may need to change as climate characteristics change.

Conclusions

- Advances in AOGCMs and downscaling of GCMs for RCMs have reduced uncertainty around trends in temperature rise; significant uncertainties in regional precipitation trends remain, despite good model agreement for drying trends in the subtropics.
- Regional downscaling of GCMs is a powerful tool for adaptation planning, although it is important to understanding its limitations as well as its potential to complement other decision-making processes for assessing impacts, vulnerability, and adaptation.
- Several types of scenario-generating approaches exist for decadal planning horizons that can be tailored to country- and sector-specific capabilities and needs. Entry- and

intermediate-level methods are appropriate for most planned adaptation activities in agriculture. Advanced-level methods can support long-range planning needs. Future refinement of RCMs, combined with national capacity building, can improve access to advanced-level methods in developing countries.

- Seasonal climate forecasting offers good potential to aid decision making for climate risk management at the district and local levels. However, achieving a meaningful level of forecast adoption by farmers will require greater support for participatory farmer workshops that build trust and forecast credibility, improvement of linkages between hydromet services and agriculture research and extension, and integration of climate forecast information into existing knowledge dissemination platforms.
- Farmers' capacity to use seasonal climate forecast information depends on timely and adequate access to inputs. Building public support for seasonal forecasting and other climate information will need to be comprehensive and not rely solely on information.
- Policies and activities associated with seasonal climate forecasts—including institutional coordination, improvements in communication infrastructure, climate sensitization by the public, and better farm-level decision making—contribute to building a good foundation for adaptation.
- Effective development and operation of EWS require building both technical and human capacity, as well as political commitment, effective coordination, and people-centered policies.

CHAPTER 5: WATER

SUMMARY: This chapter discusses the water management challenges confronting agriculture in the context of climate change. It also examines major adaptation options for rainfed and irrigated systems that may face water shortages, as well as for risk reduction of rural communities and agricultural systems situated in flood-prone areas. The rainfed agriculture section focuses on capacity-building and investment needs for rainwater harvesting systems, from low-cost microcatchments up to macrocatchments with supplemental irrigation. The irrigated agriculture section examines adaptation-relevant issues in irrigation policies, water productivity, improved water management in irrigated rice systems, use of marginal water sources, and expansion of irrigation. The final section focuses on vulnerability and adaptation of agriculture in flood-prone areas.

I. Climate Change and Agricultural Water Management Planning

Temperature rise, changes in runoff volumes, and an increased frequency and severity of extreme events with climate change are likely to exert severe pressure on agriculture's water supply. Future water resource availability for agriculture could be further constrained by the increasing urbanization and industrialization of society. Agriculture—which currently accounts for three-quarters of water withdrawals in developing regions and has a lower economic value of water compared with industry, mining, and domestic supply—will face increasing pressure to share water resources. (See Chapter 2 for a review of projected climate change impacts on water resources by region.)

Given the combination of agriculture's large footprint in regional water budgets and the expected impacts on water resources caused by climate change, planning for agriculture's future water needs will require more than simply investing in more infrastructure to meet demand; rather, policies and measures will need to be put in place to improve water productivity, reduce water losses from irrigation delivery infrastructure, and reconfigure production systems to accommodate the use of marginal water sources. Integrated water resource management (IWRM) approaches will take on greater importance as societies seek to assess trade-offs in water resource use and meet multiple objectives of environmental sustainability, economic efficiency, and social equity. The IPCC's Fourth Assessment Report (Kundzewicz et al. 2007) identified the need for basic data gathering on geophysical, hydrometeorological, and environmental components and knowledge generation about social, cultural, and economic values as important for bringing adaptation considerations into IWRM planning processes. Additional measures to improve the effectiveness of IWRM efforts include building the capacity of transboundary institutions to develop, implement, and enforce relevant policies for water resource allocation; better inter-ministerial coordination of water management; improving existing communication systems; establishing training curricula; and developing joint learning processes between local water users and technical experts.

The challenges presented by climate change will require significant adjustments in the way that water is captured and utilized for food production, especially in dryland areas that currently support rainfed agriculture. In some of these areas, absolute shortages of water in the future could simply render agriculture unviable or propel a shift toward less reliance on annual crop production and more on perennial and livestock-based production systems. In other areas, adaptation measures to capture and conserve more rainfall use drought-tolerant crops and supplementary irrigation, which, when combined with livelihood diversification, could moderate some of the expected negative effects of climate change.

Many commonalities exist between the adaptation issues confronting rainfed and irrigated agriculture in that both systems need to:

- Improve water productivity[1] (more crop per drop) to better cope with potentially lower soil water supply and higher evaporative demand.
- Protect the soil resource base through soil and water conservation measures to reduce evaporation and protect soils against increased erosion potential caused by high-intensity rainfall and aridification.
- Improve resilience of crops to projected increases in biotic stresses, including those such as weeds and root diseases that directly diminish the ability of the root system to access soil water reserves.
- Adopt new varieties or switch to different crops that are more tolerant of heat and moisture stress.

Rainfed and irrigated systems diverge in their respective adaptation needs to the extent that:

- Rainfed systems are more sensitive to variability in seasonal rainfall.
- Rural infrastructure and markets are generally weaker and the magnitude of poverty greater in rainfed agriculture.
- Irrigated systems, if not properly managed, face serious resource degradation issues related to salinity and waterlogging.
- Irrigated systems in some regions will need to adapt to lower quality water sources or drastically improve efficiency.

II. Rainfed Agriculture and Adaptation

Rainfed agriculture produces between 60 and 70 percent of the world's total food, and, in 80 percent of the world's

1 The term "water productivity" in this report is defined in terms of the ratio of economic biomass over the amount of water received by irrigation and rainfall plus the amount lost through evapotranspiration.

countries, accounts for more than 60 percent of production. These systems tend to be associated with poverty and low rates of development due to chronically low yields and high volatility in inter-annual production levels—problems that are reinforced by poor markets, rural infrastructure, and land degradation. The expected increase in temperatures and seasonal rainfall variability with climate change will further compound the difficulty of managing rainfall and could lead to greater risk of crop failure.

Development policies in the agriculture and water management sectors have largely neglected the needs of rainfed agriculture over the past several decades, relative to the policy support provided to high-potential irrigated areas. This underinvestment has contributed to an adaptation deficit, especially in dryland areas. (See Chapter 3 for a discussion of the adaptation deficit.) In considering future climate change risks, development policies for these areas should be aimed at increasing flexibility in farming and nonfarming livelihood sources, and in production systems, by targeting policies at whole farming systems rather than at particular crops. A recently implemented World Bank adaptation project in Andhra Pradesh (see **Box 5.1**) illustrates this approach.[2]

2 The topics discussed in Box 5.1 are covered in various chapters of this report. This chapter focuses on rainwater harvesting; other chapters cover topics of soil erosion control and integrated soil fertility management (Chapter 6), livestock (Chapter 6), seed production (Chapter 7), and diversification into high-value crops (Chapter 9).

Rainfed Crop Production and Risks from Seasonal Climate Variability

Moisture limitations resulting in chronically low crop productivity in rainfed cropping systems are generally attributed to poor seasonal distribution of rainfall with respect to sensitive crop growth stages and to low utilization of incident rainfall by the crop rather than to absolute water shortages. In semi-arid rainfed cropping systems, productive water use, represented as green water flows in **Figure 5.1**, is quite low, averaging 10 to 30 percent of total rainfall. In addition, ephemeral dry spells that occur during crop reproductive growth are an important source of the yield gap. Barron and others (2003), in an analysis of 20 years of rainfall data from a semi-arid maize area in eastern Africa, estimated that in nearly three-quarters of the growing seasons, dry spells that occurred during sensitive growth stages were of sufficient duration (around 15 days) to cause significant maize yield reductions. In some cases, yield loss was up to 75 percent. Increased seasonal rainfall variability (including longer dry spells between rains) and higher temperatures that increase evaporative losses from the system are very likely to occur under future climate change, thus magnifying current risks in rainfed crop production. These kinds of risks could even occur in areas where mean annual precipitation increases.

Despite the challenges confronting rainfed agriculture, there is good potential to improve yields through enhanced water productivity arising from rainwater harvesting, improved

Box 5.1

DROUGHT ADAPTATION STRATEGIES AND RURAL LIVELIHOOD OPTIONS FOR RAINFED AGRICULTURE IN ANDHRA PRADESH, INDIA

Andhra Pradesh is highly dependent on the monsoon rains and is prone to widespread drought during years when the monsoon fails. The potential for climate change to bring increased variability of the monsoon, along with projected warming of around 3°C by the end of the century, is expected to exacerbate risks of chronic water scarcity and drought conditions. Better managing drought risks is therefore a pressing need for current development as well as for adapting to future climate change. The World Bank's *Andhra Pradesh Drought Adaptation Initiative (APDAI)* project is designed to address this threat by bringing a climate risk focus to agriculturally based natural resource management and rural economic diversification efforts.

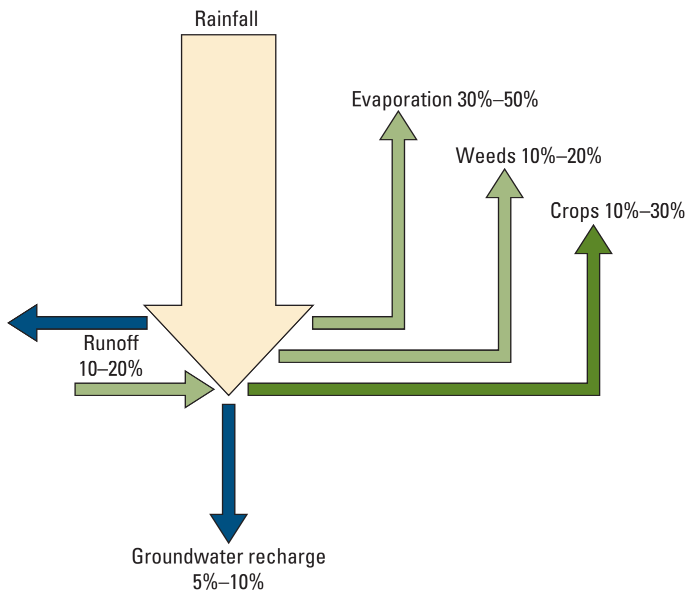
The central strategic approach of the APDAI for drought adaptation planning involves lowering production costs through internalizing inputs to the farming system that minimize financial risks; diversifying farming systems to make them more resilient to drought shocks; and reducing covariant risks, such as pests and diseases, that constrain food production. The project has developed a range of potential interventions for enhancing drought risk management, including:

- Integrated soil fertility management.
- Crop diversification into vegetable, fodder crops, and flowers.
- Water harvesting and erosion control through contour planting, farm ponds, and construction of bunds.
- Livestock integration into farming systems through backyard poultry, improved veterinary care, livestock marketing, and fodder tree plantations.
- Seed production, including community managed seed banks and seed marketing.
- Community resource planning that addresses groundwater supply issues through resource collectivization and rehabilitation of common lands.

The ADPAI is being implemented in two phases. The recently completed Phase I primarily consisted of 19 drought adaptation pilot projects, which have been developed into a comprehensive package of measures for Phase II. The second phase aims to further scale up these efforts and mainstream them into government operations, including watershed development planning and livestock management programs.

soil fertility management, and soil conservation practices. The adoption of these practices can improve the ability of farmers to better manage risks associated with seasonal climate variability and, in so doing, narrow the adaptation deficit. The scope for positive nonlinear growth in crop production with increased water productivity is good for low-yielding cereal systems (see **Figure 5.2**). Indeed, over the past decade, impressive

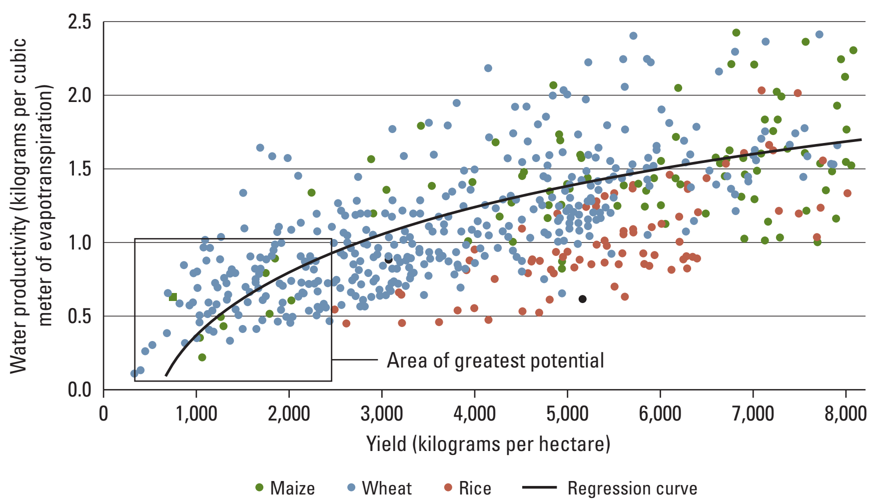
FIGURE 5.1 Typical partitioning of rainfall for a rainfed crop in a warm semi-arid environment



The dark green line represents the portion of total rainfall that the crop uses; the light green lines represent potential sources of productive green water for crop use; and the blue line represents the blue water resource for surface and ground water.

Source: Adapted from Hatibu and Rockström (2005).

FIGURE 5.2 Relationship between water productivity and cereal yields



Water productivity increases quickly at low yields and levels off at high yields.

Source: Gurib-Fakim et al. 2008, adapted from Zwart and Bastiaanssen, 2004

gains in water productivity and yield have been secured in rainfed systems through the use of soil and water conservation practices, as documented in **Table 5.1**.

Rainwater Harvesting

Rainwater harvesting (RWH) describes a range of different techniques and practices that increase the physical

TABLE 5.1 Change in water productivity by major crop type from adoption of sustainable agriculture technologies and practices
n = number of projects surveyed

Crop	Increase in Water Productivity (%)
Irrigated	
Rice (*n* = 18)	15.5
Cotton (*n* = 8)	29.4
Rainfed	
Cereals (*n* = 80)	70.2
Legumes (*n* = 19)	102.3
Roots and tubers (*n* = 14)	107.5

Source: Pretty et al. 2006

capacity to collect, store, and conserve surface runoff, which can be directly stored in the soil profile for use by the crop (in situ RWH) or diverted into holding structures for subsequent use through supplemental irrigation.

Better capture and utilization of rainfall through RWH is a priority issue for enhancing climate risk management in semi-arid and dry subhumid rainfed agriculture areas and will thus better position these systems to adapt to climate change. In addition to the obvious benefit of higher yields, better managing rainfall also decreases the inter-annual volatility of production levels, which is important for stimulating growth in agriculturally based economies that can then produce development outcomes that allow for a greater range of options for future adaptation (as described in **Box 5.2**).

In-situ RWH practices capture surface flow and concentrate runoff through such methods as bunding with stones along contour lines and in semicircles, contour ridge tillage, and small dug pits to break surface crusts and capture rainwater. Simple diversionary methods of RWH can significantly improve the ability to manage rainfall for higher yields. For example, Reij, Tappan, and Belemvire (2005) attributed the revived use of planting pits in Burkina Faso, starting in the mid-1980s, as critical to stemming cereal yield declines during low rainfall periods; similarly, contour ridge tillage in Mali significantly increased cereal yields, particularly in dry years (Traoré et al. 2004). In both cases, the use of these microcatchment methods increased the survival of field tree and perennial grasses planted within the catchment area, thus further enhancing the land rehabilitation effect. Microcatchment methods can also be applied to rangelands. In Syria, the presence of contour bunding enhanced the survival rate and growth of agroforestry shrubs and trees, providing a reliable source of animal fodder on what were otherwise marginally productive grazing lands (Oweis and Hachum 2006). Conservation tillage practices such as zero tillage using direct seed drilling, subsurface tillage, tied ridges, and crop residue retention also essentially function as a form of RWH. (For further discussion of conservation tillage, see Chapter 6.)

Box 5.2

RAINWATER HARVESTING AND CLIMATE RISK MANAGEMENT IN ZIMBABWE: IMPLICATIONS FOR ADAPTATION

Changing perceptions of RWH and drought management among policy makers in Zimbabwe has increased the visibility and viability of RWH in drought-prone areas. Previously, policy makers did not recognize runoff as a drought management resource, preferring instead to divert "hazardous" runoff away from cropland, but, with the introduction of RWH technologies, this has begun to change. Although adoption rates of RWH technologies remain relatively low, those who have adopted the technologies in northern Zimbabwe are realizing significant improvements in productivity and in household economic security. Farmers have adopted a range of techniques from simple infiltration pits to tied ridges and macrocatchments. The benefits accruing from RWH have led farmers to introduce new varieties and improved tillage methods and to diversify into high-value fruit and vegetable crops. The extra income has allowed adopter families to pay school fees and invest in livestock. Implementation bottlenecks associated with labor costs and equipment shortages have been partially overcome through the formation of labor clubs.

The process through which RWH is transforming these systems—exposure to technology and knowledge gained in the technology adoption process, increased interactions with nongovernmental organizations (NGOs), the increase in social capital through the pooling of resources, the intensification of production systems, and the building up of assets—improves the ability to manage current climate risks. Moreover, technologies to increase rainwater capture, diversify cropping systems away from sole reliance on maize, and encourage irrigation are appropriate for adaptation in maize-based systems in southern Africa, a region that is projected to become drier with climate change.

Source: Mutekwa and Kusangaya 2006

How Does in Situ RWH Help Support Climate Risk Management?

- Increased soil water retention better bridges the periods between rainfall events, which are projected to increase with climate change.
- Promotion of ancillary benefits, such as agroforestry trees and perennial grasses, provide livelihood resources and help rehabilitate degraded soils.
- Decreased soil erosion and runoff from in situ RWH decreases land degradation and flood risks, both of which will likely increase with climate change.
- Increased soil moisture retention reduces crop moisture stress at critical plant growth stages.
- Stabilization of and increases in yields can lead to other land improvement investments and livelihood diversification

activities that bolster adaptive capacity, as long as there are adequate markets to stimulate these investments.

Macrocatchments and Supplemental Irrigation More complex RWH systems include those that use macrocatchments to channel storm water surges from gullies or ephemeral streams into crop- or pastureland. One innovative use of macrocatchment systems involves channeling road drainage onto fields, which, if done properly, can provide a means for protecting road infrastructure from flash flooding while providing water for agriculture (described by Hatibu et al. 2006). Catchment systems can be further improved through the construction of diversionary storage ponds for supplemental irrigation. While more expensive and labor intensive, the return on investment can be high, because catchment systems can provide a reliable supply of water at critical plant growth stages. Indeed, the use of RWH with supplemental irrigation, in conjunction with small fertilizer doses, can increase cereal yields tremendously, as Fox and Rockström (2003) demonstrated in Burkina Faso, where the bridging of dry spells with irrigation and higher soil fertility tripled cereal yields. This study is useful for demonstrating how current technologies can be better deployed to unlock the yield potential in high-risk rainfed environments. However, these are relatively complex and expensive methods for rainfed cereal systems in Africa and are thus unlikely to be economically feasible without significant improvements in underlying socioeconomic conditions.

RWH with supplemental irrigation can be viable in cereal and legume systems where there is adequate technical support and linkages to markets. For example, supplemental irrigation methods are being increasingly adopted in the Loess Plateau region of northwest China for rainfed field crops (Xiaoyan et al. 2002) and are being promoted in West Asia to improve rainfed wheat production. The amount of supplemental irrigation needed to significantly boost production is not large; rather, it is the access to supplemental irrigation during sensitive crop growth stages (flowering and grain filling) that is critical. In the case of wheat production in Syria, 150 to just over 200 millimeters of supplemental irrigation were sufficient to increase yields two- to fourfold, with the larger increase occurring in dry years. Supplemental irrigation also decreased the coefficient of yield variation by four-fifths (Oweis and Hachum 2006). Careful consideration is needed to ascertain whether coverage by macrocatchments is sufficient to meet the irrigation needs of the surrounding area and whether conditions are conducive to tailoring the cropping system to the water source, such as through prioritizing production of high-value crops adjacent to the catchments. Also, access to climate change projections is needed to determine whether such investments would be resilient under future climatic conditions.

How Does Macrocatchment RWH Help Support Climate Risk Management?

- Use of supplemental irrigation during critical crop growth periods substantially reduces risk of crop loss or failure from inadequate or untimely rains, a situation that is projected to increase with climate change.
- A reliable water supply improves the ability to diversify into high-value crop production and thus reduce reliance on climate-sensitive rainfed agriculture.

What Capacity-Building and Investment Needs Are Necessary to Spur Adoption of RWH?

- Addressing technical components, such as liners to reduce seepage of stored rainwater and foot pumps, as well as addressing access to crop varieties that resist lodging. The first two could be achieved through developing the private-sector and more reliable input markets and the latter through crop breeding and varietal dissemination.
- Reducing socioeconomic barriers to adoption by supporting rural finance, including social fund financing and local credit systems, community-based management through forming cooperatives, village labor and water-user organizations that can initiate cost-sharing and labor-saving measures, and local organizations for governing the resource.
- Enhancing education and outreach programs to farmers that address deficit irrigation and RWH benefits through support for local NGOs and farmer networks and developing tailored programs for female farmers.
- Improving the performance of linkages among research, extension, and NGOs.
- Upgrading road-drainage systems for better market linkages and designing roads to serve runoff catchment needs.
- Developing or improving market potential for high-value crops that could become more prominent with the use of catchment irrigation systems.
- Integrating human health issues into macrocatchment planning. The malaria risk has been shown to increase where surface water impoundment is introduced, an important consideration give that where the range and activity of the vector and parasite are expected to increase with climate change.
- Building capacity for climate and hydrologic modeling to estimate potential negative downstream impacts from scaling up of RWH and promoting policy dialogue between the government and upstream and downstream water users.
- Improving farmer access to animal traction and conservation tillage equipment, including ridgers and subsoilers, through credit and shared-cost programs for lease or purchase.
- Improving private-sector capacity to supply input markets.
- Packaging RWH efforts with other technologies, such as short-duration varieties,

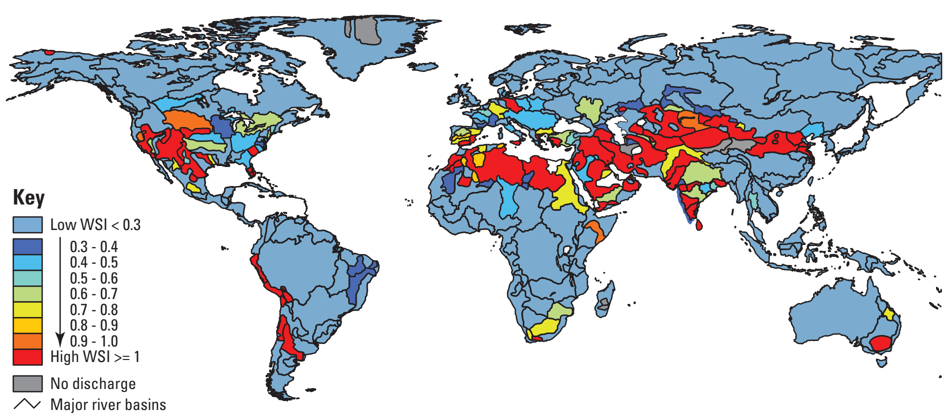
and improving local access to long-range weather and seasonal climate forecasts (see Chapter 4).

- Supporting policies for land tenure security and local resource ownership.
- Supporting local institutions that encourage labor pooling through the formation of farmer organizations and other local level collective actions (see Chapter 3).

III. Irrigated Agriculture and Adaptation

The reliance on irrigation in its current configuration will be difficult to sustain because of large-scale over-appropriation of water for irrigation (which accounts for approximately three-quarters of water withdrawals in the developing world), widespread degradation of soils in irrigated areas from waterlogging and salinity, increasing demographic pressures, and competition from industrial sources as societies develop. Higher temperatures, more variable precipitation, and increased salinization risk resulting from climate change will further exacerbate these problems, particularly in areas where unsustainable extraction of irrigation for agriculture is widespread, such as the Middle East and North Africa, Central and South Asia, and northern China (**Figure 5.3**). Salinity and waterlogging pose major constraints to the world's irrigated lands, 20 percent of which are salt affected, with about half of all irrigation schemes susceptible to salinization. These problems are widespread in irrigated production systems that have high regional importance for food security, such as in the rice-wheat system of the Indo-Gangetic Plain (7 million hectares are salt affected) and in some agricultural areas in the Aral Sea Basin, which are estimated to lose 10 to 15 percent of their

FIGURE 5.3 Water withdrawal in relation to water availability



Water scarcity index values >0.7 (yellow, orange, and red areas) indicate over-appropriation relative to total availability of the resource.
Source: Falkenmark and Rockström 2006

land area per year to salinization (World Bank, 2006a).

Developing more sustainable irrigation systems is crucial for adapting to climate change, meeting future food demands in fast-growing regions, and maintaining irrigated agriculture's role as a major driver of economic growth in the agricultural sector. Potential entry points for promoting more sustainable irrigation management that would bolster adaptation efforts include:

1. Reformulating irrigation policies.
2. Engaging water users.
3. Enhancing water productivity.
4. Improving water management in irrigated rice systems.
5. Expanding the economic and environmental viability of marginal water sources.
6. Expanding the area under irrigation.

Many of these measures are needed—even in the absence of anticipated climate change impacts—in response to unsustainable water allocation rates for agriculture and from competition for freshwater to meet human consumption needs in rapidly growing water-scarce regions. Climate change will further aggravate these existing pressures on agriculture. The additional adaptation element principally stems from the need to facilitate broad-scale and rapid scaling up of sustainable irrigation practices and technologies. This will require simultaneous and complementary investments and capacity building in infrastructural improvements, water policies, and water productivity/conservation, as well as prioritizing these efforts to systems that are expected to be highly vulnerable to climate change. A recent World Bank adaptation project in China's 3H River Basin is one of the first to address adaptation issues in an intensively managed irrigated system and illustrates some of the key issues (**Box 5.3**).

Reformulating Irrigation Policies to Address Distortions in Water Use

Irrigation policy failures have contributed to overuse of water resources and degradation of the resource base, both of which have increased vulnerability to climate change. These policy failures have been most apparent in South and Central Asia and China, which account for the bulk of the world's groundwater withdrawal for irrigated agriculture. Implementing policy reforms targeted at inappropriate energy pricing policies for irrigation water pumping, property rights for ground- and surface-water use, and environmental externalities that have arisen from excess irrigation take on an added urgency in considering expected impacts of climate change and population growth.

Policy reform measures that push the cost of irrigation water closer to its shadow price can increase the incentives to switch to water-conserving practices or to crops with less water demand. Areas in which policy

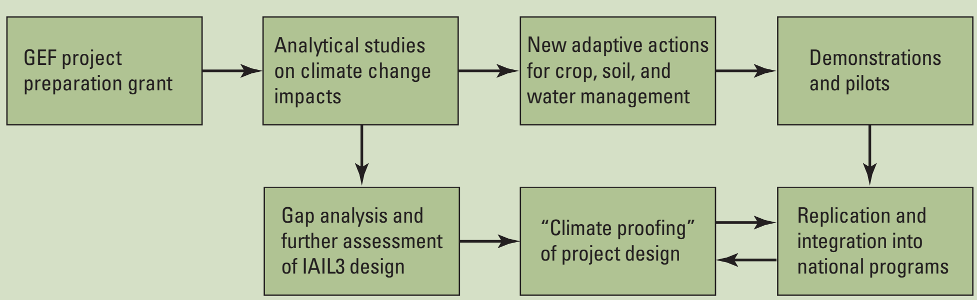
Box 5.3

ADAPTATION PLANNING FOR IRRIGATED AGRICULTURE IN CHINA

Agriculture in northern China's Huang-Huai-Hai (3H) River Basin is an important concern as China begins to grapple with potential negative impacts from climate change on its food production systems. The 3H Basin produces half of China's grain, and yet it faces significant challenges caused by a recent increase in the frequency and intensity of droughts and flooding, stagnant grain production, and water resources that are fully allocated and often overexploited. Temperatures in the region are projected to increase by 2°C by mid-century, placing a significant additional burden on water availability and crop productivity.

In response to this anticipated threat, the World Bank recently initiated a Global Environment Facility (GEF)-funded project (*Mainstreaming Climate Change Adaptation in Irrigated Agriculture*) to introduce climate change adaptation concepts and measures into the Irrigated Agriculture Intensification Project III (IAIL3) as shown in the accompanying diagram. The IAIL3 is a comprehensive initiative to modernize irrigated agriculture throughout many areas in China, including the 3H Basin. The aims of the GEF adaptation project are:

- Identification and prioritization of adaptation options through a climate change impact assessment using integrated hydrologic, agronomic, economic, and climate models; gap analysis of potential climate change sensitivities in the IAIL3 design; and a selection of adaptation options at the local scale.
- Implementation of pilot-scale adaptation measures, including water-conserving irrigation and drainage practices, deep plowing, improved fertilizer management, introduction of crop varieties suited to warmer and drier conditions, and capacity building of water-user and farmer associations. The pilot actions target areas with different vulnerabilities, including severe groundwater depletion, high inter-annual climate variability, and high dependence on surface water and groundwater irrigation.
- Mainstreaming of adaptation into national agriculture planning through the development of an adaptation action plan and awareness raising aimed at all levels, including national and local levels.



reform can help support adaptation include:

- Changing irrigation water pricing from a temporal to a volumetric basis, as was recommended in an adaptation assessment for Bangladesh (FAO 2006).
- Prioritizing irrigation policy reform efforts toward agroecosystems where sensitivity to drought is high. For example, irrigation costs for paddy rice in groundwater-stressed Tamil Nadul and northern Gugarat are two to three times less than in areas of eastern India, which receive more rainfall and have relatively well-endowed groundwater resources (Alauddin and Quiggen 2008).
- Phasing out incentives for rice production in soils that are highly permeable and have high leaching losses, such as the northwest Indo-Gangetic Plain, in order to promote better climate proofing of irrigation investments (Humphreys et al. 2005).
- Redirecting subsidies from energy use to water-saving technologies.
- Building capacity to integrate climate change scenarios into water resource policy planning (see the discussion on scenario generation in Chapter 4).

Engaging Water Users and Local Communities—Water-User Associations and Adaptation

Policies that provide well-defined property rights to water-user associations[3] (WUAs) or other local entities can help promote greater local accountability over resource use and provide better incentives for collective action to innovate than would be possible with centralized decision making. For example, WUA participation is critical to overcoming problems of water service inequity and unreliability, which is needed to help induce farmers to invest in the types of productivity innovations needed for adaptation, such as improved crops, water conservation, and soil fertility maintenance.

In the Indian context, for example, WUAs have been viewed as central to participatory irrigation management strategies for coping with population growth, climate change, and water resource degradation (Mazumdar 2007). Their joint collaboration with the government in irrigation water management has the potential to allow for greater flexibility over resource use between regions and irrigation systems. Flexibility that leads to locally appropriate technical innovations and water conservation can enhance adaptive capacity. Moreover, the interaction of WUAs with formal institutions opens up information and knowledge transmission channels between rural communities and the government that could enhance local decision making with respect to climate change impacts and adaptation. For seasonal climate risk management, WUAs can serve as a hub for receiving and transmitting seasonal climate forecasting and projections of seasonal water supplies in order to help farmers plan for appropriate planting densities and irrigation water use.

3 A water-user association (WUA) is a group of water users, such as irrigation users, who pool their financial, technical, material, and human resources for the operation and maintenance of a water system.

Capacity Building for WUAs The World Bank Participation Sourcebook provides a set of indicators for the institutional strength of community organizations that would have relevance to WUA capacity-building needs. Indicators include the ability to control and audit fund use, administrative capability, and technical capacity of the organization, including education, availability of special courses, and training of leaders and members. Additional measures or opportunities with respect to adaptation include:

- Climate change education campaigns.
- Targeting of seasonal climate forecasts to WUAs and conveying forecast information from them to the broader community.
- Mechanisms to encourage the participation of marginalized groups in WUAs.
- Assessing the potential for comparable capacity building of analogues to WUAs (farmer organizations, cooperatives) in regions where WUAs do not exist, such as in Africa.

Enhancing Water Productivity in Irrigated Systems

Gains in water productivity can be achieved through improved management of crop biotic and abiotic stresses; modernization of existing irrigation systems to reduce water loss; and adoption of technologies and practices that use less water, such as drip, furrow, and deficit irrigation. Increasing water productivity is important for reducing:

- Crop moisture stress, where supplies of freshwater could diminish as a result of climate change.
- Negative impacts on crops and soils, where reliance on marginal-quality water sources will become more prevalent with climate change (as subsequently discussed later in this chapter in section 5).
- Agricultural water withdrawals in water-scarce regions facing greater conservation challenges.

Crop Stress Management Low water productivity, in both irrigated and rainfed systems, results from poor matching of crop genotypes to water regimes, excessive pest and weed pressure, and poor soil fertility and structure. Integrated strategies to address these multiple stressors not only improve water productivity, but also enhance the resiliency to the cropping system of other threats associated with climate change, such as increased soil erosion risk and greater pest pressure. (These issues are treated separately in Chapters 6 and 8, respectively.)

Very good potential exists to increase water productivity using existing technologies for nutrient management, crop breeding, and reduced tillage. For example, a significant amount of recent research has gone into improving water productivity in irrigated rice-wheat rotation areas of South Asia and China, through technologies such as direct drilling of seed, raised beds with furrow irrigation rather than flood irrigation, aerobic rice production, stubble mulching, site-specific nutrient management, improved germplasm, zero tillage, integrated pest management, and irrigation scheduling (Humphreys et al. 2005). Adoption of some of these technologies, particularly zero tillage and direct seed drilling, has been rapid in highly mechanized production systems of northwestern India and Pakistan. Their adoption has reduced irrigated water consumption in wheat production by one-third, representing large water savings given the scale of wheat production in South Asia. It has also allowed farmers to plant wheat earlier, thus avoiding late-season heat stress. In addition, increased retention of organic matter in soils improves resilience against erosion.

India's Punjab region, where technology adoption rates are greatest, is well developed relative to the rest of the region, while in less affluent areas, the barriers to adoption are significant. These barriers (whether in the current example of South Asia or elsewhere) can be lessened through:

- Community-based extension programs and policies to develop stronger linkages between national agricultural research systems and extension and locally based NGOs.
- Credit and cost-sharing programs with farmer organizations that encourage group investments in technologies.
- Improvements in the seed sector that enhance farmer access to improved varieties (see Chapter 7).
- Investments in input markets for conservation tillage equipment through private sector development.
- Programs to improve the potential for off-farm income generation that can then provide the means for reinvesting into on-farm production improvements.
- Basic investments in research, extension, and education.[4]

Modernization of Irrigation Systems

Modernization can reduce water loss and improve the performance of irrigated systems in a manner that reinforces water conservation. Approximately half of agricultural water withdrawals for irrigation are lost through the irrigation infrastructure as leakage and/or through evaporation from irrigation canals and pipes. Higher evaporation rates from temperature rise are likely to exacerbate evaporative water loss from irrigation delivery infrastructure. In addition, poor service delivery and high maintenance costs associated with outdated irrigation infrastructure can impede farmer adoption of productivity innovations that better adapt irrigated agriculture to climate change, such as diversifying to crops with variable water demand.

Modernizing irrigation systems requires an integrated approach that considers physical improvements to water extraction and

4 South Asia, the most irrigation-dependent region in the world, currently has one of the lowest agriculture research intensities in Asia, with public agricultural research investment in India and Pakistan half as much, and Bangladesh a quarter as much, as that of Thailand, Malaysia, and Taiwan (Alauddin and Quiggin 2008).

delivery "hardware," as well as improvements in crop water management and institutional changes that address the underlying causes of infrastructure deterioration. Appropriate institutional measures center on creating a more demand-responsive irrigation delivery system through encouraging public–private partnerships, promotion of decentralization, and agency accountability. In addition, measures to modernize infrastructure include lining canals or replacing them with pipes, variable-pressurized systems to deliver sprinkle and drip irrigation, and gates and other control structures to give farmers more control over the timing and quantity of water (World Bank 2006b).

Infrastructural improvements in drainage are also needed to address problems caused by waterlogging and the associated buildup of soil salinity. Drainage problems affect an estimated 20 to 30 million hectares of irrigated land worldwide, and these areas could be further affected by increased surface evaporation from higher temperatures that compound the negative effects of salt stress. In addition, the generally low productivity in salt-affected systems could impede efforts to adopt new technologies and diversify production systems, which would be needed for adaptation. Measures such as investing in drainage tiles and other physical means of draining waterlogged lands would help alleviate salinity stress and improve productivity. However, significant institutional and governance issues need to be addressed in order to improve the prospects for initiating drainage efforts, including:

- Integrating drainage with irrigation planning, because the two are currently viewed as separate entities and coordination is lacking.
- Building capacity of institutions responsible for drainage management to work with stakeholders under an IWRM framework.
- Developing an enabling legal framework to set up levy fees for drainage user organizations, initiate cost sharing with nonagricultural beneficiaries, and engage with the private sector.
- Address agricultural policies that externalize poor water management and fertilizer pollution, as these exacerbate the impacts of poor drainage. (World Bank, 2006b)

Despite these hurdles, investments in drainage management are more cost effective than creating new irrigation sources.

Water Conservation Technologies

Deficit irrigation Deficit irrigation is a technique that deliberately allows a crop to sustain some degree of water deficit and yield reduction. A potential adaptation measure for irrigated systems in semi-arid and arid areas would be to switch irrigation practices from the current practice of full irrigation to deficit irrigation in order to cope with reduced water supplies from climate change and population growth. Deficit irrigation could become important in for irrigated areas of North Africa and West Asia, which are currently water stressed and are expected to experience long-term drying trends. In these regions, "conventional water management guidelines should be revised to ensure maximum water productivity instead of land productivity" (Oweis and Hachum 2006), which could entail sustaining some yield loss while maintaining the overall integrity of irrigated production. Farmer field research in Syria has shown that deficit irrigation, in which half of full irrigation is applied, only reduced overall yields by 10 to 15 percent. In addition, adopting deficit irrigation over an entire production unit increased aggregate productivity by one-third compared with conventional practices of applying full irrigation to part of the unit.

Deficit irrigation is very knowledge intensive and adopting it as an adaptation measure will require:

- Significant research and extension to educate farmers about its appropriate use in terms of crop water demand and the timing of applied deficits vis-à-vis sensitive growth stages.
- Timely and affordable access to other production inputs—including improved seed varieties and fertilizer and pest management—to minimize the effect of other stresses on the crop.
- Crop modeling to understand how warmer temperatures with climate change affect this practice.
- Economic analysis to assess viability and determine incentives.

Drip irrigation Drip irrigation minimizes water and fertilizer use by allowing water to drip slowly to the plant roots through a network of valves, pipes, tubing, and emitters. Significant potential exists to expand drip irrigation through the use of low-cost drip irrigation (LCDI) methods. Technologies for LCDI, which cost 60 to 80 percent less than conventional drip irrigation technologies, have been developed for use in semi-arid areas of India (Sadangi 2006) and have the potential to be rapidly adopted with the right set of incentives. For example, robust uptake of this technology in Maharashtra has been due to considerable private-sector and government efforts to promote horticultural development and food processing, and because awareness of the negative environmental costs associated with large-scale irrigation projects has made microirrigation more attractive (Kulecho and Weatherhead 2006, and references therein).

The absence of these public- and private-sector enabling factors has stymied efforts to spark microirrigation elsewhere. For example, introducing LCDI technologies for horticultural crops in Kenya failed due to the lack of sustained adoption, caused by the absence of WUAs as a learning platform, poorly developed markets for irrigated crops, lack of credit for accessing LCDI technologies, and lack of RWH systems to provide reliable water supplies (Kulecho and Weatherhead 2006). In Zimbabwe, however, LCDI use has been more successful because it was implemented as a replacement for previously developed canal-based irrigation in response to increased drought. In this case, socioeconomic capacity building was viewed as equally critical to the project's success as the technical interventions. Measures included leadership training, opportunities for collective action, management principles, financial record keeping, and basic business skill development.

Drip irrigation can be a viable strategy for adaptation in that it provides a means for diversifying away from high-risk rainfed crops in water-scarce regions. (For a discussion of crop diversification, see Chapter 9.) Introducing drip irrigation as an adaptation measure will necessitate investment and capacity building to ensure robust farmer adoption of the technology through:

- Better education regarding technology costs and benefits, including capacity building for management principles, financial record keeping, and basic business skills development that improve farmer capacity to market new agricultural crops.
- Supporting the creation of WUAs, where absent.
- Extension and education for technical problem-solving measures that allow drip irrigation to be sustained.
- Credit or cost-sharing programs for purchase of drip irrigation equipment.
- Private sector capacity building in input markets for supplying drip irrigation equipment and other inputs, such as seeds and fertilizer.
- Economic assessments of output markets for high-value crops and building capacity for increased demand.
- Improving water supply reliability through support for construction of diversionary structures and holding ponds for RWH.

Improved Water Management in Rice Production

Efforts to improve water management in rice production are critical for both adaptation to climate change and mitigation of greenhouse gas emissions from rice production practices. Approximately 154 million hectares of rice are grown worldwide, of which 90 percent occurs in Asia, mostly as lowland rainfed and irrigated paddy production. Rice is sensitive to yield loss from temperature rise; for example, Peng and others (2004) estimated that rice yields decrease by about 10 percent for every 1°C rise in minimum temperatures. An increase in minimum (nighttime) temperatures can cause loss of maintenance respiration during grain filling, and increased maximum temperatures can cause spikelet sterility.

Greenhouse Gas Mitigation[5] *and Future Rice Production Trends* Future economic water scarcity in Asian rice production, caused by rapidly growing water demand from industry and urban centers, is expected to affect 15 to 20 million hectares of rice area by 2025, potentially propelling

5 For a broader discussion of the mitigation potential in agriculture, see Chapter 6.

greater adoption of water conservation technologies for rice and possibly shifts toward upland nonrice crops. Given the scale of rice production, shifts in how water is managed has important implications for greenhouse gas emissions from agriculture.

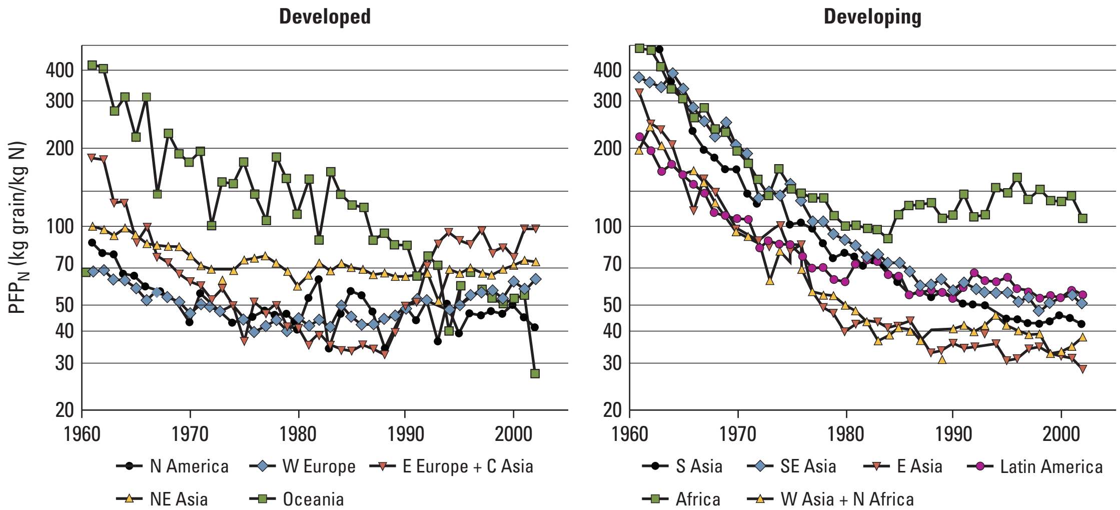
Rice production is a major source of global methane (CH_4) emissions from agriculture. Fortunately, recent changes to water management for paddy rice in East Asia, driven by increased irrigation costs, have begun to reduce CH_4 emissions. For example, over the past two decades in China, a large portion of the paddy (flooded) rice production area has shifted from being continuously flooded to being drained at mid-season, resulting in an average 40 percent reduction in CH_4 emissions and an overall improvement of yield due to better root growth and fewer unproductive panicles (DeAngelo et al. 2005). An estimated additional 20 to 60 percent reduction in rice-based CH_4 emissions in China is possible by 2020—without sacrificing yield—through additional changes in production practices and advances in plant breeding.

While these water-use changes are beneficial from the standpoint of CH_4 reductions, achieving overall net reductions in greenhouse gas emissions from rice requires careful consideration of the entire system, because the very wetting and drying practices that reduce CH_4 emissions increase nitrous oxide (N_2O) emissions. Also, diversification away from flooded rice could lead to mineralization of substantial soil carbon reserves normally protected from decomposition by flooded conditions in onsAsian monoculture rice systems (Wassmann, Butterbach-Bahl, and Dobermann 2007).

Higher rates of N_2O emissions from rice depend on the extent of rice area conversion from predominately aerobic to anaerobic production environments, which increases N_2O emissions, and the rate at which improved fertilizer management practices could be adopted to offset this expected emissions increase. Irrigated rice systems in Asia consume 8 to 9 million tons of fertilizer nitrogen (N) per year, of which 60 to 70 percent is lost to volatilization or leaching. With a per-unit global warming potential 300 times greater than that of carbon dioxide (CO_2), these losses represent a significant share of agriculture's contribution to climate change. The annual amount of N_2O emissions from fertilizer N application to rice is currently the equivalent of 100 million tons of CO_2 (Wassmann, Butterbach-Bahl, and Dobermann 2007).

Asia accounts for more than 50 percent of global fertilizer nitrogen use, its agricultural systems have diminished factor productivity for nitrogen (**Figure 5.4**), and the region faces high future fertilizer demand to meet its growing food demand. In addition to its contribution as a greenhouse gas, nitrification of the environment via anthropogenic nitrogen sources causes significant degradation of water sources, leads to loss of biodiversity, and has ancillary impacts on

FIGURE 5.4 Partial factor productivity for nitrogen (PFP_N), expressed as a unit of crop yield per unit of nitrogen input



A sharp initial decrease in PFP_N normally occurs when yields are moved along a fixed nitrogen response function, as was the case with the Green Revolution (1960–1980) in Asia (right). The continued decline in PFP_N in the post–Green Revolution is a concern given the high rates of fertilizer nitrogen use and stagnation of yields. The increase in PFP_N for Eastern Europe and Central Asia (left) and Africa (right) reflects the depletion of native soil nitrogen reserves. Stabilization of PFP_N in the developed regions reflects high levels of investment in research and extension, new fertilizer products, and management technologies.

Source: Dobermann 2006

human health,—all of which can increase a society's vulnerability to impacts from climate and other environmental changes.

Site-Specific Nutrient Management A key technology for increasing nitrogen-use efficiency is site-specific nutrient management that aims to better match nitrogen application to crop demand, using complementary additions of organic and inorganic nitrogen sources. Research on rice systems suggests that this technology can be used to both increase nitrogen-use efficiency by 30 to 40 percent and produce higher yields, thus improving the economics of production (Dobermann et al. 2002; Pampollino et al. 2007).

Complementary efforts that will help promote site-specific nutrient management, as well as sustainable and adaptive systems more generally, include:

- Breeding for stress tolerance in modern cultivars and improving management of production factors other than nitrogen.
- Supporting investments in research, soil and plant nutrition testing facilities, and extension servicess that facilitate scaling up of nitrogen-use efficient technologies.
- Raising public awareness about the problem, possibly through using public awareness campaigns similar to those currently being used in Southeast Asia to reduce unnecessary pesticide application in rice.
- Promoting policies to modify fertilizer subsidies where input overuse is prevalent.

The need to improve nitrogen-use efficiency and reduce nitrogen leakage from agricultural systems applies to a range of production systems in the developed and developing world and is not confined to rice production. (For a broader discussion of the mitigation potential in agriculture, see Chapter 6.)

Adaptation Options and Strategies for Rice Production Higher temperatures, increased variability of the monsoon system, and increased competition from nonagricultural water users could place additional pressures on paddy rice systems to either use less water or to use it more efficiently. Options for adapting flooded rice production to these changes include promoting current water conservation practices more widely. For example:

- Current water conservation practices in rice (such as direct seeding in wet or dry soils as opposed to transplanting into flooded soils) and the recent introduction of permanent raised beds with furrow irrigation in India, could figure more prominently in future strategies for paddy rice.
- Fully aerobic (upland) rice could be another adaptation response to reduced water availability. While upland rice is usually relegated to marginal production zones, the development of high-yielding upland rice systems in Brazil's Cerrado (Pinheiro et al. 2006) and northern China using improved upland varieties and supplemental irrigation, coupled with strong research and extension, provide evidence that the transition to high-yielding aerobic rice is possible with investments in plant breeding and agronomy.
- Assessing the potential to introduce alternative upland crops, and building national and local capacity to accommodate a transition away from rice, would be appropriate in some systems. For example, the World Bank's Andhra Pradesh Drought Adaptation Initiative identified the need to switch from rice to pearl millet for adapting to more intensive water shortages. Obviously, cultural considerations and future market demand are critical to any efforts to transition out of a major crop like rice.

Support for research and extension in the areas of crop breeding, seed systems, soil fertility, tillage, deficit irrigation, and pest management will be needed, especially in low-income countries where significant investment and capacity building will be required. (See relevant sections in this chapter and in Chapters 6, 7, and 8.)

Expanding the Use of Marginal-Quality Water for Irrigation

The expected reduction in the supply of freshwater for irrigation, resulting from population growth and climate change, is likely to force irrigated agriculture in water-scarce areas to utilize marginal water sources and, correspondingly, to switch crop types in order to adapt. Possible measures to adapt to these changes include using brackish water and treated and nontreated wastewater; switching cropping patterns toward salt-tolerant crops, including halophytes (which are plant species that can thrive in saline environments); and conserving water through drip irrigation systems and water productivity improvements that reduce the volume of low-quality water applied to crop land (Qadir et al. 2007). The ability of marginal water use to be sustainable in the long term will depend on actively managing salinity stress and, in some cases, minimizing the buildup of heavy metals in soil.

Irrigation water management practices to minimize salinity stress are very knowledge intensive and will likely require significant investments for developing the monitoring capacity to detect the emergence of negative environmental effects; enhance crop modeling capacity for salinity stress; invest in drip irrigation and other water conservation technologies, as well as in infrastructure for reuse or disposal of saline/sodic drainage waters from irrigated areas; and establish input and output markets for novel crop types (**Table 5.2**). Clearly, initiating these kinds of far-reaching adaptation measures will require careful consideration to determine whether they are economically and socially sustainable.

Water Use Strategies Several use/reuse strategies for saline/sodic water exist, which enable high-value crops to be grown in rotation with low-value salt-tolerant ones, thus increasing the economic viability of marginal water use. As suggested by Qadir and Oster (2004), they are:

- Conjunctive use of freshwater and saline water, wherein the least saline-tolerant crops or crop growth stages receive freshwater and the more saline-tolerant ones receive marginal water.
- Blending of good- and poor-quality water to extend water supplies.
- Sequential reuse, which involves adding relatively better quality water to the least tolerant crop and using sequential drainage water on more salt-tolerant crops downslope.

Successful use/reuse strategies depend on reconfiguration of cropping systems, better soil management practices, and increased coordination at regional scales for managing marginal water in agricultural landscapes. Also, better coordination among agriculture, environment, and health ministries will be needed given the risks to humans and the environment associated with use of marginal-quality water. Formulating policies and building institutions for IWRM, as discussed at the beginning of this chapter, is important.

Seawater desalinization offers another opportunity for expanding water resources for both human consumption and agriculture. However, the high economic costs, energy intensity, and greenhouse gas emissions associated with seawater desalinization call into question its broad application, and its use for agriculture would likely be restricted to technologically intensive and high-value agriculture. In places expected to experience rapid loss of freshwater sources, such as in Andean population centers dependent upon glacial meltwater, desalinization may become viable by necessity.

TABLE 5.2 Challenges, actions, and capacity needs for enhancing the sustainability of saline irrigation sources for agriculture

Challenges	Actions	Capacity Needs and Gaps
Plan for increased use or introduction of marginal-quality irrigation water into production systems that rely on freshwater.	Monitoring and testing of water salinity levels. Economic and agronomic viability studies. Health and toxicity studies.	Improve capacity of economic, environmental, and crop production models to account for changes in irrigation sources. Expand research capacity and field trials. Formulate policies that incentivize use of saline water sources. Promote inter-ministerial coordination between agriculture and public health sectors, and mobilization of health resources.
Minimize sensitivity of cropping systems to salinity effects through developing use/reuse systems for saline water.	Expand reservoir capacity for crop water storage. Develop cropping systems that are matched to temporal and spatial gradients of water quality through strategies that optimize conjunctive and sequential uses and blend saline and freshwater.	Bolster research and extension capacity; promote field trials. Increase/improve wastewater storage capacity. Cooperation and coordination on a regional scale for developing sequential reuse systems that are sustainable. Improve pumping systems for blending.
Develop cropping systems that can optimize environmental and economic sustainability for saline irrigation water sources.	Target domestication of halophytes that provide novel forage and oilseed crops and agroforestry systems. Conventional breeding of salt-tolerant crops to develop genotypes with desirable agronomic traits. Research on transgenics.	Research into basic physiological and agronomic criteria; modeling. Physiological breeding using molecular tools. Bolster extension services. Development of market infrastructure.
Ensure environmentally acceptable disposal of drainage waters.	Reduce offsite impacts through constructed wetlands.	Impact modeling to determine suitability of wetlands under future climate change.

See Chapter 9 for a discussion of marginal-quality water use in peri-urban agriculture.

Cropping System Changes Greater support for plant breeding and agronomic research is needed to develop the full potential of salt-tolerant crop species (such as barley, wheat, and tomato) and of halophytes (which can thrive in saline environments). The greatest economic potential for halophytes is in the production of oilseed and forage crops and agroforestry products. Several halophyte species produce edible oils that have fatty acid profiles on par with high-quality oils such as canola (Weber, Ansari, and Khan 2007). These halophytic oilseed plants tolerate harsh (hot, saline, and low-moisture) environments and could be suitable for regions that will become increasingly water scarce with climate change, such as Pakistan, which currently imports 70 percent of its edible oil needs. A large number of halophytic grasses and shrubs also exist, which would be good candidates for developing "biosaline" forage and livestock production systems (Masters, Benes, and Norman 2007). Halophytes can also be used to restore lands degraded by waterlogging and salinity (Barrett-Lennard 2002; Ravindran et al. 2007).

Prospects for future development of these species is good, given that little effort has been made to improve biomass production and feeding value of forage species or to select livestock that can tolerate high salt intakes. However, ensuring their economic viability will require substantial investments in market infrastructure, extension, and education; research and production trials to integrate them into existing production systems; and detailed demand analysis (Table 5.2).

Reliance on saline water in the mixed use-reuse systems, as described earlier, will also require reconfiguring conventional crop production systems in a manner that is suitable to the water source and its management needs. In the case of perennial systems, this could require changing landscape configurations of tree crops, such as planting salt-tolerant olive genotypes in areas where brackish water use is likely and salt-sensitive citrus genotypes where freshwater sources are available (Paranychianakis and Chartzoulakis 2005).

Expansion of Area under Irrigation

Over the next several decades, the area under irrigation is expected to expand significantly, irrespective of climate change, to meet future food demand. According to the Food and Agriculture Organization (FAO; 2003), the area under irrigation will need to expand by 40 million hectares by 2030, and Fischer and others (2007) placed the expansion of irrigation due to development alone at 122 million hectares by 2080, representing a 25 percent increase over 2000 levels in global agricultural water withdrawals for irrigation. In addition to this, climate change is projected to generate an additional 20 percent increase in global irrigation water withdrawals by 2080. In developing countries, three-quarters of the additional irrigation requirements are expected to result from increased daily water requirements caused by warming and changed precipitation patterns, with about one-quarter of the increased agricultural water withdrawals attributed to a longer growing season. The global annual costs of additional irrigation water withdrawals resulting from climate change could be in the range of US$24 to $27 billion, with roughly two-thirds of that cost borne by developing regions. With mitigation of greenhouse gas emissions, these costs could be reduced by US$8 to $10 billion annually.

The largest relative increases in crop irrigation water requirements caused by climate change are likely to occur in Africa (300 percent) and Latin America (119 percent), according to estimates by Fischer and others (2007). Sub-Saharan Africa has the greatest potential for expanding irrigation as an adaptation option because of the current predominance of rainfed agriculture and the very low level of irrigation development on the continent. Some large-scale irrigation development may be possible, although, historically, large-scale irrigation projects in Africa have had high unit costs and, as such, have been unsustainable. Small-scale and community-based irrigation schemes are generally more cost effective. Irrigation expansion is least viable in East and South Asia because of the currently unsustainable rate of water withdrawal for agriculture; in these regions, rehabilitation of degraded systems will be more important.

Water Sources for Irrigation Expansion The viability of future irrigation expansion will likely be influenced by how groundwater resources are impacted by climate change. The IPCC Fourth Assessment Report (Kundzewicz et al. 2007) estimated that climate change will adversely affect groundwater recharge rates, with many areas experiencing a shift in spring recharge toward winter and a decline in summer recharge caused by warmer conditions.

Projections of future groundwater recharge indicate a significant decrease in northeast Brazil, southwest Africa and the Maghreb (Kundzewicz et al. 2007). Regions projected to experience increased groundwater recharge include the Sahel, northern China, and Siberia, although significant uncertainty remains regarding the direction of future precipitation in the Sahel. In general, an increased magnitude of flooding and high rainfall events in semi-arid areas can be expected to benefit groundwater recharge, although at a cost in terms of infrastructure damage and lost land productivity caused by flooding, soil erosion, and runoff. Diminution of mean rainfall in some regions and increased climate variability, manifested within climate change, in most regions will affect the viability of surface water resources for irrigation expansion. For example, in semi-arid areas of Africa, a 10 percent drop in mean precipitation, combined with higher temperatures, has been estimated to cause a 50 percent reduction in surface drainage volumes (deWit and Stankiewicz 2006).

Adaptation Needs for Irrigation Expansion A priority issue for most developing regions will be to improve basic data gathering on groundwater supply and recharge combined with downscaled projections of temperature and precipitation changes from regional climate models. Although similar assessments for surface water are also needed, groundwater has received considerably less attention in climate change impact assessments. Capacity building needs for modeling and use of environmental data sets, as described in Chapter 4, would apply here. These include:

- Education and training in hydrology and climate science, including training curricula on how to use and interpret hydrologic and climate models.
- Development of programs to facilitate cross-learning among climate modelers, hydromet services, and relevant government institutions.

- Development of sampling and modeling networks at the local and district levels that could interface with national-level ministries and put policies in place to ensure that capacity in spatial data analysis is adequate across ministries or that mechanisms are in place to share this expertise among ministries.

  Assessing water resources and future climate change impacts should be coupled with policy efforts to assign water rights to legitimate users and define institutions and policies to administer these rights. Having these elements in place would make it easier to then establish functional WUAs. Lastly, socioeconomic analyses would be needed to develop pro-poor policies regarding access to irrigation water and to ascertain where efforts to establish and strengthen markets would be needed.

IV. Adapting Agriculture in Flood-Prone Areas

The damage caused by floods has doubled over the past decade compared with the middle of the last century. The increased rate of damage is more likely attributable to greater population settlement in flood-prone areas and land-use changes that increase flood risk than to climate change. The climate change signal in flood severity trends will very likely increase, and the fact that settlement patterns and land-use change have dramatically increased the vulnerability to floods means that any incremental reinforcement of conditions that spawn floods could cause marked increases in the loss of life and property. The extent to which climate change intensifies flood damage potential will depend on future settlement patterns and land-use practices, as well as access to risk mitigating factors such as flood forecasting and early warning systems.

Addressing rural vulnerability to increased flood risk will require adaptation measures that directly reduce the potential loss of crops to floods; promote rural livelihood diversification away from reliance on risky economic activities; and strengthen rural infrastructure, particularly health systems.

Agricultural Systems and Rural Livelihoods

Community-level adaptation studies in South Asia (described in Moench and Dixit 2007) have revealed a number of intervention points for improving adaptive capacity in flood-prone agricultural areas. These rural community assessments revealed that "soft" flood risk reduction approaches that emphasize building infrastructure resiliency, wetland restoration, livelihood diversification, early warning and communication networks, education, and organizational strengthening were preferable to "hard" structural flood prevention approaches. For example, river embankments can actually contribute to flooding severity by forcing sediment deposition in embankment channels, thus raising river levels. Embankments and elevated roads that cause congestion of floodwater have contributed to extensive waterlogging of agricultural lands. In addition, the combined effects of salinity and flooding contribute to declining rice productivity in affected areas.

Specific measures that could improve adaptive capacity of rural communities include:

- Flood-coping strategies through the development and adoption of flood-resistant crop varieties (see Chapter 7).
- Flood-avoidance strategies that allow for early planting and harvesting of rice through the use of short-duration crop varieties and improved irrigation infrastructure.
- Desilting drainage canals and strengthening bunds.
- Dry-season vegetable crop production, irrigation, and marketing to diversify household income and reduce reliance on rainy season crops.
- Methods to dry and preserve seed stocks, hanging seed beds, seed banks, and training programs for seed multiplication of desired varieties.
- Flood-resistant fodder banks and vaccinations for and deworming of livestock.
- Access to rural finance to foster livelihood activities for both flood preparedness and recovery.
- Training for alternative livelihood activities.
- Construction of flood-adapted buildings, using heavier and higher foundations, flat roofs that allow for emergency storage, and electrical wiring close to the ceiling.
- Construction of schools or places of worship with sturdy materials to provide shelter.
- Limited embankment construction to places where high-value property needs to be protected.
- River bank stabilization.
- Improved communication infrastructure to broadcast weather and flood risk information.

Instituting these measures will require investments and capacity building in GIS facilities and training, seed storage facilities, research and extension in varietal dissemination, small-scale horticulture and other agricultural activities, microenterprises for women, flood proofing of vital infrastructure, and village-level communication for early warning systems. (For more on early warning systems, see Chapter 4.)

Health risks from flooding are also expected to increase as climate change intensifies flood patterns. Flooding and the subsequent displacement and clustering of people creates unhygienic conditions conducive to the spread of cholera and other water-borne diseases, as well as increased incidence of respiratory disease. This is also expected to severely affect the agricultural sector in that productivity will be affected if illness in workers increases and if health systems are damaged.

Conclusions

- Projections of regional drying trends in water-scarce subtropical regions, combined with population growth projections for these regions, are likely to aggravate already significant water management constraints in dryland agriculture.
- From a biophysical standpoint, there is good scope for significantly increasing rainfed crop yields through bolstering water productivity. This could lessen the adaptation deficit that currently exists in rainfed agriculture and provide a foundation for adaptation to longer-term climate impacts.
- Broadening the potential for uptake and dissemination of rainwater harvesting technologies will require concerted efforts in participatory research and dissemination, improvements in rural infrastructure, access to rural finance, considerations of labor bottlenecks, improved markets to rationalize farmer investments, and analysis of where the technologies are feasible.
- Policy reform for irrigation water use, research and development in water conservation methods, and engagement with water-user associations could improve the resiliency of irrigated systems to climate change.
- Promoting water conservation in lowland irrigated rice systems as an adaptation measure will require careful attention to net greenhouse gas emissions to avoid increasing the climate forcing potential of agriculture.
- In water-scarce regions, reduced freshwater supplies (from population growth and climate change) could force irrigated agriculture to utilize marginal water sources, switch cropping patterns toward salt-tolerant crops, and conserve water through drip irrigation systems and land-based practices that reduce the volume of low-quality water applied to arable land.
- The ability of marginal water sources to be sustainable in the long term will depend on intensive management, investments in new production technologies, and development of knowledge systems, as well as systematic environmental monitoring of their effects on the natural resource base.
- Adapting flood-prone areas to climate change will require mitigating risk through integrating "hard" flood prevention investments with "soft" investments to improve the performance of agriculture and diversify livelihoods.

CHAPTER 6: SUSTAINABLE LAND MANAGEMENT, ADAPTATION, AND MITIGATION

SUMMARY: This chapter addresses options for reconfiguring agricultural systems and sustainably managing land to enhance agriculture's mitigation and adaptation potential. It begins with an overview of opportunities for realizing both adaptation and mitigation benefits through adopting sustainable production practices, explores mitigation options, and reviews potential trade-offs between the two. It also examines linkages between sustainable land management and adaptation—with a focus on reducing heightened risks of soil erosion caused by extreme climate events—and opportunities to enhance soil fertility management for both mitigation and adaptation benefits through integrated soil fertility management, agroforestry, and conservation tillage. The chapter also explores the use of market-based approaches, such as payment for environmental services schemes including the Clean Development Mechanism, for fostering mitigation and adaptation actions in smallholder agriculture. Lastly, it discusses livestock management in the face of climate change and adaptation strategies to enable livestock to cope with heat stress and to minimize impacts on crop and rangeland resources.

I. Opportunities for Linking Adaptation and Mitigation

Global agriculture will need to become much more efficient in its use of water and other inputs in order to meet future food demand without significantly increasing its contribution to anthropogenic climate change, while at the same time it will need to adapt to increased climate risks. Within the agricultural sector, several potential entry points exist through which greenhouse gas mitigation and climate change adaptation needs can be simultaneously met in the process of securing more sustainable food production systems for development. These include:

- Emissions avoidance through increased production efficiency and reconfiguration of systems to reduce reliance on external inputs, including improved nitrogen-use efficiency in crop production.
- Sustainable agronomic and rangeland practices that both increase yields of crop and fodder systems and enhance carbon residue retention in soils.
- Enhanced land-based carbon sequestration through activities such as agroforestry, integrated soil fertility management, and conservation tillage.
- Enhanced water management, such as reduced flood irrigation in paddy rice (emissions avoidance) and increased capture of rainwater and its conversion into crop biomass in rainfed

systems (carbon sequestration), which also help agriculture adapt to changing water availability.

- Advances in livestock feeding practices and use of supplements that can both lessen animal heat generation and methane emissions from livestock and improve animal breeding to reduce heat stress.

Mitigation of Greenhouse Gas Emissions from Agriculture

According to the IPCC Fourth Assessment Report, greenhouse gas emissions from agriculture constituted 10 to 12 percent of global anthropogenic emissions in 2005, with agriculture responsible for approximately 60 percent of total anthropogenic nitrous oxide (N_2O) emissions, and 50 percent of total anthropogenic methane (CH_4) emissions; the global net carbon dioxide (CO_2) flux from agriculture is approximately balanced (Smith et al. 2007b). Between 1990 and 2005, agricultural emissions of N_2O and CH_4 trended upward in developing regions (+32 percent), while declining slightly in developed regions (−12 percent) (**Figure 6.1**). Between 2005 and 2020, agricultural emissions from developing regions are expected to continue to grow at about the same rate, while those from developed regions will increase only slightly. The largest source of non-CO_2 agricultural emissions in developing regions comes from fluxes of N_2O from soil and CH_4 from manure and, to a lesser extent, flooded rice.

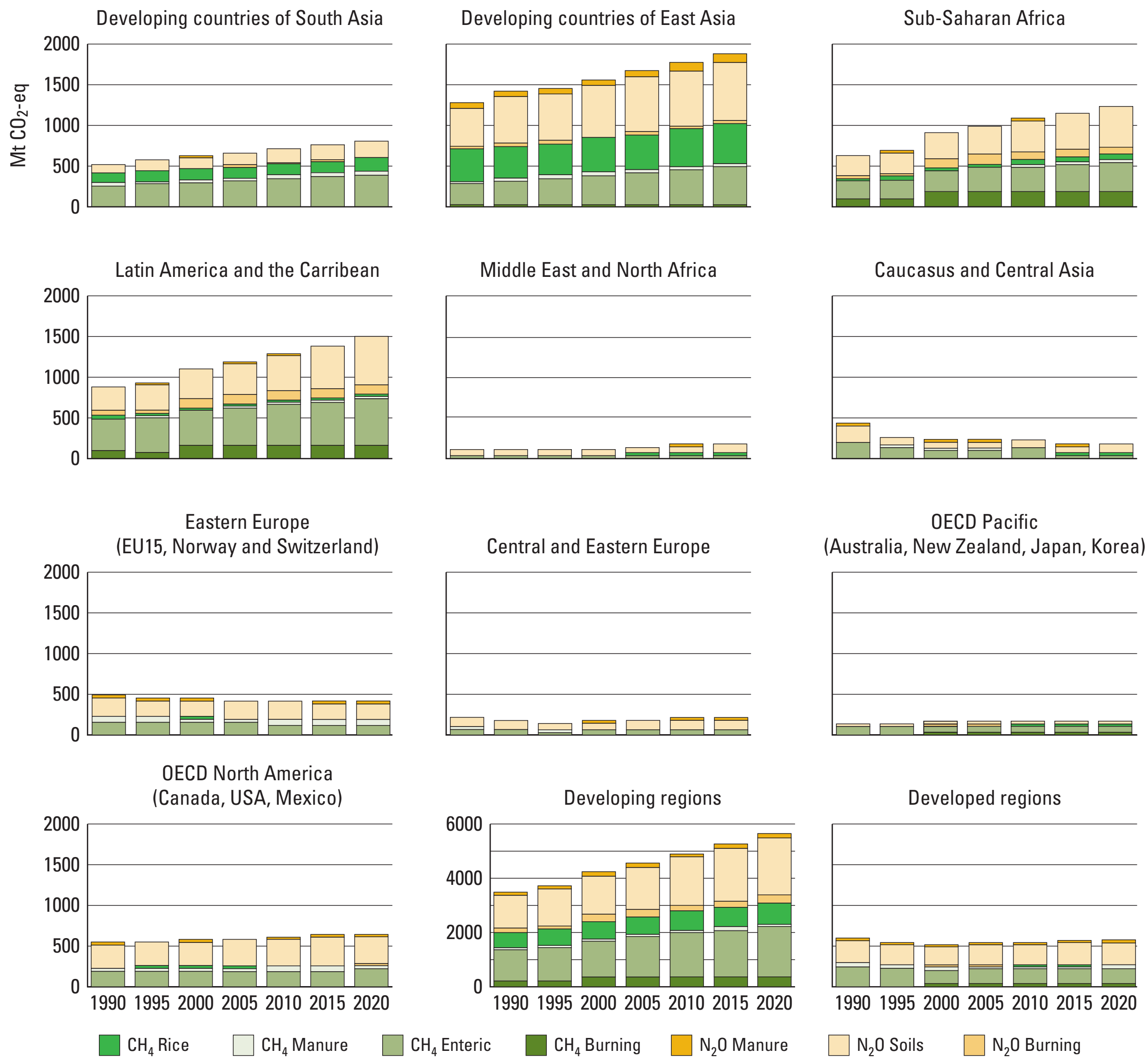
No systematic projections of agricultural emissions beyond 2020 have been calculated. However, in the absence of major efficiency improvements in how food is produced, agricultural emissions are expected to increase until at least mid-century, given the projected 50 percent increase in human population globally. For example, an estimated 60 percent increase in global use of nitrogen (N) fertilizer for cereal production will be required by 2025 to meet the increased food demand generated by population growth in developing regions (Dobermann 2006). This will, in turn, lead to higher N_2O emissions. Two important challenges with respect to enhancing the mitigation potential from agricultural land use are to improve the efficiency of inputs and to address land degradation.

Input Efficiency of Input-Intensive Systems

Avoiding emissions through better input-use efficiency (particularly nitrogen-use efficiency) is critical to balancing the increased demand for food with the need for environmental protection. Approximately two-thirds of the fertilizer N applied to croplands worldwide is lost to volatilization and, to a lesser extent, leaching and runoff. Improvements in nitrogen fertilizer-use efficiency are particularly critical in East Asia, Europe, North America, and parts of South Asia and South America, where current levels of fertilizer use are high[1]. Actions that better target fertilizer use to plant needs such as precision agriculture (where technologically

1 For a discussion of nitrogen-use efficiency, including policies and measures for promoting site-specific nutrient management, see Chapter 5 on nitrogen-use efficiency in rice. Many of the underlying issues for site-specific nutrient management in rice are relevant to other cropping systems.

FIGURE 6.1 Estimated historical and projected N_2O and CH_4 emissions in the agricultural sector during the period 1990–2020.



Source: Smith et al. 2007b

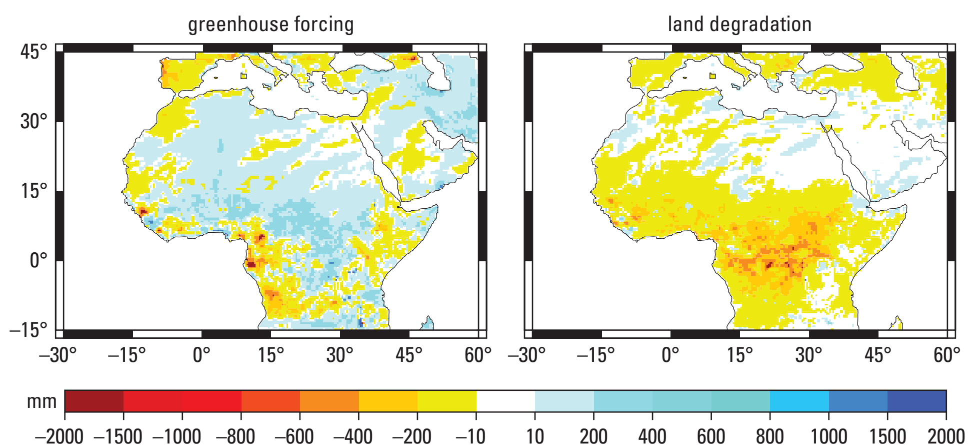
feasible), site-specific nutrient management, and integrated soil fertility management (discussed later in this chapter) can reduce the environmental costs of excess nitrogen in agroecosystems. At the same time, these actions can lower production costs and, by improving productivity, increase the amount of carbon retained in the system.

Addressing Land Degradation Land degradation directly contributes to climate change through emissions of heat-trapping gases caused by deforestation, land conversion, forest fires, and soil erosion and indirectly, through reductions in the size of terrestrial carbon sinks resulting from soil and vegetation loss. Land degradation also influences local and regional climate dynamics, via changes in surface albedo, heat fluxes, and evaporation that alter the land surface energy balance and through increased loading of dust particles (or aerosols) in the atmosphere, which appear to affect precipitation patterns by slowing down the formation of water vapor into raindrops.

Recent advances in coupling of land cover and atmospheric regional climate models have begun to account for potential influences of land degradation in modifying regional climate dynamics. For example, in incorporating land cover change into climate model simulations for 2100, Feddema and others (2005) found that agricultural expansion could result in reduced rates of warming in some mid-latitude areas and additional warming over the Amazon Basin, compared with temperature rise projections based on greenhouse gas emissions alone. Similar methods used by Paeth and Thamm (2007) revealed a significant drying tendency over much of tropical Africa by 2025 that would be driven more by land degradation than by radiative forcing from greenhouse gas emissions (**Figure 6.2**).

These two studies point to the importance of considering land degradation dynamics in regional climate models. They underscore the need to improve modeling capacity to allow for more robust evaluation of joint land degradation and greenhouse gas forcing; develop policies that are cognizant of the potential to both mitigate climate change through addressing the drivers of land degradation; and enhance the resilience of natural and managed ecosystems to climate change impacts. The combined extent of

FIGURE 6.2 Estimated changes in total annual precipitation (in millimeters) in 2025 due to enhanced greenhouse gas concentrations (left) and from ongoing land degradation (right).



In the right-hand figure, loss of vegetative cover and reductions in soil moisture are determined to be important drivers of diminished transfer of moisture between the land surface and the atmosphere.

Source: Paeth and Thamm, 2007.

degradation of rangeland and arable lands is at least several hundred million hectares, although estimates contain significant quantitative uncertainties (Gisladottir and Stocking 2005).

Benefits and Drawbacks of Linking Adaptation and Mitigation

The greatest potential for mitigation in agriculture exists in changing cropland and rangeland management practices to enhance carbon sequestration, given the scale at which agriculture is practiced worldwide. Over the next 40 years, conservation agricultural practices will have the technical potential to restore more than half of the carbon lost (50 Gigatonnes) from the world's agricultural soils currently under cultivation (Rosenzweig and Tubiello 2007). The majority of these mitigation strategies (described in **Table 6.1**) also improve the adaptive capacity of production systems[2] through:

- Improved crop moisture management to cope with warmer temperatures and prolonged intervals between rainfall.
- Reduced soil erosion, runoff, and flooding risk.
- Income generation from secondary agroforestry and legume green manure products, and intensification of small-scale livestock production.
- Stabilization of the resource base as a foundation for diversifying agriculture and rural livelihoods in order to facilitate adaptation to longer-term impacts of climate change.

In turn, reducing soil erosion risk and increasing land productivity enhance the strength of the carbon flux from the atmosphere to biomass and from biomass to soils.

Potential Trade-offs between Mitigation and Adaptation Although very good potential exists for realizing synergies between mitigation and adaptation, potential trade-offs need to be considered as well. For example, adaptation can contribute to a growth in agricultural emissions where:

- Increased rates of fertilizer N are applied to compensate for climate-induced production losses in crop- and pastureland leading to increased N_2O emissions.
- Changes in agricultural land management practices, such as conversion from conventional to zero tillage or the introduction of nitrogen-fixing agroforestry species, can increase N_2O emissions from agricultural lands.
- Introduction of mid-season drainage of paddy rice or conversion from flooded to upland rice for water conservation can increase N_2O emissions and potentially increase CO_2 emissions.

Mitigation can undermine adaptation in situations where:

- Bioenergy crops compete directly for land needed to ensure food security in climate-sensitive regions.

2 Evidence of this "double dividend" can be found in the increased resilience to and faster recovery from extreme weather events in conservation farming systems compared with conventionally managed systems. For example, multitiered agroforestry and mulch-based cereal/bean systems in the Central American highlands fared better when exposed to El Niño drought (Cherrett 1999) and to the catastrophic effects of Hurricane Mitch (Holt-Gimenez 2001) than adjacent areas where these practices were not in use.

TABLE 6.1 Proposed measures for mitigating greenhouse gas emissions from agricultural ecosystems, their apparent effects on reducing emissions of individual gases where adopted (mitigative effect), and an estimate of scientific confidence that the proposed practice can reduce overall net emissions at the site of adoption

		Mitigative Effects[1]			Net Mitigation[2] (Confidence)	
Measure	**Examples**	**CO_2**	**CH_4**	**N_2O**	**Agreement**	**Evidence**
Cropland management	Agronomy	+		+/−	***	**
	Nutrient management	+		+	***	**
	Tillage/residue management	+		+/−	**	**
	Water management (irrigation, drainage)	+/−		+	*	*
	Rice management	+/−	+	+/−	**	**
	Agroforestry	+		+/−	***	*
	Set-aside land and land-use change	+	+	+	***	***
Grazing land management/pasture improvement	Grazing intensity	+/−	+/−	+/−	*	*
	Increased productivity (e.g., fertilization)	+		+/−	**	*
	Nutrient management	+		+/−	**	**
	Fire management	+	+	+/−	*	*
	Species introduction (including legumes)	+		+/−	*	**
Management of organic soils	Avoid drainage of wetlands	+	−	+/−	**	**
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+		+/−	***	**
Livestock management	Improved feeding practices		+	+	***	***
	Specific agents and dietary additives		+		**	***
	Longer-term structural and management changes and animal breeding		+	+	**	*
Manure/biosolid management	Improved storage and handling		+	+/−	***	**
	Anaerobic digestion		+	+/−	***	*
	More efficient use as nutrient source	+		+	***	**
Bioenergy	Energy crops, solid, liquid, biogas, residues	+	+/−	+/−	***	**

Notes:
[1] + denotes reduced emissions or enhanced removal (positive mitigative effect)
− denotes increased emissions or suppressed removal (negative mitigative effect)
+/− denotes uncertain or variable response
[2] A qualitative estimate of the confidence in describing the proposed practice as a measure for reducing net emissions of greenhouse gases, expressed as CO_2–eq. Agreement refers to the relative degree of consensus in the literature (the more asterisks, the higher the agreement); Evidence refers to the relative amount of data in support of the proposed effect (the more asterisks, the more evidence).

Source: Adapted from Smith et al. 2007b

- Tree species suitable for carbon sequestration may not be desirable from a rural livelihoods perspective.
- Afforestation in high watersheds may reduce water availability downstream.

II. Agricultural Land Management

The following section describes soil fertility management, agroforestry, and conservation tillage measures presently being used to enhance the sustainability of agricultural production. These practices also enhance the resilience of the land base to more intense storms and extreme events, which are expected to be increasingly prominent under climate change, increasing the risk of soil erosion and other forms of land degradation. Semi-arid landscapes are particularly vulnerable to degradation because of sparse vegetative cover and the distribution of annual rainfall in a small number of intense storms. In addition, soil erosion "hotspots"—where human-induced erosion is high due to topography, climate, and population growth—occur in regions vulnerable to climate variability and change. These include the Andes and Central American highlands, China's Loess Plateau, the West African Sahel, and highland areas of eastern and southern Africa (Boardman 2006). Also, the Central Asian drylands have become more vulnerable to degradation due to increased prevalence of poverty and a heightened risk of desertification.

The adoption of conservation agricultural practices, such as conservation/zero tillage and crop residue management, green manures, and agroforestry, as well as appropriate crop rotations, lessen the risk of accelerated soil erosion from climate change and, in some cases, generate economic benefits that buffer against increased climate risks, as discussed later in this chapter.

Soil Fertility Management and Adaptation

Efforts to enhance soil fertility should consider how to improve system productivity to compensate for reduced yields caused by increasing climate risks (see **Box 6.1**), while simultaneously protecting soils from increased risk of erosion. Specific measures that could be taken to improve soil fertility in a manner consistent with adaptation include increasing fertilizer use in low-input systems and promoting integrated soil fertility management (ISFM).

Increasing Fertilizer Use in Low-Input Systems This can be done through tailoring fertilizer recommendations to high-risk rainfed environments, such as through maximizing the rate of return from inputs rather than maximizing yields. In the context of these production environments, policy support is needed to move national research and extension priorities from the fine tuning of high-input fertilizer recommendations to focusing on giving farmers greater information, which will allow them to make incremental adjustments in fertilizer use consistent with their risk management strategies.

An example of recent progress in this area is the "accelerated learning" pilots

Box 6.1

SOIL FERTILITY AND CROP WATER MANAGEMENT IN SEMI-ARID ENVIRONMENTS

The need for soil fertility improvement is particularly great in semi-arid rainfed systems, where low soil fertility compounds crop losses from low soil water availability. Chronically poor crop performance and a high risk of crop failure in these systems, combined with overall low levels of rural development, act to dissuade farmers from making the necessary investments in soil fertility improvements that could, in turn, lead to more efficient water use by the crop. Productivity constraints from low soil fertility in these systems can be of equal or greater magnitude than soil moisture deficiency, as is the case of soil phosphorous deficiencies in the West African Sahel (Shapiro et al. 2007). Improving soil fertility produces several benefits for water productivity, including enhanced early vigor of seedlings, better competition with weeds, root access to a larger area of soil water, and early maturation that avoids terminal drought, all of which contribute to higher yields and better management of risk in rainfed agriculture. Shapiro and others (2007) reported that improved soil fertility in a Sahelian dryland cereal system increased water productivity by 50 percent and resulted in a fivefold increase in yield. Rainwater harvesting methods that partition more of the rainfall to the crop can help dampen risk and decrease inter-annual production volatility, both of which are important precursors for farmers to invest in soil fertility improvements. (For a full discussion of this topic, see Chapter 5.)

aimed at providing information to farmers, extension workers, and NGOs about economic rates of return for fertilizer use in highly variable rainfed climates, through the use of Agricultural Productions Systems Simulator (APSIM) models (Cooper et al. 2008). In semi-arid Zimbabwe, this model was field tested with 170,000 farmers, who applied microdoses of fertilizer nitrogen (at rates affordable to farmers rather than officially recommended rates) and realized yield gains of 30 to 50 percent under below-average rainfall conditions. The APSIM model is driven by daily climatic data and can be used to predict the impact of climate variability on the probability of success over a range of crop, water, and soil management practices. APSIM has been developed for a number of cereal, legume, and oilseed crops for rainfed systems. Using tools like this to better manage seasonal climate variability is an important starting point towards lessening the adaptation deficit.

Promoting Integrated Soil Fertility Management (ISFM) practices can help better manage risks because, in addition to improving productivity, these practices protect against soil erosion and provide secondary products that contribute to livelihood diversification. ISFM refers to a range of practices that combine organic and mineral nutrient sources. The organic component (animal manure, compost, crop residues, improved fallow, intercropping, legume green manures, N-fixing agroforestry species, etc.) provides soil conservation, maximizes on-farm nutrient recycling, and improves input efficiency and soil water retention.

Assessing the appropriateness of green manure legumes and agroforestry trees used in ISFM for heat, drought, and submergence tolerance (as needed for climate change) will be an important consideration for adaptation. Many drought-tolerant green manure species exist, including canavalia, crotalaria, mucuna, and lablab. Rotation of food crops with these green manures is appropriate for building resilience to climate change in smallholder systems because of their value in replenishing soil fertility and soil organic matter, protecting soils against erosion, and reducing weed competition. However, the presence of high agroecosystem benefits does not necessarily lead to high rates of farmer adoption in situations where land cannot be taken out of crop production or where the green manure is perceived as incongruous to livelihood needs. For example, Kiptot and others (2007) documented how intensive efforts to improve soil fertility in Kenya through the use of legumes failed to result in sustained adoption of this technique because immediate and tangible economic benefits were missing. As is the case with most interventions to promote sustainable production practices, whole-systems research and development approaches for legume green manures, which involve collaborations among plant breeding, integrated pest management, soil and water management, livestock, and social scientists linked to farmer-participatory research, are needed to improve the socioeconomic viability of this resource.

To improve the likelihood of farmer adoption of ISFM, support is needed in the following areas:

- Improvements in input and output markets and rural infrastructure so as to provide a financial incentive for on-farm investments.
- Education and extension through both formal channels, as well as through training of para-extension agents, and capacity building of local NGOs for extension and financing.
- Access to flexible credit programs, especially those targeting women.
- Support for farmer cooperatives and local organizations to jointly purchase inputs and share labor.
- Capacity building of farmers and local organizations to use seasonal climate forecast information for crop management decisions.
- Germplasm improvement and local seed availability for multipurpose nitrogen-fixing legumes.
- Promotion of land tenure security and resource ownership policies.

Agroforestry

The establishment of agroforestry in marginal croplands offers significant potential to sequester carbon and improve the resilience of the agroecosystem to extreme events. The high carbon sequestration potential of agroforestry stems from the potentially large land area (several hundred million hectares) to which land-use modifications to accommodate agroforestry are possible. These include degraded pastures, semi-arid cereal systems, secondary forest fallow, and low-quality grasslands. For example, in Southeast Asia, an estimated 35 million hectares of *Imperata* grassland could be put into more productive use with agroforestry (Roshetko, Lasco, and de Los Angeles 2007).

The benefits of agroforestry derive both from the ecosystem services it provides (improved nutrient cycling, soil protection and enhanced soil water recharge, decreased crop canopy temperatures, and enhanced biodiversity), as well as from its potential to diversify rural economies through the generation of relatively high-value food, animal fodder, and medicinal and fuelwood products. Agroforestry has the greatest productive potential in humid/subhumid zones at the margins of secondary forests (Albrecht and Kandji 2003). It has also proven critical for restoring degraded lands and managing climate risk in semi-arid environments, most notably in the recovery of agricultural lands from long-term drought, as in the case of farmer managed natural regeneration in the Sahel (see **Box 6.2**). (See Verschot et al. 2007 for an overview of the agroforestry-climate change issue.) Agroforestry has been

Box 6.2
FARMER-MANAGED NATURAL REGENERATION AND DROUGHT RECOVERY IN THE SAHEL

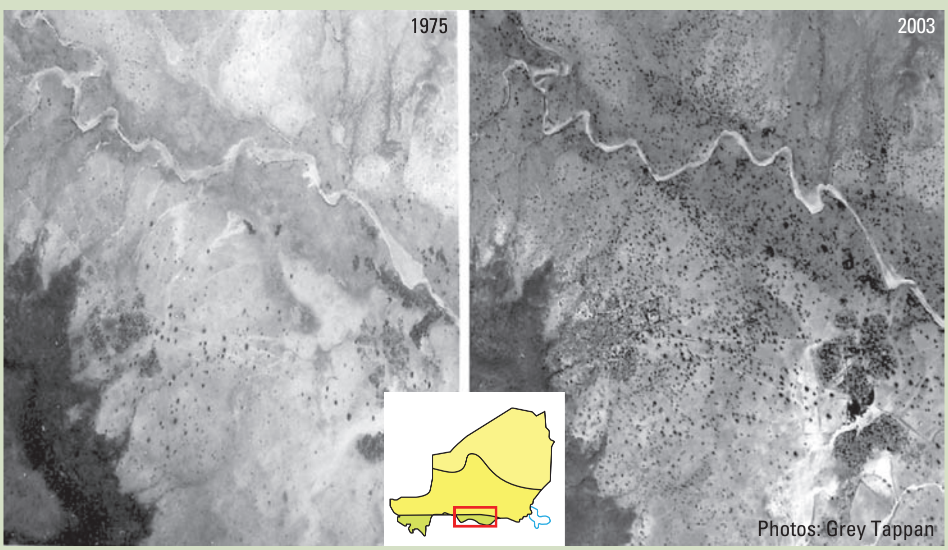
Farmer management of naturally regenerating field trees and modifications of land-use practices to improve rainwater capture appear to have played an important role in the recovery of cropland in the southern Sahel from recent long-term drought. While a slight increase in rainfall since the mid-1980s likely contributed to the "regreening" phenomenon, a critical factor appears to have been land management and farming system modifications made during, and in response to, drought. Evidence from Burkina Faso and Niger is highlighted here.

Burkina Faso The situation in the semi-arid Central Plateau of Burkina Faso, documented by Reij, Tappan, and Belemvire (2005), illustrates well the importance of local capacity and resourcefulness in coping with climate risk. Drought in the 1970s and 1980s led to a crisis of low and declining yields, diminished vegetation cover, and falling groundwater levels across the Central Plateau. In response, farmers and NGOs initiated a series of soil and water conservation (SWC) practices to bring highly degraded impermeable soils back into production. This was accomplished through the deployment of contour rock bunds, rock dams, and traditional planting (zai) pits to improve water capture and control runoff, which, in turn, led to increased natural regeneration of field tree species. These interventions, which have occurred over an estimated 250,000-hectare area, have helped to stabilize and improve cereal yields, resulting in enhanced household food security and reduced poverty. Reij, Tappan, and Belemvire estimate that yields have increased by around 50 percent where SWC practices were established.

Niger In Niger, a transformation in the direction of sustainable land management has been much more extensive, with an estimated 5 million hectares of farmland having undergone varying degrees of increased tree densification, primarily as a result of farmer-managed natural regeneration of nitrogen-fixing *Faidherbia albida* and other field trees across the broad band of sandy soils in the southern central part of the country (WRI 2008) (**Figure 6.3**). Land tenure security and decentralization of authority over tree ownership were essential preconditions for land reclamation and farmer-managed natural regeneration, and the process has been sustained through increasing urban fuelwood markets and demand for animal feed from fodder-producing trees. Reclamation of highly degraded land fostered the creation of land markets, with women as a main benefactor. In many situations, women took the initiative to reclaim abandoned land, resulting in ownership of what eventually became productive land (Mike McGahuey, USAID, personal communication).

While the region's agriculture undoubtedly faces significant future challenges from climate change, the resilience of rural Sahelian communities in the face of extreme variability illustrates a high degree of internal adaptive capacity. Using simple land management technologies and practices to stabilize and steadily improve yields has helped narrow the "adaptation deficit" with respect to current climate variability. This, in turn, makes it possible to modify production systems in a manner consistent with longer-term adaptation needs. For example, drought-tolerant varieties that will be required for adaptation will perform better in rehabilitated soils than in degraded ones. In addition, an increased buffer against climate variability reduces the need to liquidate productive assets, thus improving prospects for long-term land investments.

FIGURE 6.3 "More people, more trees"; aerial photographs of the same landscape in the Tahoua district, Niger, 1975 and 2003



The dots represent trees. U.S. Geologic Survey (USGS) aerial photography and landsat imagery, along with transect analysis, have been used over the past few years to estimate changes in tree density. Grey Tappan (USGS) and Chris Reij (Free University, Amsterdam) estimate that more than 70 percent of the 7 million hectares making up the sand belt of southern Niger have experienced increased tree density as a result of farmer-managed natural regeneration, with much of this occurring during the past 15 years, before the cessation of the Sahel drought in the mid-1990s.

Source: Photos courtesy of Grey Tappan identified as a preferred adaptation strategy in recent assessments of adaptation options, such as that by Thomas and others (2005) for a semi-arid climatic zone.

The viability of agroforestry as an adaptation measure depends on sustaining farmer access to information, support and training for tailoring agroforestry to variable environments, appropriate policy conditions, access to necessary inputs, and viable markets for agroforestry products.

Specific areas of support that are needed include:

- Technical assessments to ensure the use of appropriate tree species given projected changes in rainfall and temperature.
- Robust cost/benefit analyses for agroforestry against projections of future climate change.
- Technical advice and knowledge exchange, including support for farmer-to-farmer exchanges and community decision making.
- Capacity building of community organizations in information sharing and marketing.
- Policy support for land tenure security, resource ownership, and usufruct.
- Opportunities for spreading the risk of investments, including through access to credit or enrollment in a payment for environmental services (PES) scheme, as described in Section 3.
- Encouragement for growing multipurpose agroforesty species that can produce marketable fruits, fodder, and/or building material.

Conservation Tillage

A shift in tillage practices from repeated annual tillage operations to minimal or zero tillage can enhance management of climate risks through better protection of soils from extreme events and improve crop productivity through increased water and nutrient retention. Cropland soils managed through a reduction or elimination of tillage operations are more resilient to erosive forces from wind and water because crop or cover crop residues provide coverage of the soil surface, which reduces surface crusting of soil, improves rainwater infiltration, and reduces the rate of soil surface drying. Also, soils exposed to less or no tillage have greater soil aggregate stability and higher levels of soil organic matter, which can help reverse the loss of carbon from agricultural soils. Under a climate change scenario of increased precipitation in the Loess Plateau, Zhang and Liu (2005) estimated that the use of conservation tillage practices in a wheat-maize rotation could reduce soil erosion by more than half compared with conventional tillage. Similarly, Zhang and Nearing (2005) estimated no change in soil erosion under no-till wheat systems compared with increased erosion rates as great as 67 to 82 percent under conventional tillage, using estimates of erosion under a range of climate change scenarios compared with current erosion rates.

More than 70 million hectares of agricultural land are currently under conservation tillage worldwide, mostly concentrated in

North America, Europe, and South America (Argentina, Brazil, and Paraguay). Given the estimated 1.5 billion hectares of arable land globally, there is significant potential to expand conservation tillage that can meet both adaptation and mitigation purposes. The recent development of inexpensive and readily converted conservation tillage implements for animal traction in East Africa and small-scale mechanized cultivation systems in South Asia has helped facilitate the adoption of conservation tillage practices in these regions. For example, in western Kenya, the adoption of such practices (subsoiling, ridgeing, and ripping) was found to increase soil moisture storage by 18 to 50 percent, resulting in combined yield increases of 30 to 150 percent for maize, beans, and wheat (Ngigi, Rockström, and Savenije 2006). In semi-arid to dry subhumid rice-wheat areas of Pakistan and the Indian Punjab, where the environmental and economic costs of irrigation are increasing, zero tillage systems with retention of straw has increased in situ water retention, resulting in significantly improved economic returns for wheat production, through reductions in fuel costs and irrigation demand (Gupta and Seth 2006).

Support is needed in the following areas to improve farmer adoption of conservation tillage:

- Strengthening input markets for conservation tillage equipment through private-sector development.
- Expanding access to credit and cost-sharing programs with farmer organizations that encourage group investments in technologies.
- Strengthening research and extension services and encouraging stronger linkages among national agricultural research systems (NARS), extension, and locally based NGOs.
- Increasing support for research on weed management in conservation tillage systems.[3]

III. Market-Based Approaches to Promote Adaptation in Agriculture

This section describes the potential for introducing market-based incentives for adopting sustainable land management practices to enhance adaptation and possible limitations of this approach given the unique challenge adaptation presents. The discussion in this section focuses on the payment for environmental services (PES) approach, which includes the service of carbon sequestration gained through afforestation activities allowed under the Clean Development Mechanism (CDM).

3 Conservation tillage increases weed management costs considerably compared with conventional tillage. Climate change simulations using increased CO_2 and higher temperatures show that weeds are more responsive than crops to both effects, and weeds in CO_2-enriched conditions allocate more to below-ground growth (see Chapter 8). These factors could make weed management more difficult under climate change; thus, greater research efforts are needed to adapt weed management strategies to these new management challenges.

Payment for Environmental Services

Many of the environmental services and benefits that ensue from sustainable land management practices represent externalities or are at least of low market value to smallholder farmers under current institutional arrangements. Recent efforts to assign market values to environmental services through a direct transfer of payment for environmental services from governments and/or "downstream" beneficiaries to "upstream" resource users have the potential to both enhance environmental protection and more fully address poverty reduction. In the case of water resources, PES is typically targeted at upstream resource users, whose land management practices affect downstream water quality and quantity. PES can also be used to address global goods such as carbon sequestration and biodiversity conservation—the former through the CDM (discussed in the subsequent CDM section) and the latter through certification approaches like shade tree coffee and certified organic production that fall outside the range of conventional PES programs.

PES and Climate Change The heightened risk of environmental degradation and changes in the abundance and quality of shared resources, expected with climate change, are likely to magnify the impact that unsustainable land-use practices by upstream communities have on the well-being of downstream communities. Because of the risks posed by climate change in exacerbating unsustainable land-use impacts, the diverse needs of upstream and downstream resource users should be considered when formulating adaptation responses. PES could provide a means to move adaptation in this direction, through providing incentives for the conservation or protection of resources at critical junctures in the ecosystem while potentially providing a means of diversifying rural livelihoods away from reliance on climate-sensitive natural resources.

The expected negative impacts of climate change on water discharge in regions where mean precipitation decreases, snow melt occurs earlier, or the distribution of annual precipitation shifts toward warmer periods, with subsequently greater evaporative demand, justify the need to more closely examine PES as a tool for encouraging water conservation. Such an approach has been proposed for managing hydrologic discharge from the Tibetan plateau under future climate change (Immerzeel, Stoorvogel, and Antle 2008). Projected climate change impacts in the Tibetan plateau—namely, accelerated glacier retreat and shifts in stream flow timing from spring to winter—could have major effects on large populations of downstream water users, both for agricultural and nonagricultural purposes. Springtime water release from the plateau represents the major water source for irrigated dry-season agriculture in downstream areas of India, China, and Bangladesh. In this situation, PES could be used to pay upstream farmers to conserve water, while also providing them with the technical means to do so, and to bring more efficient water-pricing policies to the use of irrigation water throughout these river basins. Such an effort would require significant investments in building the capacity of institutions to support intra-regional coordination and to meet the needs of local communities engaged in a PES scheme, as discussed later in this section.

Applying PES to Climate Change Adaptation Current applications of PES to actual adaptation planning have been quite limited. PES has been proposed for use in adaptation projects by the Center for International Forestry Research (CIFOR) in Indonesia, Central America and West Africa as a means of promoting adaptation to water shortages, forest fires and landslides, and for a UNDP-led mitigation-adaptation project for watershed management in Panama. China's Sloping Land Conversion Program (see **Box 6.3**), while not designed as a PES initiative to support adaptation, does provide some potential lessons regarding how PES can be used as a tool for reducing risks from extreme events.

Operational Considerations for PES Incorporating PES into adaptation planning will require access to climate projections at reasonably fine scales for resource allocation decisions by implementing agencies and significant coordination among institutions responsible for financing PES and implementing agencies and institutions. Even without considering climate change impacts and adaptation, the coordination issue is substantial. Institutional capacity building needs at the local level include basic literacy and education in understanding contractual agreements, climate change educational campaigns at the local level, and technology transfer and extension support to farmers for conservation practices. Other operational issues associated with PES include addressing the period of time payments will be needed, who will pay, and who will be targeted by PES.

Over how long will payments be needed? Pagiola and others (2007) pose this question with respect to a PES project on silvopastoral systems in Nicaragua. Short-term payments are sufficient only if the project can generate enough secondary benefits to "tip the balance" in favor of sustained use of environmentally correct practices, beyond the life of the project. Even where this is achieved, long-term payments may still be desirable to provide some conditionality over other land-use decisions that affect ecosystem service flow. Risks of ecosystem service disruption from climate change would likely necessitate a long-term horizon for environmental service payments.

Who will pay? Long-term payments, such as those that would be targeted at adapting to climate change, require long-term financing. Public-sector funding, some of it through development assistance, is the main source of funding for PES programs in agriculture and related natural resource management sectors. Programs financed from government budgets may require continual justification of the environmental service. This is where

Box 6.3
"GRAIN FOR GREEN" AND PES

The Sloping Land Conversion Program (SLCP), also known as Grain for Green, was initiated by China in 1999 in response to severe drought in the Yellow River Basin and a series of devastating floods in the Yangtze River Basin. This initiative essentially serves the function of a payment for environmental services (PES) scheme by providing farmers with in-kind grain and cash compensation or free seedlings for planting perennial grasses, fruit trees, or timber-producing trees on sloped lands vulnerable to erosion in return for rehabilitating severely degraded land. While the SCLP does not explicitly account for climate change adaptation, the program does have the potential to enhance the adaptive capacity of communities in the affected area by reducing risks of soil erosion, desertification, and flooding associated with increased extreme events from climate change. Grain for Green represents the largest land retirement program in the developing world, with 15 million hectares of degraded cropland targeted for afforestation by 2010. Programs on this scale are not possible in most developing countries, both in terms of large public expenditures for a PES scheme and the required level of social compliance to make top-down initiatives like the SLCP possible. However, this example does contain some insights on how to make environmental service initiatives like the SLCP more responsive to potential adaptation needs:

- *More careful targeting of environmental services to current and future precipitation trends*. Increased water consumption from the widespread planting of trees in the arid north-central Loess Plateau region could further strain the region's water resources. Near- and long-term projections of how the region's water budget will be affected by climate change are needed to assess whether large-scale afforestation efforts can be sustained or whether alternative revegetation approaches are needed.
- *Greater integration of rural development priorities into PES planning*. Multiple approaches are needed to diversify rural livelihoods so as to take pressure off of threatened ecosystems. Complementary programs in rural credit, off-farm livelihood diversification, access to extension services, and land rights enforcement, among other factors, need to be integrated into a PES scheme so as to amplify its socioeconomic benefits (Bennett 2008).
- *Careful consideration of permanence issues*. There are no guarantees that set-aside land will not be brought back into crop production after the subsidy period ends. Program surveys in some areas have indicated potentially high reconversion rates because of inadequate access to nonfarm income sources. Bringing an adaptation focus to a program such as the SLCP could necessitate a risk analysis of how reconversion to cropland would fare with potential changes in the magnitude and frequency of extreme climate events and temperature rise and what remedial efforts (stress tolerant crop varieties, new types of crops, water and soil conservation practices, pest management, etc.) would need to be put in place to ensure that forested land reconverted to crop production is resilient to climate change risks.

policy makers will need access to information about potential climate change impacts on the targeted resource.

Who will be targeted by PES? By its design, PES is not a poverty reduction program. However, it can be made more pro-poor by addressing high program transaction costs through innovative mechanisms such as collective contracting, by complementary efforts to improve land tenure security, and by ensuring that the social context of the PES project is well understood so that further marginalization of the landless poor can be avoided or mitigated through specific measures. Making the project explicitly pro-poor raises the cost of PES, for which sustained donor funding of these extra safeguard measures may be necessary. In light of the adaptation challenge, the question of whether a PES project would enhance or diminish a community's social networks and ability to engage in collective actions needs to be assessed.

In addition to these issues, promoting PES will require investment and capacity building in:

- Modeling capacity to better understand relationships between land management and ecosystem services, integration of climate models into the assessment process to determine how the resource availability and quality could change over time, and economic modeling of cost/benefit allocation.
- Generating knowledge of how to match PES with people's actual willingness to pay and mechanisms through which payment transfer would occur.
- Capacity building for institutions that provide support services for monitoring, financing, and complying with PES projects and provide participant farmers with access to credit, information on prices, market opportunities, and conflict resolution mediation.

A potentially critical shortcoming of using PES for adaptation relates to its timeframe. PES is not designed to be a long-term intervention; yet adaptation to climate change is a long-term challenge. PES can be used to complement or possibly accelerate longer-term adaptation efforts aimed at livelihood diversification. Climate change will also present unique challenges to the PES approach in that historical cause-and-effect relationships may no longer hold, and there may be a lack of clearly definable thresholds for some ecosystem services, particularly in response to extreme climate events.

PES and the Clean Development Mechanism

The capacity of agroecosystems to capture and store carbon is one important ecosystem service for which a formalized payment scheme, the Clean Development Mechanism (CDM), has been developed. The CDM is an arrangement under the Kyoto Protocol allowing industrialized countries with emission-reduction commitments to invest in projects that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries. It provides a means for establishing an agricultural carbon market through Certified Emission Reductions (CERs) for reforestation and afforestation projects, including agroforestry projects.

As currently configured, the CDM has low potential in the agricultural sector because it excludes two other major forms of carbon storage: soil carbon sequestration and avoidance of deforestation. Agriculturally relevant land-based activities that are currently acceptable under the CDM, such as agroforestry, only account for 1 percent of total funding. With the Kyoto Protocol's first commitment period expiring in 2012, the carbon market for agriculture could be greatly expanded if new rules are adopted for the CDM post-2012 to provide payments for these other forms of carbon sequestration. Indeed, developing regions offer the greatest future potential for greenhouse gas mitigation in agriculture. However, significant barriers exist to fully realizing agriculture's technical mitigation potential: low permanence and potential reversibility of terrestrial carbon sinks, mechanism and measurement uncertainty with respect to trace gas emissions and carbon storage in biological reservoirs compared with those from industrial mitigation activities, and high transaction costs associated with establishing a carbon market in rural areas of the developing world (Smith et al. 2007b).

The CDM and Agroforestry Agroforestry systems best positioned to take advantage of the CDM are those that occur in humid agroecological zones and include such systems as tree gardens, plantations, and community forestland. The scope for developing markets in the provision of environmental services or carbon offsets in agroforestry systems of dry subhumid and semi-arid agroecological zones is less promising. These systems (fodder trees in silvopastoral systems, improved fallows, and farmer-managed natural regeneration) have low carbon densities and permanence and occur where infrastructure and markets are poorly developed. However, decentralization and the rise of rural communes, in the context of semi-arid West Africa, could offer a potential avenue for developing aggregate carbon offset schemes, administered by village-level committees, that would be more aligned with pro-poor development policies than is possible through the current CDM configuration (Tschakert 2007a).

Improving the prospects for the CDM in agroforestry requires generating better quantitative information about above- and below-ground carbon stocks and non-CO_2 greenhouse gas emissions from different agroforestry systems and addressing the regulatory and operational hurdles of the CDM, including:

- Information about technology, markets, and market players.
- Viability of provisions to allow farmers to periodically harvest and market wood.

- Creation of impartial institutions for project implementation, monitoring, verification, and selling, as well as conflict resolution issues related to CDM projects. (Reviewed by Roshekto, Lasco, and de Los Angeles 2006)

The considerable transaction costs associated with these regulatory issues must be addressed if agroforestry under the CDM is to be viable. Formation of producer organizations, linkages with NGOs, and support for education and literacy can all help to improve local buy-in and reduce risks to participating farmers. Also, mechanisms for bundling carbon so as to reduce unit transaction costs need to be developed in order to improve the economic viability of the CDM for agriculture. Lastly, safeguards need to be built into CDM projects—such as social financing that tailors CDM projects to low income groups—to reduce the likelihood that benefits are disproportionately captured by wealthy landowners (Brown et al. 2004; Tschakert 2007a) Initiatives such as the World Bank's Community Development Carbon Fund are beginning to address equity issues (see **Box. 6.4**), although a range of approaches must still be developed and tested to determine whether they are appropriate to meet the needs of targeted communities. For example, mechanisms that address conflict management issues that could arise from implementing the CDM in impoverished regions need to be developed (Roncoli et al. 2008).

IV. Livestock Management in a Warming World

Livestock represent a critical livelihood resource, and one that is likely to increase in importance in areas that become increasingly marginal for annual crop production as a result of climate change. Livestock are an important fungible asset for the rural poor; they provide a major source of savings and help farming communities buffer against emergencies, including crop failure.

Climate change is expected to significantly affect the livestock sector through direct impacts on livestock physiological processes and indirect impacts on crop and rangeland resources, which affect feed allocation and land management decisions. Increased temperatures are one of the most pervasive climate change risks to livestock, directly affecting species across geographic regions and production systems. Livestock systems in the tropics and subtropics are expected to be the most strongly affected by temperature rise, with the exception of high-altitude areas. See **Box 6.5** for a discussion of regional impacts. High ambient temperatures affect animal performance by increasing body temperature that must be dissipated, and humidity intensifies temperature effects, further affecting animal comfort and performance. Livestock productivity in temperate areas, however, is expected to benefit from temperature rise because of milder winter months and longer growing seasons. In addition, the projected

Box 6.4

WORLD BANK CARBON FINANCING INITIATIVES AND ADAPTATION IN THE AGRICULTURAL SECTOR

The BioCarbon Fund and the Community Development Carbon Fund were developed by the World Bank to promote sustainable low carbon development. Funding adaptation through these types of carbon-financing schemes could potentially serve to also expand the effective financial base for adaptation. The three principal entry points for achieving this are:

- Optimizing synergies between carbon storage in CDM reforestation/afforestation projects and adaptation benefits, such as those derived from agroforestry projects that provide natural resource base protection, buffer against flood damage, and diversify rural livelihoods.
- Direct diversion of financial flows generated by carbon finance projects to community-level development efforts, whose focus could be shifted to support community-level adaptation.
- Premium payments added onto a carbon finance project that would be specifically allocated for adaptation.

Developing the necessary pathways for funding adaptation through these types of carbon finance measures do, however, face significant constraints related to a temporal mismatch between carbon finance and adaptation (time scales for the former are generally shorter than for the latter), additional costs of including adaptation in carbon finance projects, and potential priority setting conflicts between carbon finance and adaptation. In the case of optimizing synergies among land use, land-use change, and forestry (LULUCF) project outcomes and adaptation, the costs of additional measures to ensure adaptation, such as technical studies that modify project design to incorporate adaptation elements, can be difficult to justify. To address these potential shortcomings, Gambarelli, Gastelumendi, and Westphal (2008) recommend incremental measures such as piloting adaptation initiatives in community benefit planning,[4] as is done through the World Bank's Community Development Carbon Fund, and developing a ranking scheme for identifying priority areas/entry points for adaptation that could be considered in Forest Carbon Partnership Facility projects.

4 An example of the piloting effort is the present collaboration between the World Bank's Africa Agriculture and Rural Development Unit (AFTAR) and the BioCarbon Fund to identify greenhouse gas mitigation projects in western Kenya that can be designed to encourage sustainable agricultural land management practices that include using various drought-tolerant crops.

increase in temperature and CO_2 concentrations and shift in precipitation patterns will affect plant communities, upon which the livestock depend, by changing the length of the growing season, species composition, and nutrient quality. The primary adaptation strategies to better enable animals to cope with heat stress include genetic modifications to improve heat tolerance, feeding modifications that reduce metabolic heat buildup, and development of structures or facilities to protect livestock against higher temperatures.

Box 6.5
POTENTIAL CLIMATE CHANGE IMPACTS ON LIVESTOCK

Asia Most semi-arid and arid lands in West and Central Asia are classified as rangelands, with low productivity grass and brush plant communities. A temperature increase of 2°C to 3°C, combined with reduced precipitation, could substantially decrease grassland productivity and amplify the effects of existing degradation and desertification. In temperate rangelands of Central and South Asia, the potential conversion of C_3 to C_4 grasses could alter the grazing season and animal productivity, though significant knowledge gaps remain as to the influence of changing grassland composition on livestock.

Africa Rising temperatures and negative precipitation trends could lead to a reduction in crop growing season length throughout Africa's vast rainfed production areas, particularly in the mixed rainfed crop-livestock systems and for rangeland species in arid grazing systems. Plant productivity may increase in humid and subhumid areas. In the Mediterranean areas, communities of forb (herbaceous flowering species) may be at risk of disappearing if precipitation patterns change.

Latin America In savannas and rangelands, brush encroachment could reduce areas available for grazing, while in humid and subhumid zones, biomass production could increase, but poor forage quality could limit livestock production. In the South American cone, increasing precipitation and temperature may permit more alfalfa production to occur.

Genetic Modification to Improve Heat Tolerance

The ability of an animal to self-cool is determined by its capacity to reduce body temperature by increasing its respiration rate, by its hair coat and coat color properties, and by phenotypic attributes (e.g., large ears, excess skin on the dewlap) that shedheat, such as described in Box 6.6. Genetically mediated physiological responses to heat stress exist for an array of traits, including anatomical characteristics, coat color, metabolic function, and protein response at the cellular level. At the cellular level, thermal tolerance is maintained as long as heat shock family proteins are elevated and lost when expression of these genes declines under continued stress (Collier and Rhoads 2007). All of these characteristics are genetically mediated and amenable to selection via traditional quantitative methods or new molecular approaches.

Breeds respond differently to heat stress as measured by their performance levels. Genetic modifications within breed selection are possible and have been success fully employed to develop more highly adapted animals. Also, research on heat shock proteins offers potential for identifying additional selection criteria.

Institutional and Policy Responses
Institutional support for genetic improvement is needed. Unlike crops, livestock ownership and decisions concerning genetic modifications are private-sector/smallholder decisions. Therefore, institutional support for adapting livestock to climate

Box 6.6
"SLICK-HAIRED GENE"

A complex genetic trait termed the "slick-haired gene" has been identified in cattle in Latin America and the Caribbean. These cattle have shorter, denser hairs with increased sweating capacity. In Venezuela, 70 percent of the Carora breed exhibits this characteristic, and, when crossed with Holstein (a breed of highly productive dairy cows) s, the progeny exhibiting this trait were able to reduce body temperature by 0.5°C, produce nearly 1,000 kilograms more milk per lactation, and had a significantly shorter calving interval (43 days less) than normal-haired F_1 sisters (Olson, 2006).

change should focus on information systems that provide breeders with the tools needed to make selection decisions. For many countries, this represents a significant departure from the experiment station model prevalent with crops. Establishing genetic research capabilities to utilize data generated by producers (e.g., pedigree and performance measures) and developing and utilizing molecular genetic techniques will become increasing necessary. Strengthening the technical capacity of extension services will be required to facilitate the flow and use of information. Policies that would support the wider use of beneficial genetic resources in livestock include those that promote the movement of animals and/or germplasm (semen or embryos) among farms, regions, and countries (assuming appropriate health protocols are in place) and reduce national or international trade barriers on genetic exchange.

Nutrition and Feeding Strategies That Reduce Animal Heat Stress

For ruminants, the digestive process contributes to increased body temperature, particularly with low quality diets. Higher quality diets can reduce metabolic heat production through the use of feed additives (ionophores), supplemental feeding, and modifying how animals are fed (e.g., time of day)—all of which have the ability to lower body temperatures by reducing the effects of heat produced during rumination (**Table 6.2**). These technologies are well tested and applicable across geographic regions and ecosystems, and their use need not permanently alter management. Rather, they can be implemented during heat waves or feed shortages and can be combined with the genetic modifications presented in the previous section. However, a primary deterrent from using these technologies will be cost and availability. Across regions, improved methods for harvesting and preserving various crops, crop by-products, and hays will be needed to raise the nutrient quality to minimize the contribution to animal heat load.

Increased ambient and body temperatures depress feed intake and performance, and less digestible diets result in a greater reduction in feed consumption (Beede and Collier, 1986). However, feeding strategies can be used to reduce body temperatures. For example, by reducing the level of roughage in ruminant diets, the effects of elevated body temperatures can be mitigated (NRC, 2000). Other strategies include

TABLE 6.2 Nutrition and management technologies for livestock

Technology	Production System	Implementation Process	Intended Result	Impact on Greenhouse Gas Emissions
Feed additives	All systems, especially mixed crop-livestock systems.	Access to input supply and finance to acquire ionophores; ability to administer correct amounts.	Decreased body heat; improved animal performance.	Reduces methane and nitrogen emissions.
Supplemental feed	All mixed crop-livestock and extensive grazing systems.	Access to crops or crop residues that can be stored and potentially processed into a higher-quality supplement.	Provision of emergency feed during dormant periods for plants; increased digestibility of total diet lowering heat production; increased animal performance.	Lowers methane and nitrogen emissions.
Feeding times	All mixed crop-livestock and industrial systems.	Shift animal feeding time to late afternoon or evening.	Lower body heat and increase in animal appetite.	No effect.

limiting the amount of feed consumed and feeding cattle in the late afternoon instead of the morning (Mader et al. 2002; Davis et al. 2003). Ionophores are a feed additive, which reduces feed intake and, therefore, lowers body temperatures and improves feed use (Guan et al. 2006). They also reduce methane emissions by 25 to 30 percent and nitrogen loss through better absorption in the small intestine (Tedeschi et al. 2003).

Shade Structures

Another strategy to reduce heat stress involves providing animals with shade. As temperatures build during the course of the day, heat stress increases cause higher respiration rates and increased water intake, sometimes by 50 percent, and a desire to seek shade. As the sun sets, animals lose excess body heat accumulated during the day. The dynamic nature of this process affords livestock managers opportunities to devise various strategies that can minimize the impact of heat stress. Livestock producers can lower the impact of heat stress by providing animals with shade, positioning corrals so they are exposed to wind currents, allowing animals to graze during the night, and providing animals with access to water (in some cases, twice the normal quantity is required).

Physical shade structures could become an essential adaptation option in warm regions (e.g. Latin America, Asia, and Africa) where livestock are an important element of food production. Shade structures can include trees planted in or around stalls in mixed crop-livestock systems, tree planting and windbreaks in pastures, constructed facilities like sheds, and more advanced structures that include fans and mist systems. Planting trees or vines that can double as a source of feed or cash crop could be appealing to mixed crop-livestock producers.

Conclusions

- Agriculture will have to become more efficient in order to reduce the growth rate of new greenhouse gas emissions in meeting rapidly rising future food needs.
- Multiple and diverse opportunities exist to couple adaptation with mitigation in a manner that can both meet current productivity and sustainability need, and prepare agriculture for adaptation to and mitigation of future climate change. However, trade-offs need to be considered.
- Soil management is one area with high potential for addressing both mitigation and adaptation needs, through efforts to reduce the global warming potential of agriculture by improving nitrogen-use efficiency, while increasing carbon storage in soils and plants. Integrated soil fertility management is a key strategy for achieving this.
- Realizing the potential of market-based incentives—such as payment for environmental services and the Clean Development Mechanism—to promote sustainable land use, and thus reduce vulnerability to extreme climate events, will require significant investments in institutional capacity building, as well as education and skill development of local stakeholders.
- Effective management of and adaptation in the livestock sector in the face of challenges posed by climate change are linked to sustainable land management. Adaptation strategies in the livestock sector include those that reduce heat stress, such as genetic modification, natural and manmade shade structures, and modified feeding strategies.

CHAPTER 7: CROP GENETIC DIVERSITY AND SEED SYSTEMS

SUMMARY: This chapter examines the potential of research and development in plant breeding to enhance adaptation efforts in agriculture. It addresses both the technical issues of developing drought, heat and salinity tolerant crop varieties, and the potential threat to the world's crop genetic heritage posed by climate change, and hence the ability to develop new crop varieties as needed. The chapter begins by describing recent progress in plant molecular biology and genomics and its implications for developing crops adapted to climate change. It then explores the potential threat of temperature rise on crop wild relatives (CWR) and suggests priorities and strategies for coping with this threat. The chapter concludes with an exploration of how poorly functioning seed systems can exacerbate vulnerability to extreme climate events and provides options for improving their performance as an adaptation measure.

I. Advances in Plant Breeding

The development of crop varieties with enhanced tolerance to heat, drought, and salinity stress is widely viewed as an essential long-term adaptation response to climate change. The potential for achieving better-adapted varieties is promising, given recent advances in molecular biology and genomics (such as marker-assisted breeding) that facilitate the process of identifying sources of abiotic and biotic stress tolerance, which can be backcrossed into existing varieties (Ali et al. 2006).

Conventional Plant Breeding

With these new tools, conventional plant breeding has made tangible progress toward developing varieties better suited to stress-prone environments. For example, the recent identification of genes responsible for salt and submergence tolerance is expected to accelerate the process of developing rice varieties that can perform well in flood-prone environments or in irrigated systems with salinity problems. Submergence tolerance is already moving in that direction, with the recent success in backcrossing the submergence gene *Sub1* onto a widely grown "mega variety" of rice capable of tolerating 14 days of submergence (Neeraja et al. 2007). Sources of heat tolerance have been identified and bred into crops such as wheat, which—because of its geographic reach into warm regions—is sensitive to temperature rise (Ortiz et al. 2008). Strategies for heat avoidance, such as breeding crops to flower earlier in the day and thus escape high-temperature stress, also show promise. Genes for drought tolerance have been identified, although developing drought-tolerant varieties is more difficult because of its complex physiological mechanisms. In all of these breeding efforts, genotype by environment interactions, which reduce the effectiveness of the targeted trait, remains a challenge.

Integrated Approaches for Plant Breeding

Plant breeding efforts for drought, salinity, and heat tolerance would benefit from greater inclusion of other yield-limiting and reducing factors in the selection process, given that changes in the crop-growing environment, either brought about directly by climate change or by adaptation measures in response to climate change, may lead to secondary effects. These multiple influences require integrated plant-breeding solutions. For example, Asian paddy rice production is beginning to move away from continuous flooding toward nonflooded upland growing conditions in response to rapidly growing water demand from nonagricultural sectors, with climate change likely to give an addition push to this effort. Yet, fundamentally altering water management for a major crop like rice can usher in a new set of pest and nutrient management problems (as has been observed in India and China with the introduction of water-saving innovations), requiring that concerted breeding efforts be accompanied with investments to improve agronomy and pest management.

Also, many of the regions in which climate change impacts are expected to be most disruptive to agriculture are dominated by soils with severe phosphorous and calcium deficiencies and aluminum and manganese toxicities, all of which limit root system development and water uptake by plants. Biotic constraints to root growth and function are also significant in these regions, with plant-parasitic nematodes and weeds among the two greatest constraints to the crop root's access to soil water. Thus, in considering an overall plant-breeding approach for adaptation, support for a more explicit emphasis on integrated problem solving would likely lead to greater efficiency in the varietal development process. The International Center for Tropical Agriculture's (CIAT) breeding program for common bean, which integrates low soil fertility tolerance with drought tolerance, is one such example of this approach (Ishitani et al. 2004).

Improved varieties have made substantial headway in improving agricultural productivity in irrigated and favorable rainfed areas of the developing world, with an estimated 50 percent of the yield growth in the late 20th century due to their widespread use (World Bank 2008). Coverage by these varieties now dominates wheat and rice production areas in most regions and is important in maize, sorghum, and potato areas in South and East Asia, although the rate at which farmers continually adopt newly introduced improved varieties as opposed to relying on old releases is quite variable.

Transgenic Technologies

The development of transgenic crop varieties can potentially offer a more targeted and efficient approach for abiotic and biotic stress-tolerance breeding than is possible through conventional breeding through processes that transfer a gene or set of genes conveying specific traits within or across species. For example, overexpression of the Dehydration-Responsive Element Binding (DREB) gene 1 and 2 (DREB1and DREB2) using a plant model (*Arabidopsis thaliana*) system was recently found to induce drought- and salt-responsive genes as well as heat-shock-related genes (Ortiz et al. 2007, and citations therein). Efforts are now under way to isolate the same abiotic stress-inducible gene response in major cereal crops.

While good potential exists for transgenics to strengthen breeding efforts, the technology faces significant hurdles. For one, transgenic lines have biophysical limitations with respect to the direct extrapolation of single-gene responses from model studies to crop species that would be exposed to field conditions. This problem is compounded by biosafety concerns that make it difficult to scale up experiments from pot studies to field trials. Secondly, current investments in transgenics are concentrated in the private sector driven by commercial interests and not focused on the needs of the poor. Public investments in the technology and transparent mechanisms for public input on its development and use, along with robust risk assessment measures, are needed. The International Maize and Wheat Improvement Center (CIMMYT; Ortiz et al. 2007) proposes development of a new research paradigm based on a "user-led philanthropy-private-public partnership." Intellectual property rights issues with the private sector would need to be resolved for this to move forward.

Capacity Building and Institutional Strengthening Needs for Plant Breeding

Responding to the challenges of developing stress-tolerant crop germplasm adapted to a changing climate requires:

- Broad investments in education and training for plant breeding.
- Improvements in physical infrastructure to support research, as well as better coordination between international and national plant-breeding centers.
- Promotion of knowledge sharing through stronger coordination among plant breeders, agronomists and soil scientists, natural resource managers, social scientists, and integrated pest management specialists and through strengthening linkages between research and extension (subsequently discussed in Sections 2 and 3).

II. Conservation of Agricultural Genetic Diversity for Adaptation

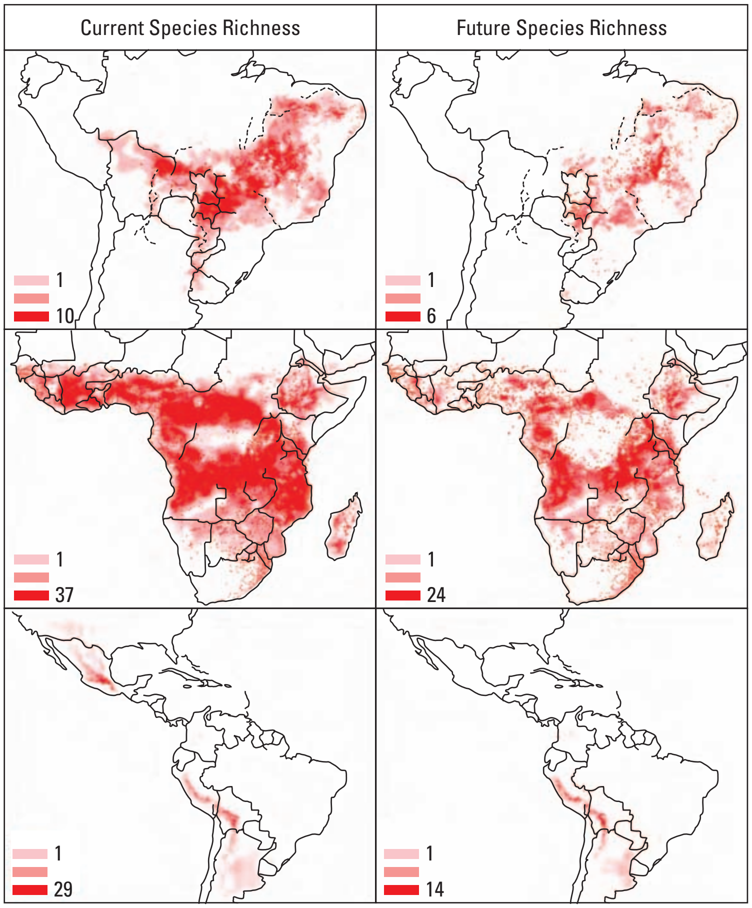
The capacity of plant-breeding efforts to provide new crop varieties adapted to increased abiotic stress, and to the emergence of new pests and increased pressure from existing pests, depends on a "continual process of genetic enhancement" from landraces (also known as farmer varieties and traditional varieties) and crop wild relatives (ancestors and closely related species of contemporary crops) . These sources of novel genes have long been critical to the ability of crop improvement programs to respond to acute pressures on crop production. The recent emergence of highly virulent and rapidly dispersed races of soybean and wheat fungal rust pathogens underscores the gravity of this threat. The need for diverse genetic parent material is also being driven by the reorientation of breeding programs toward the development of varieties that contain both modern high-yield potential and specific traditional crop characteristics. For example, reinserting photoperiod sensitivity back into modern sorghum cultivars gives farmers more flexibility in sowing dates in semi-arid environments where the onset of the rainy season can be highly variable (Dingkuhn et al. 2006).

Crop Wild Relatives

The genetic diversity contained in CWR and landraces is essential to the future viability of global food production irrespective of climate change. Three-quarters of the world's crop diversity was lost during the previous century, and only a fraction of the total genetic variability is stored in the world's genebanks. Climate change could exert a significant additional pressure on existing drivers of genetic erosion—uniformity in agricultural systems, land degradation and habitat loss. Jarvis, Lane, and Hijmans (2007) recently evaluated potential changes in diversity, range size and fragmentation caused by climate change to CWR of peanut (*Arachis*), potato (*Solanum*) and cowpea (*Vigna*) using species migration scenarios of none, limited, and unlimited. They estimated that 16 to 22 percent of wild relatives of these three crops could become extinct by mid-century, that most species could lose more than 50 percent of their geographic range size, and that suitable habitats could become highly fragmented (**Figure 7.1**).

Wild peanuts were found to be the most affected, with 47 to 61 percent of *Arachis* species projected to go extinct and their average distribution reduced by 85 to 94 percent. The vulnerability of these *Arachis* species arises from the fact that they occur in relatively hot and dry environments and in flat regions, thus requiring large migration distances to track their climatic bands. Several of the *Arachis* species projected to be most affected are critical for breeding resistance to economically important pests and pathogens, including root-knot nematodes, corn earworm, southern corn rootworm, and early leaf spot. Wild potato species are projected to lose an average of 52 percent of their climatically suitable habitat, with sources of resistance to the highly destructive Colorado potato beetle pest among the species affected. For example, *Solanum* species are at high risk for habitat fragmentation. Cowpea was projected to lose only zero to two species, but with an average of 51 percent reduction in climatically suitable habitat. The estimates by Jarvis, Lane, and hijmans (2007) do not account for other sources of habitat alteration, such as land degradation and harvesting pressure from wild habitats; thus, the potential threat to these and wild relatives of other important crops could be even greater.

FIGURE 7.1 Effect of climate change on species richness of CWR of (top) groundnut (Arachnis sp.); (middle) cowpea (Vigna sp.); and (bottom) potato (Solanum sp.).



Estimates are for 2055 and were derived using climate envelope models. The scale represents the number of species in each richness class.

Source: Jarvis et al. 2007

The extent and distribution of CWR genetic diversity is difficult to estimate, given the paucity of information available from crop centers of origin, many of which are in developing world regions that have low or competing resource demands for conducting inventories. A strategy to begin defining the scope of the threat and to formulate priority-determining mechanisms is currently being prepared under the auspices of the International Treaty on Plant Genetic Resources for Food and Agriculture. **Box 7.1** describes how a climate change adaptation focus can be applied to crop wild relative conservation.

Conservation management efforts also need to be targeted to unique and highly threatened microenvironments (such as desert oases) that, while not necessarily

Box 7.1

CONSERVING AGROBIODIVERSITY RESOURCES AS AN ADAPTATION RESPONSE TO CLIMATE CHANGE IN YEMEN

As the center of origin for several of the world's important crop species, the Middle East region contains a high diversity of landraces and CWR. In Yemen, traditional agricultural knowledge and practices have helped to maintain high agrobiodiversity through active use of diverse landraces, a strategy that has also helped rainfed communities cope with drought. Agriculture margins in these systems provide habitat for CWR. However, these critical agrobiodiversity resources are threatened by land degradation, globalization, temperature rise and increased drought tendencies projected with climate change, loss of traditional knowledge, and poor institutional support for rural communities.

The World Bank is mobilizing resources to protect Yemen's agrobiodiversity—both because of its global significance regarding efforts to develop cultivars adapted to future climatic conditions and because of the important role that agrobiodiversity plays in allowing communities in rainfed areas of Yemen to effectively manage climate risks. A central component of the Bank's Yemen project (*Adaptation to Climate Change Using Agrobiodiversity Resources in the Rainfed Highlands of Yemen*) involves developing vulnerability profiles of landraces and CWR to climate change, assessing the role of these resources in local coping strategies, and addressing how indigenous knowledge and traditional farming methods influence agrobiodiversity. The project also seeks to improve Yemen's capacity to standardize weather- and climate-related data gathering and to conduct assessments using climate models. This adaptation project was conceived out of a larger World Bank–funded project on rainfed cropping-livestock systems in the Yemen highlands.

a center of origin for food crops, nonetheless have very high landrace diversity (Gebauer et al. 2007). These areas have not been well described. The center of origin for globally important crops is listed in **Table 7.1**.

Land Policies and Conservation

People, not landscapes, conserve agricultural diversity; thus, policies for safeguarding plant genetic resources should be attentive to how the complex dynamics of local collective action and property rights influence conservation. Understanding the local context in which policies are implemented is crucial, whether those policies are for conservation, property rights reform, or agricultural modernization. Examples of how agrobiodiversity and property rights play out include:

- Restriction of access by the landless poor to formerly communal areas, whether through formalization of land tenure or the creation of nature reserves, can lead to loss of knowledge of and incentives to maintain useful species.

TABLE 7.1 Center of origin of globally important crops

Center of Origin	Crops
Near East (Fertile Crescent)	Wheat, barley, flax, lentils, chickpea, figs, dates, grapes, and olives
Africa	Pearl millet, Guinea millet, African rice, sorghum, cowpea, yam, and oil palm
China	Japanese millet, rice, buckwheat, and soybean
South East Asia	Wet- and dryland rice, pigeon pea, mung bean, citrus, yams, banana, and sugarcane
Mesoamerica and North America	Maize, squash, common bean, lima bean, peppers, amaranth, sweet potato, and sunflower
South America	Lowlands: cassava; mid-altitudes and uplands: potato, peanut, cotton, and maize

- Traditional communal property rights systems are more effective for protecting CWR than formalized private land ownership because communities are more likely to recognize the value of protecting these species, whereas individuals have no incentive for providing the space and resources for CWR protection.
- Effective local-level property rights are an essential precondition for developing appropriate institutions and mechanisms to address genetic erosion. (Eyzaguirre and Dennis, 2007)

Capacity-building and institutional-strengthening needs for CRW conservation include:

- Support for research efforts to characterize climate change impacts on CWR species richness and distribution and for priority determining mechanisms of threatened species or ecosystems.
- Building of national/local capacity to conduct species surveys in areas with high endemic CRW diversity.
- Provision of policy support for local and communal access to resources that foster agrobiodiversity.

Landraces

The genetic diversity contained in landraces is also important for adaptation to climate change in that cultivating locally adapted landraces buffers farmer risk in unfavorable environments and natural selection processes that occur through active use of landraces enhance the value of the genetic resource for future crop breeding. (**Table 7.2** provides examples of climatic and nonclimatic risks to landraces and efforts to characterize their genetic attributes.) Cropping systems in marginal farming environments often consist of a mixture of landraces and modern varieties, depending on factors such as the physical environment, level of rural infrastructure, and access to the formal seed sector.

Introducing high-yielding short-duration crop varieties into these environments is a desirable outcome for reducing poverty and improving adaptive capacity to climate change, and some success has been achieved in this area through conventional channels and participatory varietal selection and breeding efforts. New Rice

TABLE 7.2 Partial survey of landrace diversity and its value for crop improvement programs and local coping strategies

Genetic Resource	Country/ Region	Hazards/Risks	Methodologies and Findings	Source
Sorghum landraces	Somalia	Drought. Dysfunctional seed system.	Characterize genetic diversity to identify accessions for use in sorghum improvement program.	Manzelli, Benedettelli, and Vecchio 2005
	Mali	Drought. Varietal diversity under threat from shortening of rainy season.	Characterize genetic diversity of Guinea sorghum race to improve sorghum breeding in the West African Sahel. Wide adaptations to different maturity cycles and microenvironments; good storage traits.	Weltzien et al. 2006
Faba bean landraces	Morocco	Low drought tolerance of commercial faba bean varieties.	Characterize genetic diversity to identify sources of drought tolerance.	Sadiki 2006
		Diminished area under production of landraces.	Identified genotypes with both good drought tolerance and good production potential.	
Maize landraces	Southern Africa	Drought. Limited areas where landraces maintained within a predominately hybrid maize-growing region.	Characterize phenotypic diversity and surveyed motivations for maintaining landraces. Drought tolerance, early maturation, good processing and storage characteristics saved seeds to minimize risk.	Magorokosho, Banziger, and Betran 2006
	Peru	Drought, excess water.	Evaluate effects of dry and wet precipitation regimes on genotypic variation.	Chavez-Servia et al. 2006
Wheat landraces	Turkey	Erosion of genetic diversity in the crop's center of origin.	Stakeholder evaluation of incentives for conservation.	Bardsley and Thomas 2005
Rice landraces	Philippines	Drought, flooding. Poorly functioning seed system, pressure on landraces. Intellectual property rights threaten local seed markets.	Local-scale biodiversity conservation program initiated that reintroduced landraces from adjacent areas and from gene banks, and introduction of or reintroduction of modern varieties. Capacity building for participatory varietal selection and participatory plant breeding.	Carpenter 2005

(*Continued*)

TABLE 7.2 (*Continued*)

Genetic Resource	Country/ Region	Hazards/Risks	Methodologies and Findings	Source
	Nepal	Pressure on landraces.	Assessment of market incentives for enhancing landrace diversity. Markets could have limited capacity to absorb a wide range of landraces; resource-rich households have greater capacity to maintain agrobiodiversity than poor households.	Gauchan, Smale, and Chaudhary 2005
Potato landraces	Peru	Drought. Seed markets for landraces weak but improving.	Investigate role of seed-size management in drought management and livelihood security. Potential conflict between potato seed needs of drought-adapted rural communities and potato breeding programs.	Zimmerer 2003
Date palm	North Africa	Salinity, drought, heat.	Study of phenotypic diversity of date palm and farmer management of genetic diversity. Described genetics-based research priorities for reducing vulnerability of date palm ecosystems.	Rhouma et al. 2006
Many arable crops and landraces	Oman	Desert oases highly diverse but highly threatened.	Survey found high agrogenetic diversity (107 crop species belonging to 39 families). Further surveys and conservation efforts needed.	Gebrauer et al. 2007

for Africa (NERICA) rice for West African environments is a good example of this effort. However, landraces are likely to continue to play an important role in many of these highly variable landscapes for a number of reasons, including high genotype by environment interactions and poor rural infrastructure and extension that limit adoption rates of modern varieties.

Landrace Conservation Efforts and Improved Varieties

Described here are policy considerations for developing more robust landrace conservation efforts and strategies for broadening the reach of improved varieties into marginal environments in a manner that maintains landrace diversity for breeding.

Knowledge of Agrobiodiversity Determinants Devising responsive conservation strategies will require an understanding of the multiple social, economic, and political forces that shape farm diversity management in smallholder production systems. Although no single set of conditions determine positive or negative trends in on-farm genetic diversity, influences that appear to be common across different farming systems include household wealth and gender of household head, livestock resources, strength of social networks, property rights, land size and degree of land fragmentation, market conditions, and access to modern inputs and extension services (reviewed by Rana et al. 2007). Knowledge of background conditions can help in formulating pro-poor initiatives that target conservation of those landraces not already protected through autonomous actions and can be used to identify situations where vulnerability to extreme climate events reinforces genetic erosion, as was recently demonstrated in the Philippines where El Niño drought followed by severe flooding from typhoons resulted in a 50 percent reduction in the number of rice landraces over a two-year period (Morin et al. 2002).

Promotion of Institutional- and Market-Based Incentives Current markets do not reward the broad "social-insurance" benefits of conserving genetic diversity that are borne by a relatively small number of resource-poor farmers. The absence of a positive market signal is further aggravated by institutional and policy failures, such as distortions created by intellectual property rights and poor usufruct of natural resources, which create additional disincentives for maintaining agrobiodiversity (Carpenter 2005). Market incentive mechanisms, such as the creation of "biodiversity-friendly" marketing, could partially address current market failures, although this will require significant institutional investment. It is also unlikely that markets will be able to absorb more than a fraction of potentially marketable landraces (Gauchan, Smale, and Chaudhary 2005; Pascual and Perrings 2007). In a few instances, markets for landraces are reemerging organically, as with the recent improvement of market conditions for "native commercial" potato varieties in the Andes (Zimmerer 2003). Institutional support is important for reinforcing these efforts, such as through support for extension services, farmer organizations, and market intermediaries to improve seed delivery systems.

Support for Participatory Breeding and Variety Selection Programs Over the past few decades, participatory plant breeding (PPB) and participatory variety selection (PVS) methods have been developed, which provide a means of reaching poor farmers in marginal environments who are generally not exposed to formal plant breeding networks. In PPB programs, breeders and farmers work collaboratively to develop varieties that have both superior yield traits and locally desirable characteristics, while with PVS, farmers test and select from a pool of varieties that are best suited to local environments. PPB and PVS have been demonstrated to increase the efficiency and effectiveness of farmer adoption of improved varieties while maintaining biodiversity through the incorporation of diverse landraces into the breeding and selection process. PVS methods that combined hardiness of local germplasm with high-yielding characteristics were central to the success of developing short-duration NERICA rice in West Africa and the Okashana 1 pearl millet variety introduced in southern Africa.

Research Expansion of Varietal Mixtures
Using varietal mixtures, in which several varieties of the same species are grown together, is a well-established practice in smallholder risk-adverse production systems. It provides good yield stability where biotic and abiotic stresses are high and would therefore be appropriate as an adaptation strategy. The performance of varietal mixtures can be enhanced by introducing improved varieties into the mix, while also maintaining a good degree of genetic diversity. The issue of improving the performance of varietal mixtures has been largely neglected by the research community.

Poverty Mapping and Variety Dissemination
Advances in GIS and increased availability of spatial data make it possible to combine agroclimatic classification methods (the conventional means for targeting plant breeding efforts) with poverty-mapping methods to provide a means of better stratifying and directing germplasm improvement programs for resource-poor farmers (Bellon et al. 2005). This approach has the potential to develop improved varieties with locally acceptable traits and is useful for adaptation in that it could increase the reach of abiotic tolerant varieties to marginal environments.

Summary of Capacity Building and Institutional Strengthening Needs for Enhancing Crop Genetic Performance in Marginal Areas

- Building the knowledge base regarding drivers of landrace diversity in rural communities as a means for formulating responsive policies.
- Supporting PVS and PPB efforts that improve the genetic performance of cropping systems while also maintaining diversity.
- Expanding research to improve the performance of varietal mixtures.

III. Seed Systems and Adaptation

Failures in the seed supply system are a critical limiting factor for maintaining landrace diversity, as well as for channeling improved varieties into marginal areas. Moreover, poor availability, access, and/or quality of seed present critical production constraints in many smallholder farming environments, which contributes to food insecurity and entrenched household poverty (Sperling et al. 2004, and practice briefs therein). Seed insecurity has both acute and chronic origins, with the former often superimposed on the latter. Seed insecurity is often brought about by short-term environmental or political crises that arise in endemically poor areas. Emergency seed system assistance in these areas is usually geared to repeatedly addressing the acute symptoms rather than alleviating underlying vulnerabilities, as Sperling and others (2004) demonstrated in their eight-country survey of seed systems in Sub-Saharan Africa. These repeated seed aid interventions can actually reinforce seed system vulnerability by distorting farmer seed procurement strategies and undermining local seed/grain markets and the development of commercial seed supply systems.

Climate shocks on top of low average yields strain seed supply systems. While mechanisms are in place to replenish seed stocks of modern varieties, no systematic means exist for replacing the seed stock of traditional varieties. Informal seed networks are obviously important, but farming communities that maintain high genetic diversity need additional support, such as through improved on-farm seed storage technologies and facilities that can reduce seed store losses from pests and diseases (Morin et al. 2002). In addition, policy development is needed to encourage cooperative seed production linkages between genebanks and their institutions, on the one hand, and seed producers and farmers, on the other, that could bolster local seed systems. For example, Carpenter (2005) describes how rice genetic diversity in a remote area of the Philippines was enhanced through community biodiversity programs that reintroduced landraces from within local and regional zones, and from ex situ seed banks, as well as promoted access to modern varieties.

Challenges in Seed System Function

The functioning of local seed systems can also be negatively affected by seed relief assistance during post-hazard recovery. The delivery of repeated seed aid discourages traditional seed procurement strategies that rely on maintaining landraces, and deliveries of seeds that are poorly adapted to adverse conditions can lead to unwanted crossing with locally adapted varieties that erode the latter's stress tolerance. Also, weed-seed-contaminated seed aid is an important avenue for the unintentional introduction of invasive alien species (Murphy and Cheesman 2006).

Climate change will seriously challenge seed system function to the extent that multiyear droughts or more pronounced drought/flood cycles increase the magnitude of acute crises and aggravate chronic vulnerability. In addition, the possible emergence of new pests and diseases lead to breakdowns in crop production. Adapting to climate change in seed-insecure farming environments requires both addressing current emergency seed relief policies, which are maladaptive with respect to current climate risks, as well as buttressing seed systems to make them more resilient to climate change. Challinor and others (2007) suggest a number of policy areas, in the context of climate change in Africa, that need to be improved in order to enhance the resiliency of seed systems:

- Recognition by governments that seeds of most crops grown by African farmers are unlikely to ever be commercially produced, and thus efforts are needed to enhance availability, access, and quality of seeds for smallholder producers.
- Governments need to decentralize their seed systems and provide greater support for local (informal) seed markets.
- Seed laws should be updated to facilitate cross-border seed movement.
- Strategic seed stocks need to be maintained locally and regionally against disaster, and buttressing the informal seed sector is an effective means for doing this.
- Appropriate strategies for post-disaster seed aid need to be developed, such as seed voucher and fair systems.

Different Capacity Needs for Formal and Informal Seed Network Adaptation

Formal seed networks, consisting of government and parastatal institutions as well as commercial seed companies, are generally associated with high-value production systems where plant-breeding institutions have a strong presence. They generally function well in providing a limited number of favored crops and varieties to high-potential environments but are susceptible to disruption during political crises (Sperling et al. 2004) and are poorly integrated with most smallholder farming systems. Informal seed networks (household stores, local/regional markets, and seed barter) fulfill more than 80 percent of seed demand in the developing world, and thus constitute the major source of seed for the majority of these systems. Informal networks show some degree of resilience in that seed channels, though diminished, do remain open during acute disruptions. However, there is ample need to improve these systems if they are going to be reasonably resilient to impacts from climate change.

Seed System Enhancement Strategies

First and foremost, rural development policies should address the underlying determinants of chronic seed insecurity, which include low and declining yields, food shortfalls during the presowing period that force consumption of the seed supply, and overall household poverty that impedes the ability to purchase seed from local markets. Such policies should address issues of low yield potential as well as access to resources for acquiring seed, such as through targeting agroenterprise development and other income-generating activities at resource-poor households to improve their purchasing power for seeds and measures to increase the availability of household credit.

Potential policy distortions created by direct seed distribution should also be addressed by making the system more demand driven and assessing the potential threat that large-scale seed distribution could have on undermining market function and local seed acquisition strategies. The recently developed innovation of *seed vouchers and fairs (SVF)* offers an alternative to direct seed distribution. In the SVF model, farmers are given a voucher for obtaining seed of their choosing from a central location (a fair) at which they are also exposed to a number of innovations concerning new varieties, production technologies, and livelihood resources. SVF has the potential to strengthen local seed systems in that farmer choice and flexibility are emphasized. In addition, target communities capture most of the benefits, as opposed to seed companies, procurement agencies, and transporters under direct seed distribution. Moreover, this type of venue expands opportunities to introduce new crop varieties as well as adaptation technologies and practices. The SVF approach is knowledge and management intensive, can only reach a relatively small number of farmers, and can be difficult to scale up quickly in response to emergencies. Technical competence in agriculture is an important skill gap in that relief agencies are accustomed to disbursing seed, with few considerations of production issues. Greater coordination between formal and informal seed sectors will be necessary to ensure the sustainability of this model (Sperling et al. 2004).

However, additional mechanisms are needed in order to channel new varieties through informal seed networks, given the absence of a profit motive by commercial seed companies to produce for-subsistence crops and open-pollinated varieties and the limited capacity of government institutions in low-income regions. *Farmer seed enterprises (FSEs)*, targeted at the creation of local and small-scale commercial seed production, offer one means for addressing this gap (e.g. David 2004). Demand-driven FSEs can be used to provide a higher volume of quality seed, increase seed availability of traditional varieties, and provide avenues for the introduction of modern varieties, while improving household income generation particularly for women in areas where they are responsible for seed maintenance. However, FSEs have high establishment costs, and scaling up these programs would necessitate significant external interventions. Also, FSEs could potentially increase social inequality, because the activity requires access to adequate land and labor and would thus favor resource-endowed households.

Summary of Capacity Building and Institutional Strengthening Needs for Seed Systems

- Providing greater support for informal seed systems, including better seed storage methods and facilities, extension support, and information and infrastructure for local/regional seed markets, as well as for demand-driven farmer seed enterprises.
- Reforming seed aid programs through building capacity for SVF systems.
- Fostering cooperative linkages between gene banks and rural communities that maintain in situ biodiversity.

Box 7.2
SEED PRIMING AND SEASONAL CLIMATE RISK MANAGEMENT

Even in the absence of acute crises, household seed supply in semi-arid systems often encounters bottlenecks, given the practice of serial resowing of crops as a hedge against an uncertain onset of the rainy season. High uncertainty around the true onset of the rainy season—often combined with poor-quality seed—leads to slow germination and emergence, causing patchy stands and multiple and delayed replanting. This situation strains seed supplies and results in poor and uneven crop establishment, which is a significant contributor to the productivity gap in semi-arid agriculture. One simple but effective technology for addressing this problem is seed priming, which is the practice of soaking seeds in water for several hours but not enough to trigger pregermination.

Extensive on-farm testing of this technology for wheat, maize, millet, sorghum, upland rice, and grain legumes in Africa and South Asia has demonstrated that primed seeds emerge more quickly, produce more vigorous seedlings with better developed root systems, and reach flowering and maturity earlier than nonprimed seeds, which is important for avoiding terminal drought. Priming often results in higher yields, such as was the case with upland rice, where seed priming increased yields by 40 percent in dry years, compared with an increase of 18 percent during normal rainfall years. Barriers to adoption by farmers are quite low, and the capacity of seed priming to reduce risk of crop loss has, in some cases, induced farmers to invest in fertilizer. This example of seed priming demonstrates that simple and effective techniques exist for better managing climate risk and points to the need for appropriate crop husbandry to guarantee that crop yield potential is fully expressed.

Source: Harris 2006

- Improving seed affordability by poor households through agroenterprises and microcredit.
- Promoting technologically appropriate methods for improving crop stand establishment and therefore conserving seed supply (**Box 7.2**).

Conclusions

- Progress in biotechnology has greatly enhanced future prospects for developing stress-tolerant crop varieties, thus advancing efforts to adapt agriculture to climate change. Greater investments in training and education at the national level and efforts to improve coordination between international agriculture research centers and national agriculture research and extension services are needed to improve development and dissemination processes for new crop germplasm.

- The diversity and abundance of crop wild relatives could be negatively affected by temperature rise, which, in turn, could hamper future crop-breeding efforts. Support is needed for research and capacity-building efforts to estimate potential climate change impacts on species richness and distribution, mechanisms for prioritizing conservation, and policy support for local and communal access to resources that foster agrobiodiversity.
- Landraces are an integral part of agrobiodiversity and are important, at the local scale, for managing risk. Efforts to improve agricultural productivity in systems where landraces are prominent would benefit from including programs for participatory varietal selection and participatory plant breeding that seek to improve the genetic performance of cropping systems while also maintaining landrace diversity.
- Poor seed access, availability, and affordability are significant production risk factors, particularly in rainfed systems that rely on informal seed distribution networks. Extreme climate events can further magnify stresses to seed networks. Greater support of informal seed networks is needed, including better seed storage methods and facilities, extension support, demand-driven farmer seed enterprises, agroenterprises and microcredit that improve seed affordability by poor households, and seed vouchers and fairs for recovery after extreme climate events and other disturbances.

CHAPTER 8: PESTS AND CLIMATE CHANGE

SUMMARY: This chapter examines the potential risks to crop production that could result from increased pest damage under climate change. It begins with a discussion of the potential means through which increased pest damage is possible under climate change and how integrated pest management (IPM) measures could be affected and provides a summary of recent observations of climate–pest linkages. The chapter then explores adaptation options related to developing a risk assessment framework and explores where investments in pest management capacity are needed in developing world regions. In addition, the chapter examines how food safety, in relation to toxins produced by fungal pathogens, could potentially be affected by climate change.

I. Impacts of Climate Change on Agricultural Pests[1]

Agricultural pests severely constrain the productivity potential of global agriculture. The most comprehensive study to date (Oerke et al. 1994) places the combined pre-harvest loss from pests at 42 percent for the world's top eight food crops, with an additional 10 percent of potential food production lost to pests during post-harvest. The overall loss of attainable yield from pests could actually be greater than this, when considering other important tropical cereal and tuber crops not included in the estimation by Oerke and others. Losses from pests are most severe in the subtropics and tropics because of warmer temperatures, longer growing seasons, and, in some regions, year-round production that creates favorable conditions for pests, combined with a generally low capacity to manage pre- and post-harvest pests.

An increase in extreme climate events, changes in moisture conditions, temperature rise, and elevated CO_2 concentrations are expected to magnify pest pressure on agricultural systems through:

- Range expansion of existing pests and invasion by new pests.
- Accelerated pest development leading to more pest cycles per season.
- Disruption of the temporal and geographical synchronization of pests and beneficial insects that increase risks of pest outbreaks.
- Promotion of minor pests to primary pests brought about by reduction in host tolerance and changes in landscape characteristics and land-use practices.
- Increased damage potential from invasive alien species.

1 For the purposes of this report, the term "pest" refers to insect herbivores, pathogens, parasites, and weeds.

- Narrowing of current pest management options, including nonchemical means such as host-plant resistance breeding and biological control. (Burdon, Thrall, and Ericson 2006; Garrett et al. 2006)

It is difficult to accurately quantify the potential impacts of climate change on pest damage because of the complex and highly variable response of pests and their hosts to what could potentially be multiple and interactive shifts in environmental conditions. These conditions include elevated CO_2, ozone, and temperature; changes in relative humidity and cloudiness; shifts in rainfall distribution and wind patterns; and land-cover and land-use change in response to climatic and nonclimatic signals. Nevertheless, there are broad trends in how agricultural pests respond to extreme weather events, such as during El Niño episodes and changes in pest behavior under elevated CO_2 and temperature from controlled studies, which provide at least an initial indication of the potential threat from climate change (see **Table 8.1**). The basic fact that extreme weather events (anomalously dry and wet periods) are a key factor in triggering endemic and emerging pest outbreaks (Anderson et al. 2004) suggests that an increased frequency of extreme weather events, which is expected to occur with climate change, is certain to increase agriculture's pest burden. Dry periods tend to encourage insect and virus outbreaks, while wet periods encourage fungal and bacterial diseases. Additional areas of concern for managing pests under climate change include pest range expansion, increased weed competitiveness, effects of root system pests on crop moisture stress, and potentially reduced effectiveness of IPM.

Range Expansion

Climate change already appears to be contributing to higher over-wintering pest populations and pest range expansion on a limited basis in temperate regions as a result of warmer winters and a reduction in the number of annual cold days. Range expansion through over-wintering is likely to be less important in tropical agroecosystems, although pest movement along elevation gradients from warm lowland to cool upland production zones is possible. Changes in wind patterns and wind intensity due to climate change are also a concern, given the importance of wind as a dispersal mechanism for insects, weed seeds, and fungal spores. For example, during the East Asian monsoon, the low-level jet stream that forms south of the Bai-u front is an important mode for transporting insects, fungal spores, and weed seeds from tropical to temperate regions. There is concern in the region that the front could shift to the north and west, bringing more rice pests to temperate (and warming) rice-growing areas, resulting in more serious outbreaks over wider areas.

Weed Competitiveness

Elevated temperatures and CO_2 concentrations could enhance weed competitiveness.

TABLE 8.1 Observed or modeled effects of climate variability and change on pest damage

Pest	Climate Dimension	Cropping System/Region	Reference
INSECTS			
Brown locust *(Locustana pardalina)**	Increased outbreaks during ENSO events.	Crop and rangeland Southern Africa	Todd et al. 2002
Leaf miner (*Caloptilia* sp.)	Range expansion projected.	Coffee Brazil	Magrin et al. 2007
Southern pink bollworm *(Pectinophora gossypiella)*	Increased winter temperatures predicted to increase range and damage potential.	Cotton Southwestern United States	Gutierrez et al. 2006
Southern pine beetle *(Dendroctonus frontalis)*	Increased winter and spring temperatures predicted to increase range and damage potential.	Forests Southern United States	Gan 2004
White fly *(Bemisia tabasci,* and *B. afer)**	Increased outbreaks during ENSO events/temperature increase effect tied to warmer temperatures. Also invasion of new whitefly species *B. afer.*	Tuber crops Andean region	Shapiro et al. 2007
Green rice leafhopper *(Nephotettix cincticeps)**; Rice stem borer *(Chilo suppressalis)**	Increased winter temperatures predicted to increase range and damage intensity.	Rice Asia	Yamamura et al. 2006
Potato tuber moth *(Phthorimaea operculella)*	Temperature increase of 2°C–3°C expands distribution by 400–800 km to the north and accelerates damage intensity.	Potato Globally	Sporleder, Kroschel, and Simon 2007
PLANT PATHOGENS AND PARASITES			
Southern root-knot nematode *(Meloidogyne incognita)*	Range expansion projected.	Coffee Brazil	Magrin et al. 2007
Soybean cyst nematode *(Heterodera glycines)**	Increased range expansion from warmer winters.	Soybean United States	Rosenzweig et al. 2001
Fusarium head blight (*Fusarium* sp.)*	Increased outbreaks during ENSO events and range expansion projected.	Wheat South America	Magrin et al. 2007
Late blight of potato *(Phytophthora infestans)**	Increased range expansion from warmer winters.	Potato United States	Baker et al. 2004
Asian soybean rust *(Phakopsora pachyrhizi)**	Heavy precipitation associated with hurricanes facilitated transcontinental invasion of the fungus.	Soybean South and North America	Pan et al. 2006
WEEDS			
Witchweed *(Striga hermonthica)*	Range expansion projected.	Wheat African highlands	Vasey, Scholes, and Press 2005)
Several weed sp.	CO_2 fertilization effect increases weed competitiveness relative to soybean.	Soybean United States	Ziska, Faulkner, and Lydon 2006
Sicklepod *(Senna obtusifolia)*; Prickly sida *(Sida spinosa)*	Enhanced weed competitiveness from simulated temperature rise.	Soybean United States	Tungate et al. 2007

* Indicates observed changes under field conditions.

In a recent CO_2 enrichment study of soybean-weed systems, weeds were found to allocate significantly more carbon to roots and rhizomes than to shoots—in some cases doubling the amount of below-ground growth relative to above-ground growth—and invasive weed species were found to be substantially more responsive to elevated CO_2 than to either existing weed species or crops (Ziska and George 2004). These findings have important implications for crop production in that changes in weed community composition, and an increase in below-ground weed growth, could lead to increased crop losses and require more intensive management interventions. Weed competitiveness has also been observed to increase at higher temperatures (Tungate et al. 2007).

Root Disease and Crop Moisture Stress

While the challenge of managing crop moisture stress is largely viewed through its physical (abiotic) dimension, biotic stress to root systems is a major constraint, particularly in the subtropics and tropics where plant-parasitic nematodes are a chronic problem in a large number of cereal, legume, and horticultural production systems (**Figure 8.1**). Future changes in crop water availability caused by shifts in rainfall patterns with climate change could have important implications for managing this pest, especially in subsistence crops. For example, in dryland cereals the negative influence of water deficits on yield has been found to increase in the presence of high nematode pressure, as noted by Nicol and Ortiz-Monasterio (2004) who reported high yield loss from the root-lesion nematode when normally tolerant wheat varieties were subjected to water-stress conditions. Predictions of longer intervals between rains and other intra-seasonal shifts in rainfall distribution with climate change can be expected to magnify this pest problem.

Effects on Integrated Pest Management

IPM is an essential component in many of the world's crop production systems, encompassing a knowledge-intensive set of practices that rely on reasonably predictable parameters of seasonal climate conditions to determine economic thresholds for pest populations. Climate change could impair the reliability of current IPM strategies, requiring the dedication of additional resources to develop new knowledge systems and appropriate measures to counter new pests or the intensification of existing ones. Potential effects of climate change on management practices include the following:

- Host-plant resistance (a major breeding strategy for pest management) may be compromised by high ambient temperatures that trigger deactivation of crop host-resistance genes, and by host exposure to a greater number of pest lifecycles per growing season.

- Loss of crop wild relatives (CWR) could reduce the scope for replenishing new genes in host-plant resistance breeding programs (see Chapter 7).

FIGURE 8.1 Effect of the root-knot nematode (*Meloidogyne incognita*) on root system development of common bean

The two leftmost root systems are infected, while the root system on the right is free of the nematode. An increase in soil moisture deficit and heat stress from climate change could increase susceptibility to yield loss from soil-borne pathogens and parasites, such as nematodes.

Source: Courtesy of John Bridge, CABI

- Increased seasonal climate variability and changes in humidity and temperature have the potential to disrupt enemy-herbivore dynamics, which are important for biological control.
- Loss of soil organic matter and increased rates of soil erosion could reduce the capacity of microbial populations to biologically control soilborne pests and diseases.
- Pesticides could become less effective or persistent under conditions of warming soils, increased rainfall, and CO_2 stimulation of weed biomass. Higher rates of pesticide usage disrupt natural biological control, cause secondary pest outbreaks, degrade the environment, and increase selection pressure for pesticide-resistant populations.[2]

II. Adaptation Options for Managing Pests

Development of a Common Risk Assessment Framework

Quantitative information about future risks of pest damage from climate change is needed in order to determine where to invest resources in technology development and capacity building for pest surveillance and management. The foremost need is to gain basic quantitative information concerning which cropping systems could be vulnerable to increased pest pressure from climate change, such as implications of increased pest damage in food-insecure regions and how that vulnerability could occur (e.g. range expansion of existing pests, potential increase in number of pest cycles per season, and invasion of new pests). A comprehensive risk assessment by experts, using a common framework, is needed given the significant knowledge gaps that exist in assessing risks of pest damage under climate change. The system-wide IPM program of the Consultative Group on International Agricultural Research (CGIAR) would be a logical entity to develop such a framework.

2 As in the case of the brown planthopper, which has developed >200-fold resistance to the pesticide imidaclorpid in a matter of 10 years in China and Vietnam (K.L. Heong, personal communication).

Pest–climate simulation models are an important component of such a risk assessment. The development of temperature- and moisture-based simulation models can help identify where shifts in pest range or intensification of pest damage are possible with climate change and where adaptation measures could be required. For example, temperature models developed by the International Potato Center for the highly invasive potato tuber moth (PTM) revealed that the PTM range could shift about 400 to 800 kilometers north in the northern hemisphere and several 100 meters in altitude in tropical mountainous regions with temperature increases of 2°C to 3°C, and that moth activity and number of lifecycles would increase in its present range (Sporleder et al. 2007).

Investments in Infrastructure, Training, and Education

While nonclimatic drivers of emerging pest problems—such as selection pressure on pests imposed by modern agriculture and pest movement through global agricultural trade—still predominate, climatic influences are expected to become more prevalent. Investments in infrastructure, training, and education are needed both to develop the capacity to respond to new threats and to better manage existing pest problems; thus, a strong synergy between adaptation and development is possible, as discussed in **Box 8.1.** Such investments include:

- Better characterizing and quantifying existing pest problems in the tropics and subtropics, as significant gaps in this basic information for some pests and diseases still exist.
- Improving capacity for surveillance and early detection of pest invasions through building remote-sensing and GIS capacity, as well as through training in the use of molecular tools to characterize pest populations and detect the presence of new pests, and improve field diagnostic skills, such as insect taxonomy.
- Fortifying national agricultural research and extension systems (NARES). In the event of fast-moving plant-disease pandemics—as is currently the case with the highly virulent Ug99 race of the wheat stem rust pathogen,—strong regional, national, and local capacity will be needed to coordinate efforts in pest surveillance and quarantine, plant breeding, and seed multiplication. Strengthening NARES in these research and development areas; rebuilding neglected infrastructure, such as laboratories and greenhouses; and increasing the reach of pest extension services into rural communities are needed.
- Broadening access to interactive database/website resources for archiving and exchanging new scientific knowledge, including relevant molecular and genetics research, as well as cataloguing indigenous pest knowledge.
- Increasing research support for linkages between using cropping system diversity as an adaptation strategy and its implications for pest management.

Box 8.1

***STRIGA* AND CLIMATE CHANGE: ACHIEVING ADAPTATION THROUGH RISK MITIGATION**

Addressing potential secondary impacts of climate change on nonclimate stressors is important for better managing risks that could be amplified by climate change. *Striga* weed management is a case in point. The single largest biotic constraint in dryland areas of Sub-Saharan Africa is the parasitic weed *Striga hermonthica* and related *Striga* species, which occur on more than 40 million hectares of maize, millet, sorghum, and upland rice areas. The weed taps itself directly into the roots of the germinating cereal crop and robs the crop of water and nutrients, causing stunting and wilting; yield losses are often in excess of 50 percent. *Striga* grows well under low-moisture conditions on degraded lands, is closely associated with drought and low soil fertility, and, by extension, with poverty. *Striga* infestations cause US$7 billion in annual yield loss in Africa and directly affect the livelihood of 100 million people and lead to abandonment of land.

Why could *Striga* control be important for managing climate risks?

- Africa is projected to lose arable land as a result of climate change and other factors; thus controlling *Striga* could reduce pressures on the land resource base. *Striga* is an important factor in reducing cereal production viability, and contributes to the abandonment of arable land.
- The altitudinal range of *Striga* is estimated to increase with temperature rise.
- Projected drying trends in Southern Africa could favor further expansion and damage potential of *Striga*.
- *Striga* weed's activity reduces the effectiveness of seasonal climate risk management strategies. Reduced rainfall and shifts in rainfall patterns that delay onset of the rainy season have been found to increase crop loss from *Striga*.

Greater support for integrated *Striga* control (ISC) strategies (*Striga* resistant cultivars, use of nitrogen fertilizers, leguminous crops to draw down the soil seed bank of *Striga* through "suicidal seed germination," hand weeding, and in situ moisture conservation) is needed at the national and local levels to scale up ISC.

Investments in ISC are needed to improve farmer access to:

- Seeds of *Striga*-resistant varieties.
- Fertilizers, which act to both reduce *Striga* viability and increase crop growth.
- Improved markets for legumes used as a trap crop in *Striga* control and the development of multipurpose legume varieties.
- Credit for fertilizer and seed purchase, along with access to seasonal climate forecasts, and risk analysis for use of legumes under highly variable rainfed conditions.
- Extension services, farmer field schools, and farmer-to-farmer networks for ISC promotion.

Sources: Dugje, Kamara, and Omoigui 2006; Stringer, Twyman, and Thomas 2007; Vasey, Scholes, and Press 2005

- Supporting sustainable agriculture efforts related to soil health, rotation methods that reduce weed pressure, and agroecosystem diversification that increases pest predator abundance.
- Encouraging education and extension to lessen pesticide misuse and policies to regulate pesticide marketing.
- Encouraging integrated participatory research efforts. As new IPM technologies and strategies are developed for adapting to climate change, the issue of sustained use will be critical. Sustainability can be bolstered through knowledge exchange between IPM researchers and farmers generated through participatory research programs. Greater policy support for participatory research could help anchor it within a formal institutional arrangement with national agricultural research institutions.

Improved Management of Invasive Alien Species

Invasive alien species (IAS) pose a significant threat to agroecosystems given the high level of damage they inflict on agricultural productivity, their role in causing deterioration of ecosystem services, and the secondary environmental hazards associated with their control. In six countries alone (Australia, Brazil, India, South Africa, the United Kingdom, and the United States), Pimentel and others (2001) calculated that IAS are responsible for approximately US$314 billion in annual damages. Invasive species impose a particularly serious burden in developing regions, through preventing access to rural livelihood resources (agriculture, fisheries, or forestry products), degrading water resources, and impeding efforts to rehabilitate degraded lands (GISP 2004). Invasive species also complicate efforts to sustain use of soil conservation practices. Perrings (2005) estimated that the costs associated with invasive species damage, in terms of agricultural gross domestic production, can be two to three times greater in low-income compared to high-income countries.

Climate change and IAS Climate change could directly accelerate the spread of IAS through changes in rainfall patterns, temperature, and elevated CO_2, which gives IAS a competitive advantage over native species (Ziska and George 2004). Indirectly, it could hasten the spread through causing changes in the structure of natural communities and accelerating landscape fragmentation and degradation that create gaps, which lead to the establishment of invasive species (Bardsley and Edwards-Jones 2007). Extreme climate events such as flooding and high winds can also favor the spread of IAS. Computer-aided assessments are beginning to provide some understanding of the basic contours of the problem (reviewed by Hulme 2005). The most common assessment approach uses a species-specific climate envelope model, where climate scenarios are applied to a species distribution under current climate conditions to predict its potential expansion with climate change. These have generally not been applied to developing-world situations.

Capacity Building for Managing IAS Several opportunities exist for shoring up IAS management that can both address current challenges and help build the capacity to respond to an increased threat level resulting from climate change. Areas for improving capacity include:

- Technical capacity (scientific, policy formulation, diagnostics, and enforcement).
- Information sharing and inter-sectoral planning among institutions that serve agriculture, natural resource management, and environmental protection.
- Policy and legal frameworks at national, regional, and international levels.
- Financial resources and political will.
- Public awareness.

Formulating policies for addressing IAS is complex in that these species can pose a threat to food production and ecosystem services, on the one hand, and provide benefits such as protection against soil erosion and income from agroforestry products and horticulture, on the other.[3] Reconciling these two opposing perceptions of IAS within government institutions and among the public is important for mounting strong public awareness campaigns and stakeholder engagement efforts necessary for subsequent management interventions (Bardsley and Edwards-Jones 2007). Awareness raising about IAS is also important within the international aid community, given that 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, such as through the introduction of fast-growing agroforestry trees and aquaculture species and weed seed-contaminated grain shipments (Murphy and Cheesman 2006).

III. Food Safety and Climate Change

The quality and safety of globally important food crops could be negatively affected by climate change through changes in environmental conditions that favor the activity of toxin-producing food contaminants. Aflatoxins, the toxic metabolites of *Aspergillus* fungal species, are an important source of food contamination that infects food grain during storage. These potent mycotoxins impair human growth and immune system functions, interfere with micronutrient uptake in the diet, are strongly carcinogenic in the liver, and can cause death through acute toxicity. Maize and groundnut are the main sources of aflatoxin exposure in humans because these crops are susceptible to infection by the fungus and are a prevalent part of the diet in the developing regions where drought

3 The vast majority of "alien" species are beneficial for humankind. A significant portion of alien species that become invasive are intentionally introduced for income generation or some perceived environmental benefit.

conditions and low access to proper food storage facilities increase the likelihood of *Aspergillus* infection.

Seasonal Climatic conditions and Aflatoxin Production

Seasonal climatic conditions exert an important influence on aflatoxin prevalence. Drought stress during grain filling and maturity that causes cracked grains and insect damage to the grain creates entry points for fungal infection. Poor timing of the harvest with respect to heavy rains during or just after the harvest and inadequate drying of the crop before storage causes proliferation of the fungus on stored grain. Shifts in temperature and precipitation within the growing season also apparently affect the community composition of aflatoxin-producing fungi (Cotty and Jaime-Garcia 2007). Climatic changes that result in warmer temperatures, increased prevalence of drought and unseasonal rains, and increased relative humidity in regions where aflatoxin contamination is high could potentially exacerbate this human health threat. For example, Chauhan and others (2008) estimated that the risk of suffering significant aflatoxin contamination went from one in 11 years to one in 3 years following late-20th-century changes in the climate in Southeast Queensland, Australia, toward hotter and dryer conditions.

The aflatoxin health threat is greatest in Africa and is also significant in Southeast Asia (Wild 2007). Surveys of stored crops and processed food in West Africa revealed concentrations of alfatoxins to be several orders of magnitude above the *codex alimentarius* standard of 20 parts per billion in some African countries and of 2 parts per billion in the European Union (**Table 8.2**). In a related study in Benin and Togo, 99 percent of the children surveyed were positive for aflatoxin, and approximately one-fourth of the stunting of affected children could be

TABLE 8.2 Aflatoxin concentration in food crops and products from West Africa

Country	Crop	Food Product	Aflatoxin Concentration (ppb)
Benin	Maize		4000
Ghana	Groundnut		216
	Sorghum		80
		Groundnut sauce	943
		Groundnut paste	3278
		Maize dough	313
Nigeria	Millet		200
		Peanut oil	500
		Yam flour	7600

Source: Adapted from Kpodo and Bankole 2008.

attributed to aflatoxins, using multivariate analysis (Wild 2007). In addition to its direct effects on human health, aflatoxin production in food grains also affects trade, particularly in the case of groundnut. The need to meet minimum standards for export also means that the best quality food gets traded while the poorest quality food is consumed domestically.

Aflatoxin Contaminant Control Measures

The presence and growth of *Aspergillus* on pre-harvested crops can be reduced by crop management practices that reduce drought stress on crops, such as planting of early-maturing or drought-tolerant varieties and use of irrigation, as well as controlling insect pest damage to grains during crop development and maturity, management factors that are wholly consistent with climate risk management. Availability of crop genotypes resistant to infection by the fungus and to toxin development can also reduce aflatoxin exposure. The CGIAR's International Institute of Tropical Agriculture (IITA) center in Nigeria has developed several maize inbred lines with good levels of resistance to aflatoxin. New biological control methods have also been developed that use atoxigenic strains of *Aspergillus* to inhibit colonization by toxin-producing strains. Simple and inexpensive post-harvest and storage practices are also effective. Strosnider and others (2006) reported that community-based programs for groundnut drying and storage in West Africa reduced mean serum aflatoxin levels by 60 percent. In addition to these control methods, the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) has developed a very low cost test to detect aflatoxins.

Further support of these efforts will be important for decreasing the potential impact of increasing food contaminant risk with climate change. Better characterization of the scope of the present aflatoxin threat (both agronomically and epidemiologically) in risk-prone regions and impacts of modeling how future aflatoxin levels in food may change with climate change should be a first-order priority. Information about the scope of the problem can help mobilize resources for education and awareness raising, rationalize wider-scale integration of *Aspergillus* control strategies into plant breeding, and prioritize efforts toward better crop storage practices and facilities.

Conclusions

- Climate change is likely to increase pest pressure on agriculture. Changes in temperature and precipitation, increases in extreme events, and loss of ecosystem integrity could increase pest reproductive rates and virulence, shift the distribution and range size of pests, and lead to greater frequency of new emerging diseases and invasive alien species.
- Current evidence of range expansion linked to higher minimum temperatures, new pest outbreaks, or more intensive infestations linked to El Niño episodes presage an increase in biotic stress to agriculture from climate change.
- Climate change has the potential to reduce the effectiveness of current pest management strategies, requiring the dedication of additional resources for developing new knowledge systems and appropriate measures to counter new pests or the intensification of existing pests. A narrowing of pest management options could potentially occur with management strategies that rely on host resistance breeding, use of biological control, and pesticides.
- Adaptation to heightened biotic stress from climate change will require significant investments in enhancing national pest management surveillance, diagnostic and management capacity, and knowledge systems both in terms of local and traditional pest management knowledge, as well as training in molecular methods for characterization of pest populations and breeding.
- Better institutional coordination, information sharing, and public awareness are needed to counter the threat from invasive alien species.
- Toxin production in basic grains could increase with climate change. Efforts to improve food storage facilities, increase adoption of short-duration improved varieties and other drought-avoidance practices, and pre- and post-harvest pest management would reduce the potential for toxin production. National awareness raising, epidemiological studies, toxin-reduction breeding efforts, and biological control are also needed.

CHAPTER 9: ECONOMIC DIVERSIFICATION PERI-URBAN AND URBAN AGRICULTURE

SUMMARY: This chapter examines specific aspects of agricultural diversification that can enhance adaptive capacity, with a focus on agricultural microenterprises and linkages to high-value urban markets. The chapter also addresses urban/peri-urban agriculture (UPA) as it relates to potential climate change impacts and the sector's unique adaptation needs.

I. Agricultural Microenterprises

Diversification of smallholder production systems through agricultural microenterprise development is an appropriate community-level action for reducing exposure to climate risks. Income generated from these practices can:

- Increase the ability of households to protect assets during acutely vulnerable periods.
- Provide additional resources that can be invested in productivity improvements of major crops.
- Enhance the ability of vulnerable groups to prepare for or recover from droughts and floods. For example, microenterprises targeted at women generate significant development benefits, which reduce their vulnerability to extreme climate events.

Examples of recent adaptation projects/assessments where vegetable, fruit, or similar enterprises were identified as preferred adaptation options include:

- *South Africa:* Vegetable gardening and fruit tree planting in drought-prone maize growing areas (Thomas et al. 2005).
- *Bangladesh:* Homestead gardening, mango cultivation, mulberry intercropping, fodder cultivation, and cottage industries in drought-prone rice-wheat areas (FAO 2006).
- *India:* Expanded opportunities for off-season vegetable gardens in flood-prone areas (Moench and Dixit 2007), and small-scale investments in livestock in Andhra Pradesh (see **Box 5.1**).
- *Mexico:* Vegetable, fruit, and aloe production in drought-prone areas.

Agricultural microenterprises can be highly profitable. For example, vegetable production generates approximately 9 to 14 times more profit per unit area than rice production for many Asian countries (Weinberger and Lumpkin 2007). Investments and capacity building in the following areas would help improve the viability of small-scale horticulture (and similar microenterprises), given the potential risks from climate change:

- Integrating climate change scenarios into economic and agronomic assessments of horticultural crops, livestock, and other microenterprises to evaluate which crop mixes would be tolerant to increased risks from heat, salinity, drought and submergence; what remedial measures would need to be taken to enhance overall system resilience; and the sensitivity of the water supply to climate change.
- Research and development on subtropical and tropical horticultural crops aimed at breeding for heat, drought, and salinity tolerance.
- Building capacity in the seed sector and other input markets to enhance their reliability.
- Improving enabling conditions for smallholder entry into horticulture through extension of credit, matching funds for smallholder investments, women-oriented programs, capacity building for crop marketing, and programs to improve the economy of production through empowerment of producer organizations.[1]
- Investing in post-harvest facilities and market chain improvements.
- Encouraging public–private partnerships.
- Developing or improving market information systems.

1 In an assessment of adaptation options for southern Africa (Thomas et al. 2005), producer organizations were found to be an important factor in reducing entry barriers for smallholders into horticulture. These organizations engaged in group purchases of inputs and served as focal points for information exchange.

II. High-Value Enterprises

Scaling up rural livelihood diversification is possible by targeting agricultural production at high-value urban markets, especially in middle-income countries with rapidly growing urban populations. In addition to spreading risks through multiple production options, the processes of agricultural diversification and the accompanying modernization of the agricultural supply chain can, through engagement with the private sector and the creation of producer organizations, improve farmer access to credit and information—both of which are important for adapting to risks from climate change. Furthermore, the kinds of public-sector investments necessary for strengthening commercial linkages for agriculture—education, rural infrastructure improvements (roads, markets, electricity, irrigation), support for the formation of producer organizations, and policy measures to foster input and credit markets—provide a basis upon which rural communities can broaden their strategies for coping with the impacts of climate change. However, downside risks with respect to climate change occur if newly introduced commercial crops are insufficiently tolerant of heat or moisture stress. Integration of climate change scenarios into planning processes for high-value agroenterprises could help to reduce this risk. Vulnerability can also increase in situations in which extreme climate events coincide with market volatility for producers locked into commercial production (O'Brien et al. 2004).

III. Urban and Peri-Urban Agriculture

Half of the world's population now lives in urban areas, and an additional 1.5 billion people will be living in cities by 2020. The highest annual urban growth rates are expected in Africa (4 percent) and Asia (3 percent), both of which will face significant adjustment pressures, particularly among the urban poor and landless whose livelihoods are derived largely from the informal economy. Agricultural activities constitute an important livelihood resource for the urban poor, and an estimated 800 million urban dwellers are involved in UPA, of which 200 million produce food directly for the market. The production of vegetables, fruit, meat, dairy, and fish through UPA is therefore critical to the nutritional security of urban populations.

Impacts of Climate Change on UPA and Undertaking Adaption Measures

The largest potential impact from climate change on UPA areas is increased risk of flooding, given that the urban poor predominately settle in unstable environments such as floodplains and steep slopes. Other climate change risks to UPA include an expected increase in the variability of precipitation that could increase the need for irrigation—and, with that, reliance on wastewater sources for irrigation—and a potential magnification of the urban heat-island effect with climate change, which could directly affect crop and livestock productivity.

Developing effective policies to lessen these potential climate change risks will depend on formally incorporating UPA into urban economic planning, where presently these activities are largely ignored by policy makers. Assessing the present and future economic value of UPA enterprises within urban planning would help justify and prioritize adaptation policy options for the urban poor and their economic resources. Such policies would include flood control measures in food-producing areas, integration of urban agricultural needs into urban land-use planning efforts, and climate change impact modeling of urban areas that includes effects on the urban agricultural sector (see **Table 9.1**). In peri-urban zones, the conversion of land from agriculture to nonagricultural uses should be managed to ensure that good-quality land for agriculture is preserved and that these peripheral agricultural zones are managed to protect urban areas from flooding. This will require strong governance to enforce land-use policies.

Adaptation strategies for UPA production will also require more investments in agricultural research and development and extension, which, for the most part, currently ignore UPA-related production issues. Heat-tolerance research for horticultural crops, poultry and small ruminant livestock,

TABLE 9.1 Challenges, actions, and capacity needs for enhancing the sustainability of urban/peri-urban agriculture

Challenges	Actions	Capacity Needs and Gaps
Visibility of UPA issues in policy planning	Formulate policies that encourage sustainable development of UPA through policy recognition of the informal economy. Perform economic and environmental risk assessments for UPA. Integrate agriculture into urban and peri/urban land-use planning.	Improve capacity to collect baseline data. Improve modeling and assessment capacity and access to GIS and spatial database resources. Improve governance and institutional coordination in the area of land-use regulations.
Economic and environmental sustainability of UPA	*Food production*: Promote crop, livestock, and fish breeding; integrated nutrient management; integrated pest management; and erosion control. *Public health protection*: Install wastewater treatment facilities; promote agronomic practices that minimize contamination of fresh produce; increase availability of protective gear and preventive medical care for farm workers; promote awareness-raising campaigns for post-harvest handling; increase food safety testing. *Environmental protection*: Develop robust testing and monitoring protocols for wastewater and soils; develop and implement water regulation policies.	Invest in research and development and extension for UPA needs; promote field trials and participatory research. Develop or enhance wastewater treatment and storage capacity; improve wastewater infrastructure systems. Target investments in public health and environmental protection for the poor.
Integration of climate change impacts and vulnerability and adaptation concerns into urban/peri-urban policies	Improve access to climate-change projections. Integrate climate-change impact modeling into assessments of health-water issues, and expand to include vector control for diseases, such as dengue fever and malaria. Enhance floodwater management in urban areas, and, where possible, protect economically important assets including agriculture. Improve the environmental sustainability of UPA systems; breed for heat tolerance.	Develop climate scenario-generating capacity for urban areas; improve modeling capacity for health and environment sectors. Prioritize high-risk areas for floodwater management (floodplains, etc.) where feasible, or design policies to discourage development in these areas. Integrate peri-urban agriculture and agroforestry into floodwater management in periphery zones.

and aquaculture are needed, in addition to conventional research and extension into nutrient management, pest control, soil protection, and reduction of nonpoint source pollution from agriculture.

Water Quality and UPA

The use of untreated wastewater for irrigation is a common practice, with irrigation from this source responsible for providing about half of the urban vegetable production in a large number of cities in Africa and Asia (IWMI 2007). The free or nearly free supply of wastewater for irrigation can significantly increase the marginal return on agriculture compared with that from freshwater sources. However, the use of untreated wastewater comes with substantial health and environmental risks, including transmission of human pathogens and parasites through contaminated food; significant farm-worker exposure to pollutants, pathogens, and parasites; and soil and groundwater contamination from use of water with high levels of nitrates and heavy metals.

Future increases in surface water temperatures resulting from climate change, and subsequent growth of waterborne toxins and parasites, will create an additional health risk of using this water source for food production. This risk could be compounded in areas where greater reliance on irrigation with wastewater is needed to address crop moisture deficits generated by heat waves and greater precipitation variability. Reducing the environmental threat from wastewater use will require the development of better wastewater treatment facilities as well as the development and enforcement of risk minimization policies for wastewater use. The greatest number of people underserved by sanitation and wastewater management live in the East Asia/Pacific, South Asia, and Africa regions. These regions are expected to experience major population growth in urban areas and significant impacts from climate change.

Several practices and policies can be implemented to reduce health threats from using wastewater for irrigation, including:

- Crop selection and irrigation practices that minimize pathogen transmission to consumers, such as substituting leafy vegetables, which tend to readily harbor pathogens, with crops that better lend themselves to post-harvest cleaning. High-value nonfood crops (ornamentals and agroforestry products) are the best alternative if sufficient demand for these products exists.
- Protective measures for producers (protective gear), preventive medical care (deworming campaigns), and education of workers and consumers about proper post-harvest handling.
- Environmental and epidemiological monitoring programs. (IWMI 2007; Qadir et al. 2007).

Conclusions

- Diversification of rural livelihoods through agricultural microenterprise development can reduce exposure to climate risks by allowing households to protect assets during acutely vulnerable periods, invest in new production technologies, and recover from climatic and other disturbances to food production.

- Rural livelihood diversification through farmer participation in high-value production chains has the potential to spread the risks through multiple production options. The processes of agricultural diversification and the accompanying modernization of the agricultural supply chain can, through engagement with the private sector and the creation of producer organizations, improve farmer access to credit and information—both of which are important for adaptation to climate change.

- With half of the world's population now living in urban areas where agriculture is an important livelihood resource, increased flooding poses the greatest potential risk from climate change on UPA areas. Developing effective policies to lessen these potential climate change risks will depend on formally incorporating UPA into urban economic planning and strong governance to enforce land-use policies.

- Using untreated wastewater for irrigation and food production comes with substantial health and environmental risks, which will only increase with climate change. Development of better wastewater treatment facilities is necessary, as is the development and enforcement of risk minimization policies for wastewater use.

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