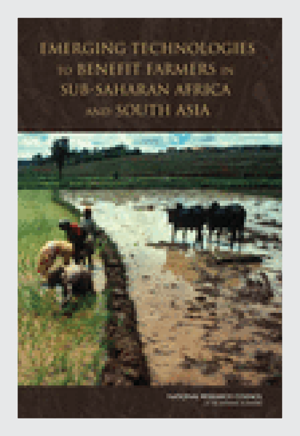

Emerging Technologies to Benefit Farmers in Sub-Saharan Africa and South Asia

DETAILS

292 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-12494-2 | DOI 10.17226/12455

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EMERGING TECHNOLOGIES TO BENEFIT FARMERS IN SUB-SAHARAN AFRICA AND SOUTH ASIA

Committee on a Study of Technologies to Benefit
Farmers in Africa and South Asia

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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This study was supported by a grant from the Bill & Melinda Gates Foundation under Contract 223-01-2460/0031. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-12494-2
International Standard Book Number-10: 0-309-12494-8

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, *http://www.nap.edu*

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Preface

In 2006, the Bill & Melinda Gates Foundation approached the National Research Council's Board on Agriculture and Natural Resources (BANR) about organizing a study to identify recent scientific knowledge and promising technologies that could transform the production capabilities of small-holder farmers in sub-Saharan Africa (SSA) and South Asia (SA). The premise underlying the proposed study was that the historical increase in agricultural productivity in the United States occurred largely through scientific and technological innovations. Crop productivity in SSA and SA lags far behind that in most agricultural areas of the world, but there also has not been a systematic application of science and technology that could improve the situation. The subsistence farming practiced in these regions results in yields and incomes that are unpredictable, leads to environmental degradation, and ultimately leads to a lack of food security. Many of the farmers produce barely enough food to survive, let alone provide a "cash crop."

Identifying ways to improve agricultural productivity in SSA and SA has been the focus of many private, national, and international organizations in recent years, and many publications describe the challenges and opportunities in addressing the factors that constrain agriculture in these regions. Among them is the 2004 publication by the InterAcademy Council, *Realizing the Promise and Potential of African Agriculture*. That report describes the unique features of African agriculture and the array of farming systems distributed across its agroecological zones and identifies broad science and technology strategies for increasing crop yields. With those reports in mind, the study committee assembled by the National Research Council began its work by querying scientists and agriculturalists at research institutions in Africa and South Asia to learn what they thought were the most serious constraints affecting farmers (see Appendix C). But although the committee believed it important to ground its study in reality, the vision and expectation of the assignment were to take a longer view of the agricultural situation in SSA and SA and to consider science and technology that would bring about dramatic improvements, even if the technology required 10 to 20 years to implement. Indeed, the committee was asked to focus on nascent innovations, including those that posed high risks, but could also be novel and powerful. In light of that scope, the committee considered basic research projects that could be performed at any location, providing there were an application and a reasonable cost:benefit ratio.

The diverse study committee included people with appropriate knowledge of science and technology in plant and animal agriculture, many of whom had knowledge of and work experience in SSA and SA. It was important to find the right combination of committee members who knew the agricultural constraints of the regions and the status of cutting-edge agricultural science and technology, but it was not possible to include experts in all the relevant subjects. That was true not only for some aspects of plant and animal agriculture but for a number of topics in nanotechnology, chemistry, physics, and engineering. To try to address that limitation, experts representing diverse fields (economics, global and rural development, metagenomics, cyberinfrastructure, soil science, weed science, livestock reproductive physiology, environmental engineering, agricultural engineering, space-systems technology, nanotechnology systems for monitoring environmental quality, and molecular genetics and genomics) were invited to the first workshop to complement the knowledge and experience of the committee. The interdisciplinary approach proved to be valuable in shaping the scope of additional workshops, and the committee is grateful to all those experts (see Appendix D). The workshops covered a wide variety of topics that are described in the report.

The severity of the current agricultural situation in SSA and SA and the accompanying social, political, and health consequences made it difficult not to consider the potential benefits of currently available technologies and approaches that could be adapted to help farmers in these regions. Consequently, as we formulated our report, we felt it important to define "emerging" technologies as both existing technologies that might not yet have been effectively applied to problems in SSA and SA and approaches that will require additional research and technological development before they can be applied. The task required the committee to take on a mindset to be realistic and visionary at the same time. As the committee developed a framework for developing priorities among different research approaches and technological directions, it was struck with the difficulty of establishing priorities among them, because improving agricultural productivity requires a systems approach. The committee's recommendations ultimately reflect that reality, and include priorities for improving all elements of the production system.

The committee believes that its report provides a compressive overview of many current and some future problems that will affect agricultural productivity in SSA and SA. It was prepared as an independent study funded by the Bill & Melinda Gates Foundation to identify emerging technologies in agriculture that have the potential to improve the quality of life of smallholder farmers in the regions. We hope that a broad range of stakeholders will find the report's conclusions and recommendations to be of value in their efforts to improve agriculture and enhance the lives of people living in those regions.

On behalf of the committee, I want to express our thanks and appreciation to Robin Schoen, director of BANR, for the time and effort she put into assembling the committee, planning the meetings and workshops, and organizing the written report. Those tasks would have been impossible without her enduring patience and hard work. We also thank all the BANR study staff for their support and assistance with our meetings and in preparing the final report.

Brian A. Larkins, *Chair*
Committee on a Study of
Technologies to Benefit Farmers in
Africa and South Asia

Acknowledgments

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Gary Anderson, University of California, Davis (*Emeritus*)
Edward Buckler, Cornell University, Ithaca, New York
Maarten Chrispeels, University of California, San Diego
Edward David, Jr., EED, Inc., Bedminster, New Jersey
Ken Giller, University of Wageningen, The Netherlands
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Jack Keller, Keller-Bliesner Engineering LLC, Logan, Utah
Fina Opio, Association for Strengthening Agricultural Research in Eastern and Central Africa, Uganda
M.V. Subba Rao, Agricultural University in Rajendranagar, Hyderabad, India
Robert Serafin, National Center for Atmospheric Research, Boulder, Colorado
Alfonso Torres, Cornell University, Ithaca, New York

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Enriqueta C. Bond, Burroughs Wellcome Fund, and R. James Cook, Washington State University (*Emeritus*). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

TABLES

FIGURES

BOXES

Abbreviations and Acronyms

ACC	1-aminocyclopropane-1-carboxylate
ACMD	African cassava mosaic disease
AGRA	Alliance for a Green Revolution in Africa
AI	artificial insemination
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
BSE	bovine spongiform encephalopathy
Bt	*Bacillus thuringiensis*
CCDs	charge-coupled devices
cDNA	complementary DNA
CGIAR	Consultative Group on International Agricultural Research
CMV	cucumber mosaic disease
CS	circumsporozoite protein
DOE	U.S. Department of Energy
ELISA	enzyme-linked immunosorbent assay
ET	embryo transfer
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GRACE	Gravity Recovery and Climate Experiment

GW	gigawatt
HHMI	Howard Hughes Medical Institute
IAC	InterAcademy Council
IARCs	International Agricultural Research Centres
ICSI	intracytoplasmic sperm injection
IG	Indo-Gangetic
IT	information technology
IWMI	International Water Management Institute
LSM	NOAH Land Surface Model
MODIS	moderate-resolution imaging spectrometer
MSV	maize streak virus
MudPIT	multidimensional protein identification technology
MUS	managed underground storage
MW	megawatt
MWCNs	multiwall carbon nanotubes
NDVI	Normalized Difference Vegetation Index
NPK	nitrogen-phosphorus-potassium
NRC	National Research Council
PASS	Program for Africa's Seed System
PCD	programmed cell death
PCR	polymerase chain reaction
PIPRA	Public Intellectual Property Resource for Agriculture
PV	photovoltaic
QTL	quantitative trait loci
RNAi	RNA interference
RVF	Rift Valley fever
RYMV	rice yellow mottle virus
SA	South Asia
SDI	subsurface drip irrigation
shRNA	short double-stranded RNA
SNPs	single nucleotide polymorphisms
SOC	soil organic carbon
SSA	sub-Saharan Africa

SSC	spermatogonial stem cell
ssDNA	single-stranded DNA
TILLING	targeting induced local lesions in genomes
TLU	tropical livestock unit
TRMM	Tropical Rainfall Measuring Mission
TW	terawatt
vCJD	variant Creutzfeldt-Jakob disease
ZFNs	zinc finger nucleases

Executive Summary

Increased agricultural productivity is a major stepping stone on the path out of poverty, but farmers in sub-Saharan Africa and South Asia face tremendous challenges improving production. Poor soil, inefficient water use, and a lack of access to plant breeding resources, high-quality seed, and fuel and electricity—combined with some of the most extreme environmental conditions on Earth—have made yields in crop and animal production far lower in these regions than world averages. This report identifies 60 emerging technologies with the potential to significantly improve agricultural productivity in sub-Saharan Africa and South Asia. Of these, 18 technologies are selected as priorities for immediate development and deep exploration (Table ES-1).

"Tier I" tools and technologies are those that should be given the highest priority for development into specific applications. Although these technologies largely already exist, they are new from the perspective of farmers in sub-Saharan Africa and South Asia because applications specific to the needs of farmers in these regions have not been developed or widely used. "Tier II" technologies include ideas that are emerging from advances in different scientific fields. In concept, applications based on these technologies would have a great deal to offer farmers in the two regions.

In general, technologies with the greatest potential impact on agricultural production in sub-Saharan Africa and South Asia are those that help to (1) manage the natural resource base supporting agriculture; (2) improve the genetic characteristics of crops and animals; (3) reduce biotic constraints (such as disease, pests, weeds) that decrease yields; and (4) provide affordable, renewable energy for farmers.

TABLE ES-1 Priority Technologies and Applications for Improving Agriculture

Focus of Technology	Tier I High Priority for Development	Tier II High Priority for Additional Exploration
Natural Resources Management	• Soil management techniques • Integrated water management • Climate and weather prediction	• Soil-related nanomaterials • Manipulation of the rhizosphere • Remote sensing of plant physiology
Improving Genetics of Crops and Animals	• Annotated crop genomes • Genome-based animal breeding	• Site-specific gene integration • Spermatogonial stem cell transplantation • Microbial genomics of the rumen
Overcoming Biotic Constraints	• Plant-mediated gene silencing • Biocontrol and biopesticides • Disease-suppressive soils • Animal vaccines	
Energy Production		• Solar energy technologies • Photosynthetic microbe-based biofuels • Energy storage technology

Although these technologies offer many opportunities to address the challenges to agricultural production in sub-Saharan Africa and South Asia, a broader set of factors will influence the ability of a technology to have a positive impact on productivity:

- *A system-wide approach:* Agricultural production is a complex system; consequently, agricultural technologies are interdependent. For example, it is difficult to improve livestock or increase meat or milk production if the animals are chronically infected with pathogens and are fed low-quality, poorly digestible forages. Solving the problem of poor agricultural productivity requires a multifaceted approach.
- *Local expertise and participation:* Agricultural technologies developed in industrialized countries may not always work in sub-Saharan Africa and South Asia. Crop breeding requires the evaluation of traits under local environmental conditions; weather prediction algorithms need data collected at the ground level; farmers need an opportunity to provide input and acquire information. These tasks require a committed, trained, local workforce—a

workforce of extension agents, scientists, veterinarians, and engineers that must be built with national efforts and international help.

- *Agricultural innovations for the developing world do not need to be "low" technology:* Technologies addressing specific needs in sub-Saharan Africa and South Asia might never materialize if they do not fill a niche in the industrialized world. As a result, important opportunities, such as the development of advanced off-the-grid electrical power, might be missed. Farmers need more than "old" or "low" technology. Incentives and support for the development of specific applications could deliver benefits faster than waiting for market forces to propel technological development.
- *Attention to the implications of climate change:* Farmers in sub-Saharan Africa and South Asia already face severe environmental constraints. By all predictions, their livelihoods will be imperiled by the future consequences of global climate change, especially water scarcity. Comprehensive planning to alleviate the economic and ecological impacts of drought will be needed, as well as technologies that increase the availability of water and efficiency of water use.

A whole suite of approaches—some technological and some not—must come together for farmers to realize the benefit of any innovation. Scientists from all backgrounds have an opportunity to become involved in bringing these and other technologies to fruition. The opportunities identified in this report offer new approaches that can be used by the Bill & Melinda Gates Foundation and other actors to help transform agriculture in sub-Saharan Africa and South Asia.

Summary

After two decades of declining international interest in the agricultural production of developing nations, it is exciting and hopeful that greater attention is now being paid to the potential of the agricultural sector to foster economic growth and reduce poverty. In sub-Saharan Africa (SSA) and South Asia (SA), international donors and national governments are investing in the agriculture economy and improving the structure of agricultural markets, the availability of financing for farmers, and the supply of inputs, such as seeds and fertilizer. To complement those investments, these organizations are seeking ways to improve crop and animal production, whose yields are far below world averages and too low to support the expanding population in the regions. Whereas much of the developed world takes its food supply for granted, a systematic effort over several decades will be needed to boost agricultural yields in SSA and SA to levels that will eliminate chronic food shortages and support steady economic growth.

How will increases in agricultural productivity in SSA and SA be achieved? Although technology is not the only determining factor in a farmer's success, having access to improved inputs, methods, and knowledge can make a substantial contribution to better agricultural production. Over the millennia, farmers have used trial and error to find effective methods of converting natural resources (solar energy, atmospheric carbon, water, and nutrients) into biomass. In the last 300 years, agricultural scientists and engineers have improved on those methods and developed technologies to mitigate the effects of stresses, such as diseases, excessive heat, and poor availability of nutrients. The innovations have included better varieties of crops and animal breeds, synthetic nutrients, pest-management tools, and irrigation equipment. Recent advances in science, including advances in disciplines not ordinarily associated with agriculture, are expanding the breadth and power of innovations to improve agriculture.

Although the principles that underpin methods of food production are as valid in SSA and SA as they are in other parts of the world, innovations developed for farming in temperate regions may not always be suitable for farmers in tropical regions, who grow a variety of different crops under different conditions. Those farmers need innovations that can help them to increase productivity and efficiency in the face of some of the world's most challenging environmental stresses and competing demands for natural resources—conditions that push science and technology to their limits.

A STUDY OF EMERGING TECHNOLOGIES

At the request of the Bill & Melinda Gates Foundation, the National Research Council's Board on Agriculture and Natural Resources (BANR) organized a study to examine the innovations in science and technology that are most likely to help farmers in SSA and SA. The goal of the study was to find innovations with the potential to transform food production in the two regions.

Eleven experts in the agricultural sciences, including some specifically familiar with the agricultural constraints facing farmers in SSA and SA, were appointed to the study committee and tasked with identifying priorities for technologies that, if developed, might substantially boost agricultural production and favorably affect the lives of poor farmers in SSA and SA. The study focused on "emerging technologies," which included existing applications that have not been widely used or adapted in SSA and SA, and innovations in the conceptual or nascent developmental stage that hold promise for improving agriculture. Appendix A of the report contains the formal statement of task for the study.

With input from scientists in SSA and SA, the study first explored critical needs for improving agriculture in the regions. Next, a "visioning" exercise and a multidisciplinary brainstorming session were held with scientists, engineers, economists, and other innovators to predict constraints that farmers in the regions would face in the future and to suggest conceptual solutions to address them. Finally, in a series of meetings with scientific experts, the committee learned about existing agricultural technologies and innovations at the frontiers of biotechnology, energy science, nanotechnology, engineering, remote sensing, and other disciplines in which novel advances potentially offer new opportunities and applications for agriculture. Scientists and other experts who contributed their insight and expertise to the study are listed in Appendixes C and D.

The committee's report describes about 60 technological tools (listed at the conclusion of this summary) that could help farmers in SSA and SA to increase agricultural productivity in a wide variety of ways. A technical strategy for developing any of the innovations into specific applications may be considered separately in a future National Research Council study. However, based on its evaluation of the merits of individual technologies described in the report, the committee recommended 18 technologies as most likely to have a significant impact on agricultural productivity in SSA and SA.

CONTEXT FOR SELECTING HIGH-PRIORITY TECHNOLOGIES

A set of criteria was used to evaluate technologies in the context of several recurring themes that arose during the course of the study. Those themes, described below, shaped the committee's perspective on how a technology would have the greatest favorable effect on farmers in SSA and SA and provide important context for the technologies ultimately recommended.

Technologies Must Be Implemented in a System-wide Approach

Technological innovations in agriculture provide fixes for specific problems in production, but they are not comprehensive solutions by themselves. Agricultural production is a complex system, and agricultural technologies are interdependent. For example, although elite, locally adapted germplasm is essential for optimal yield potential, the value of such seed is substantially diminished when it is planted in poor-quality soil that is infested with weeds that harbor insect-borne viruses that infect the crop and limit its yield. Many of those conditions are likely to coexist in SSA and SA. The same is true for livestock production: it is difficult to improve livestock reproduction or increase meat or milk production if the animals are chronically infected with pathogens and are fed low-quality, poorly digestible forages. The development of solutions to the problem of poor agricultural productivity requires a multifaceted approach to address deficiencies throughout the farming system.

The Development and Success of Innovations Require Local Expertise and Participation

It cannot be assumed that agricultural technologies developed and used in industrialized countries will work in SSA and SA. Not all innovations need to be developed locally, but at some point a technology will need to be evaluated with respect to whether it meets local needs and conditions. For example, the development of a vaccine for cattle will need to be tested against regional variants of a pathogen in local breeds of cattle. Crop breeding requires the evaluation of phenotypes under local environmental conditions. Unique soil conditions need evaluation and remediation plans. Weather prediction algorithms need rainfall data collected at ground level. Those tasks require a trained, local workforce. In addition, the successful implementation of an agricultural technology requires that farmers be convinced of its benefits and understand how it works. Agricultural systems in industrialized nations have substantial public and private extension services, and farmers in SSA and SA need the same support. Although many countries in SSA and SA maintain a large number of agricultural extension agents on government payrolls, they do not have sufficient resources to get into the field or to develop and provide the information they need if they are to support farmers. In addition to local radio, the growing access to the Internet and cellular phones can be used to great advantage in the regions to transform services.

The people of SSA and SA can become innovators on behalf of their own farmers; the eradication of rinderpest from cattle in Africa, a process led by scientists and practitioners from the continent, attests to that. However, generating successful applications of emerging technologies for agriculture in SSA and SA will require long-term human-resource development at the technical, extension, engineering, and professional levels. As in industrialized countries, building a science base can be achieved through multiple approaches, such as the establishment of the equivalent of the U.S. land-grant institutions that integrate research, teaching, and extension; creating special incentives to engage the world's top-tier scientists as research leaders; and giving outstanding students in the region both the opportunity to learn abroad and the resources to conduct research on returning home. Lasting solutions to agricultural productivity in the regions will be achieved only with the participation of their citizens.

Agricultural Innovations for SSA and SA Do Not Need to Be Based on "Low" Technology

Because farmers in SSA and SA are generally resource-poor, there is a need for innovations that are affordable, and these are historically associated with "low" or "appropriate" technologies. But cost and cost-effectiveness are different concepts. For example, although farmer-saved seed will continue to be important for the very poor, it is counterproductive to suggest that it is the *only* good policy, given the performance of high-quality hybrid seed that has a high germination rate, is pathogen-free, and is clear of weed seed. The challenge to science is to reduce the cost of hybrid seed or to find a way to maintain the performance of seed from one generation to the next.

It is generally accepted that advanced technologies will be developed and used in industrialized countries before they are introduced to SSA and

SA, but this means that technologies addressing specific needs in SSA and SA will never materialize if they do not fill a niche or need in the industrialized world. As a result, important opportunities may be missed, such as the development of state-of-the-art biofuels or of off-the-grid energy sources more suited to SSA and SA than to other regions. The use of biocontrol and biopesticides might be much more successful in SSA, where synthetic pesticide use is lower than in industrialized countries. Incentives and support for the development of specific applications could deliver benefits faster than waiting for market forces to propel technological development and letting benefits eventually trickle down to developing countries.

Climate Change Has Implications for Technological Applications in SSA and SA

Farmers in SSA and SA already face severe environmental constraints, but by all predictions, their livelihoods will be imperiled by the consequences of global climate change, especially water scarcity. Comprehensive planning to alleviate the economic and ecological impacts of drought will be needed. In Africa, where only 5 percent of agricultural land is irrigated, compared with more than 60 percent in Asia, small-scale farmers suffer from the vagaries of weather that are inevitable in rain-fed agriculture. In Asia, water use is inefficient, water quality is increasingly poor, and the receding of Himalayan glaciers is an ominous sign. For those reasons, technologies that improve the availability and efficiency of water use—whether by irrigation, by the use of drought-tolerant crops, or by other mechanisms—will be needed.

There are many unknowns in the future effects of global climate change on temperature, carbon dioxide concentrations, and the annual rain cycle in SSA and SA. In part, that is because existing models and forecasting tools for determining weather conditions in those regions are underdeveloped. If climate change creates more erratic weather conditions, it will be even more important to provide farmers with forecasts of the onset of the rainy season, the prospect of severe weather events, and the likelihood of droughts.

In the context of the themes described above, the committee used a set of criteria to examine the relative merits of different technologies (Box S-1). In general, the criteria placed higher value on technologies that could be clearly aimed at a problem specific to agriculture in SSA and SA and that could provide the greatest overall benefit to farmers. That meant giving high priority to technologies that could help the largest number of farmers or could most completely overcome the most severe problems. The next most important factor was the speed at which a field-testable application could be developed, followed by the ability to easily disseminate the technology or to use it in applications of different scales. Other factors considered

BOX S-1
Criteria for Evaluating Technologies

- Is the technology relevant and applicable to agricultural constraints in sub-Saharan Africa and South Asia?
  —Does it address a problem that is specific to these regions?
  —Would it have a direct effect on agricultural productivity in these regions?
- What is the magnitude of the expected benefit?
  —Will many farmers and the rural poor benefit from the technology?
  —Will it address a widespread or severe problem?
  —How complete a solution would it provide?
  —Would it empower the farmer?
  —Is it likely to have a direct effect on farmer income?
- How long would it take for the technology to become available?
- Could the technology be easily disseminated and adapted? Is it scalable?
- Does the technology address an issue that cannot be approached in any other way?
- Is the technology a gateway to other innovations in agriculture? Will it leverage the development of other technologies to help farmers in sub-Saharan Africa and South Asia?
- Is the technology already under consideration, or is the problem already being addressed?

important, although given lesser weight, were the uniqueness of the "fix" provided by the application, the likelihood that development of the technology would lead to other breakthroughs, and whether the contemplated technological application was being developed elsewhere and was directed at a problem already receiving attention by many groups.

Although the criteria were useful for evaluating technologies, using them to set priorities had limitations, especially because the magnitude of the benefits expected from a particular technology could not be judged independently—the impacts of a single intervention depend heavily on the overall environmental conditions of farm systems.

RECOMMENDATIONS

Priority Technologies for Development and Exploration

The technologies that have the greatest potential impact on agricultural production in SSA and SA are the ones that address four major components of agricultural systems: (1) the management of the natural resource base supporting agriculture; (2) the application of genetic diversity to improve the production characteristics of crops and animals; (3) the reduction or elimination of biotic constraints (disease, pests, and weeds) that reduce yields of crops, meat, and milk; and (4) the availability of affordable, renewable energy for farmers. Technologies effective in addressing those components are listed in Table S-1 and grouped in two tiers.

The committee recommends that Tier I tools and technologies, which already exist and are connected to fundamental elements of agricultural production, be given the highest priority for development into specific applications. Applications based on those existing technologies will have the greatest impact on production in the shortest time. From the perspective of SSA and SA, the technologies are emerging in that applications specific to the needs of farmers in the regions have not been developed or widely used. Such applications, which will have a high payoff for farmers in the regions, can be built on technological platforms and knowledge that have, in most cases, proved to be effective, but building them will be a unique and challenging endeavor.

Tier II technologies include ideas that are emerging from advances in biology, chemistry, materials, remote sensing, and energy science that have

TABLE S-1 Priority Technologies and Applications for Improving Agriculture

Focus of Technology	Tier I High Priority for Development	Tier II High Priority for Additional Exploration
Natural Resources Management	• Soil management techniques • Integrated water management • Climate and weather prediction	• Soil-related nanomaterials • Manipulation of the rhizosphere • Remote sensing of plant physiology
Improving Genetics of Crops and Animals	• Annotated crop genomes • Genome-based animal breeding	• Site-specific gene integration • Spermatogonial stem cell transplantation • Microbial genomics of the rumen
Overcoming Biotic Constraints	• Plant-mediated gene silencing • Biocontrol and biopesticides • Disease-suppressive soils • Animal vaccines	
Energy Production		• Solar energy technologies • Photosynthetic microbe-based biofuels • Energy storage technology

important implications for agriculture. In concept, applications based on these technologies would have a great deal to offer farmers in the two regions. These applications are in various stages of development and some are not conceptually new but are being revitalized by scientific advances. Although these advances will be universally important, farmers in SSA and SA may stand to gain the most from novel capabilities and agricultural applications that could meet their specific needs. The committee recommends that Tier II technologies be given high priority for further exploration to elucidate their potential for implementation in SSA and SA. Some of them will require long-term research to ascertain their potential value and to determine whether it is possible to develop them into cost-effective applications.

Descriptions of Priority Technologies

Technologies for Natural Resources Management

Soil quality was the number 1 issue identified by scientists from SSA and SA as important for increasing agricultural productivity in these regions. The prospect of water scarcity was the most commonly raised issue of greatest concern in the future. The committee attaches high priority to the development of soil-management and water-management applications. Because soils and water are closely related and the climatic and socioeconomic conditions in which they exist differ regionally, approaches to their management are highly situational and should be area-specific and integrate natural and social factors. Soil management and water management are integrative technologies—they require multiple methods determined for a particular site.

Tier I Technologies

Soil management techniques. The physical structure of many soils in SSA and SA is less than ideal for agriculture, and poor agricultural practices (overgrazing, deforestation, intensive row cropping, and removal of crop residue) contribute to the problem both by robbing soil of nutrients and by promoting erosion. If the degraded soils of SSA and SA were remediated, the magnitude of benefits to crop production would be substantial. Because climatic and socioeconomic conditions differ regionally, approaches to soil management are highly situational and require individual planning efforts. Techniques to improve soil include controlled grazing, mulching with organic matter, applying manure and biosolids, use of cover crops in the rotation cycle, agroforestry, contour farming, hedgerows, terracing, plastic mulch for erosion control, no-till or conservation tillage, retention of crop residue, appropriate use of water and irrigation, and the use of integrated nutrient management, including the judicious use of chemical fertilizers. Land-use planning and land-tenure reform are policy tools to accompany those techniques.

Integrated water management. The water-related problems of SSA and SA are two sides of a coin. In SSA, farms are primarily rain-fed; there is too little installed irrigation. In SA, water is used inefficiently, and this use degrades the resource. An array of efficient, on-farm irrigation-water capture, storage, pumping, field application and drainage technologies could be used to address both situations. Water management technologies include tube wells, on-site storage tanks, and effective irrigation methods. The efficiency of traditional surface irrigation (flood and furrow) techniques is 30-50 percent. A major improvement is drip irrigation that distributes water on the surface through inexpensive tubing. However, water can be used most efficiently if it is applied only to the active root zone of plants. Subsurface drip irrigation (SDI), which uses buried plastic tubes that contain embedded emitters, is an emerging technology that is very effective in delivering water to the root zone. The widespread use of SDI is limited by the cost and maintenance of the system. If those issues can be overcome, the technology will offer some advantages, such as the possibility of using wastewater for irrigation and longer life than surface tube systems because of lower ultraviolet light exposure.

Climate and weather prediction. The ability to more accurately predict the onset of the tropical rainy season or drought would be a transformative development for farmers in SSA and SA and enable them to make pivotal timing and management decisions about their growing operations. In spite of intense international interest in the influence of the large land masses of the regions on global climate and weather, the data and algorithms needed to enhance existing climate models for SSA and SA have not been developed. The types of models, databases, and monitoring devices that enable weather prediction based on climate data are taken for granted in many parts of the world, but these tools need to be built for SSA and SA. Specific attention is needed to ensure the generation of information that farmers can easily receive and use.

Tier II Technologies

Nanotechnology-based applications for soil. Nanotechnology is an emerging field that is enabling the creation of materials with unique characteristics. Naturally occurring minerals, such as zeolites, exist as prototypes for the development of nanotechnology-based soil amendments that could have utility for some specific applications. The utility of zeolites is derived from their unique flexible internal structures, which permit ion exchange and reversible dehydration. Because they absorb and slowly release water, zeolites can improve water retention in sandy and low-clay soils and improve the porosity of impermeable soils. When pretreated with nutrients, zeolite molecules can be used as agents for the slow release of nitrogen and phosphorus and can confer greater control over the conditions for or timing of fertilizer release. They can also be used to enhance the availability of micronutrients or to absorb metal cations and reduce local concentrations of toxic substances that inhibit plant growth and nitrogen-fixing soil microbes. The potential diversity and multiple uses of these nanotechnology-based substances make them ripe for further research and development.

Manipulation of the rhizosphere. The rhizosphere is a diverse and complex ecological environment that encompasses intracellular root tissue, root surfaces, and the surrounding soil that is influenced by the root. Current research suggests that it is possible to optimize root structure for various purposes, including increases in carbon sequestration, grain yields, and water and nutrient uptake. In addition, understanding of how root exudates and leachates influence microbial community structure is growing. Those effects create a functionally complex community with a high level of competition for colonization by bacteria and fungi that may be beneficial, neutral, or pathogenic to plants. In the last 10 years, research has increasingly indicated the feasibility of manipulating soil microorganisms to reduce the need for off-farm inputs and to stimulate plant growth. To develop those strategies as technologies, it is imperative to have a better basic understanding of microbial ecology in major crop systems of SSA and SA.

Remote sensing of plant physiological status. Optical sensing of plant physiological characteristics is an emerging tool for nutrient management and for determining the state of plant health and growth. Current technology gives us the ability to predict yield potential midway through the growing season and to suggest future fertilizer requirements according to the amount of nitrogen being removed from the soil by plants. Hyperspectral information (information on the full electromagnetic spectrum) collected remotely could be connected to satellite-based, information-gathering systems that would be used by both farmers and scientists. Farmers could use it for decision-making, and scientists could use it for many purposes, including documenting changes in the landscape and the collection of phenotypic information from plants that is important for breeding programs. At first glance, that might seem to be an unlikely tool for poor farmers, but the power of remote sensing to obtain indicators of diverse changes on the landscape (from the conditions of crops to the spread of plant and animal diseases) is increasingly sophisticated and has the potential to become a practical and valuable decision-making tool.

Technologies for Using Genetic Diversity for Crop and Animal Improvement

Plant and animal improvement involves bringing together new combinations of genes that perform well in specific environments, and genomics is transforming that capability. In order for farmers in SSA and SA to benefit from genomics, information about the local genetic diversity of crops (including forages) and animals needs to be established. A key scientific goal is to more rapidly establish the relationship between genetic diversity and phenotype (the expression of the genes that make up a trait in a given environment) to speed up breeding. That knowledge is the key to a future revolution in plant and animal trait improvement.

Tier I Technologies

Annotated plant genomes. High-quality annotated reference sequences do not exist for the genomes of many of the crops that are important to farmers in SSA and SA, but given the advances in the rate of DNA sequencing, some of these sequences could be built very quickly by using the existing *Arabidopsis*, rice, and sorghum genomes and the emerging maize genome sequence. That information will speed crop improvement, particularly if plant breeders in SSA and SA are given the sequencing tools to explore variability in local germplasm. Plant genomes and the various tools to analyze them are essential for the creation of a modern plant improvement program for both regions.

Genome-based animal breeding. The use of well-established quantitative genetic tools for identifying genetically meritorious individuals is thwarted by the absence of systematic information on the genotype and phenotypes of *Bubalus bubalis*, the Asian water buffalo, or any farm animals (such as goats and hair sheep) raised by subsistence farmers in SSA and SA. However, it may be possible to "reverse engineer" family pedigrees by using a reference genome of the breed of interest and DNA and phenotype samples from several thousand animals in geographic regions that have common environmental stresses. Single nucleotide polymorphisms (SNPs) would be generated from the DNA samples by sequencing regions of the genome that have proved to be informative in related species. The database of tag SNPs generated from the sequencing data would be aligned with the reference sequence to build family pedigrees. With pedigrees in hand, traditional quantitative tools could be applied to identify animals of superior genetic merit.

Tier II Technologies

Site-specific gene integration. The ultimate dream of breeders is to be able to replace one allele of a gene with another allele that performs better for the trait that it controls under the conditions desired without carrying along other genes that have no relevance and may even be deleterious. Current transgenic approaches make possible the introduction of specific new genes or better alleles of existing genes, but the site at which they integrate is usually random. Whereas homologous recombination (the precise exchange of one allele for another) has become fairly routine in many animal systems, it has not been possible until recently to achieve in plant systems with any useful frequency. However, emerging new technologies for optimizing site-specific integration in plants are now at hand and should be pursued with vigor with an emphasis on exploring its potential for crops that are important to the poor. Having such a technology available should transform breeding and ease the path to the use of safer and more precisely controlled transgenic approaches to crop improvement.

Spermatogonial stem cell transplantation. Spermatogonial stem cell (SSC) transplantation is a way of distributing superior germplasm widely; because resources are inadequate and refrigeration requirements are difficult to meet, this capability does not now exist in developing countries. SSCs (which give rise to sperm cells) could be harvested from genetically superior males and transplanted into sires with less genetic potential. The transplanted SSCs would grow and multiply, and the sires could then be distributed to villages or small farmers. Alternatively, the transplantation procedure could be performed on the farm with the farmer's males as recipients. The recipients would serve as the distribution mechanism for the sperm, mating with many females and siring genetically superior offspring. That is a practical and portable alternative to the current approach of artificially inseminating many females to spread superior germplasm.

Microbial genomics of the rumen. A major constraint for livestock of SSA and SA is their poor nutrition; they feed mainly on grasses that are difficult to digest because of high lignocellulose content. If the animals could get more nutrition from grasses, their meat and milk production would improve. Digestion of grasses depends on the microbial ecology of the bovine rumen, which is a subject of great interest to animal nutritionists and those interested in ways to break down lignocellulose for biofuels. The function of microbial communities in the rumen and the complex enzymology of fiber digestion are slowly being understood, but the information is insufficient to improve animal nutrition. Because of the global interest in cellulose conversion to glucose as a feedstock for biofuels, this is an opportune time to capitalize on the research to study and improve fiber digestion.

Technologies for Overcoming Biotic Constraints

Diseases and insect pests rob the world of more than 40 percent of the attainable yield of the eight most important food crops, and invasive species threaten both crops and native biodiversity. The lives of small farmers in SSA and SA would be transformed if technologies were focused on mitigating the most damaging biotic constraints on their crops. They include *Striga* (witchweed) in grain and legume crops in SSA; *Echinochloa* and feral/weedy rice, intractable weeds in rice; *Phalaris minor*, the major weed of wheat in SA; viruses such as Cassava Brown Streak, Cucumber Mosaic Virus, African Cassava Mosaic Virus, and Cotton Leaf Curl; insect pests such as weevils and stem, fruit, and grain borers; and insects that serve as vectors for disease transmission, such as the whitefly, leaf hopper, and aphid.

Tier I Technologies

Plant-mediated gene silencing. One of the most exciting developments in plant biology in recent years was the discovery of various types of small RNA molecules that play key roles in plant development and resistance to stresses. The discovery enables researchers to design and overexpress genes encoding RNAs that can target and silence critical genes that are unique to pests or pathogens; pests and pathogens receive gene-silencing RNAs by interacting with the host plant. Research strongly suggests that plant-mediated delivery of RNAs can be used to control viruses, nematodes, and some insects, and it may also find applications for use against parasitic plants and fungi. If this natural molecular tool can be harnessed, it has the potential to tackle some of the most recalcitrant pests and diseases facing agriculture in SSA and SA.

Biocontrol and biopesticides. Biocontrol involves the release of an insect pest's specific natural enemies to control its population. With foreign insect species invading Africa at an increasing rate and threatening agriculture and conservation, biological control has become increasingly relevant because a pest's enemies can keep its population in check. Africa has seen some of the most successful examples of classical biological control because the insects introduced to control an invading species have not been exposed to pesticides, given the low application rates commonly used by subsistence farmers. Biopesticides that make use of the toxins that some organisms (such as fungi) produce as a substitute for chemical insecticides or herbicides also show promise. Both approaches require systematic planning to be successful.

Disease-suppressive soils. Soils in which crop-associated microbial communities are actively managed have been shown to reduce the incidence of plant disease and pests, but our use of this knowledge as a tool is only now emerging. One approach to developing disease-suppressive soil is to manipulate carbon inputs (such as mulches and cover crops). A second approach involves crop sequencing to increase the presence of beneficial organisms; for example, repeated planting of wheat in the same field enhances growth of the rhizobacterium *Pseudomonas fluorescens*, which produces an antibiotic that inhibits a soil-based fungal pathogen of wheat. A third approach is to inoculate the soil with or enhance disease-suppressive microorganisms. Molecular tools now allow us to identify suppressive microbes in situ and recover them in a directed fashion; they can then be developed into inoculants for commercial use in SSA and SA.

Animal vaccines. Estimates of losses due to disease in SSA and SA are not well quantified, although one estimate of the annual economic loss due to animal diseases in SSA is around US$40 billion, or 25 percent of the total value of livestock production. There are constraints on the use of existing vaccines, but the control of brucellosis, leptospirosis, bovine virus diarrhea, and other respiratory and intestinal diseases in young, preweaning animals could reduce mortality and improve long-term productivity. The potential exists to support a variety of approaches to vaccine development for animals (from attenuated bacteria to DNA vaccines). Vector-borne parasitic diseases present the greatest challenge to vaccine developers because the discovery of antigens that will result in a protective immune response in the host is elusive. Such a discovery will be assisted by the mapping in the last 2 years of the complete genome sequences of all six major vector-borne pathogens: *Anaplasma marginale*, *Babesia bovis*, *Ehrlichia ruminantium*, *Theileria parva*, *Theileria annulata*, and *Trypanosoma bruci*.

Technologies for Opportunities for Energy Production

The largest concentrations of the world's energy-poor live in SSA and SA. In most of the poorer countries, less than 25 percent of rural households have access to electricity, and only 5 percent of the rural population is connected to the electric power grid. Agriculture in these regions is therefore energy-limited, and releasing this constraint would change life dramatically. However, it is critical that cost-effective, clean, renewable energy sources replace the fuels now used. This is an opportune time to take advantage of global interest in the development of distributed renewable energy production. Moreover, the climates of parts of the two regions make them good locations for systems such as solar power and microbe-based oil production. The technologies in question are listed as Tier II.

Tier II Technologies

Solar energy. Over the next decade, "third-generation" nanomaterials and multijunction solar photovoltaic (PV) cells are expected to realize their potential for cost reduction and improved performance. PV cells are already sold in SSA and SA; expanding existing markets and capturing innovations for rural applications would allow these regions to be at the forefront of technology adoption. Concentrating solar power uses mirrors to convert the sun's energy into high-temperature heat and thus has particular relevance to arid and semiarid regions. The energy can be used to generate electricity by making steam or in conjunction with a Stirling engine. Large projects of this sort are being contemplated in industrialized countries, where climate conditions are not as conducive as in SSA and SA. The technologies are potentially scalable and inexpensive to operate and would produce a source of off-the-grid energy for rural communities.

Photosynthetic microbes. Algae and cyanobacteria efficiently use the sun's energy to convert water and carbon dioxide into biomass, which can then be made into biofuels. Several algal species can be induced to accumulate substantial quantities of lipid, sometimes to more than 60 percent of their biomass, and they can grow in saline waters that are not suitable for agriculture or drinking. The requirements for growth are simple: solar radiation, carbon dioxide, water, and nutrients (primarily nitrogen and phosphorus). Furthermore, up to 90 percent of the water used in algae production can be recycled, in contrast with conventional biodiesel production from oilseeds. A byproduct of microbial biomass production can be used as animal feed after the oils are removed. Photosynthetic microbes produce much larger quantities of biodiesel than palm oil, *Jatropha*, and soybean.

Energy storage. Pumping water to the top of a hill is a classic means of storing potential energy for future use and, although it is a simple concept, remains relevant where energy sources such as wind and solar power are intermittent. Another type of energy-storage device is the supercapacitor. Such devices have several advantages over batteries, including very high rates of charge and discharge and low rates of degradation over thousands of cycles. Unlike batteries, they are made of materials with low toxicity. Supercapacitors are expected to replace batteries in the future and could be used to power rechargeable, small-scale mechanical devices used for agricultural production and processing. Locally produced energy, such as solar energy, could be used to recharge village-level capacitor systems. Recent advances in supercapacitors have been realized because of the use of carbon nanotubes, which are currently expensive to produce. Replacing

BOX S-2
Technologies Examined in the Study

- Annotated sequences of crop and model species for comparative genomics
- DNA marker development
- Mutation breeding and mutant analysis
- Rapid sequencing and annotation of crops of SSA and SA
- Information technology and computational biology
- Proteomics
- Systems biology
- Analysis of gene-trait associations
- Hyperspectral imaging and digital capture
- *Bt* toxin
- Herbicide resistance
- Engineering transgenes in metabolic pathways
- Plant-based gene silencing
- Site-specific gene insertion systems—zinc fingers, other nucleases, site-specific recombination systems
- Meiotic recombination
- Artificial chromosomes
- Apomixis
- *Bt* alternatives
- Transgenic sentinels of plant physiology
- Chemical-induced switching
- Classical biological control
- Biopesticides
- Genetically engineered biocontrol—suicide-inducing genes
- On-farm integrated water management
- Water storage
- Wastewater reclamation
- Desalination
- Cloud seeding

batteries in the developing world would be a major step toward providing power for small-scale agriculture.

CONCLUSION

Together with improvements in the structure of agricultural markets, the use of scientific knowledge and technology to increase agricultural

- Weather and climate forecasting—data capture and modeling
- Soil management practices
  - —Increasing carbon in soil for productivity and carbon sequestration
  - —Improving soil-nutrient budget
  - —Soil-water conservation practices
- Remote sensing of plant physiology for nutrient management and soil quality
- Zeolites and synthesized nanomaterials
- Root improvement through breeding and biotechnology
- Transgenic nitrogen fixation in non-legumes
- Rhizosphere manipulation
  - —Phytostimulators
  - —Disease-suppressive soil
  - —Biological nitrogen fixation
  - —Microbial enhancement of phosphorus uptake by crops
- Microbe-enhanced drought tolerance
- Improving grass and legume forage
- Rumen metagenomics
- Molecular breeding for animal improvement
- Engineering animals for disease resistance
  - —Use of transgenes
  - —Use of RNAi to target animal viruses
- Spermatogonial stem cell transplantation
- Improving neonatal passive immunity
- Animal vaccines (bacteria-, plant-, DNA-based)
- Rapid diagnosis and surveillance of disease
- Hydro, wind, geothermal, wave, and tidal power
- Solar photovoltaic
- Concentrated solar (solar-thermal) energy
- Energy storage (supercapacitors)
- Hydrogen and fuel cells
- Biofuels (cellulosic, halophytes, oilseeds, photosynthetic microorganisms)

production may offer hope to nearly 70 percent of the world's poor whose livelihood is connected to the land on which they live and toil. If farmers can reliably produce greater quantities of staple crops, they can ensure their own food supply. If they can sell what they do not consume, they can improve their income while meeting the needs of a growing regional population. If they can produce diverse high-value products, they can capitalize on the demand for a greater variety of food on the part of urban dwellers whose incomes are rising. Increased agricultural productivity is a major stepping stone on the path out of poverty.

The potential of new scientific capabilities to address agricultural constraints in sub-Saharan Africa and South Asia is substantial, provided that they will be pursued with the specific problems of farmers in these regions in mind. Scientists from all backgrounds have an opportunity to become involved in bringing the 60 technologies described in this report (see Box S-2) and other technologies to fruition.

1

Introduction

AGRICULTURE AND POVERTY

Nearly 75 percent of the people who live in dire poverty (earning less than US$1 per day) in the developing world live in rural environments and rely on agriculture as their major source of food and income (Pingali et al., 2006; World Bank, 2007). In its 2006 report *The State of Food Insecurity in the World*, the Food and Agriculture Organization of the United Nations (FAO) provides extensive data on the distribution of undernourished people in the world and the prevalence of undernourishment in many parts of the developing world (Figure 1-1). It may be surprising to many that the number in India alone surpasses the total in all of sub-Saharan Africa (SSA).[1] Among all the regions that struggle with undernourishment, only SSA continues to show a decline in food security and agricultural productivity per capita (FAO, 2006).

Because so many of the world's poor live in rural agricultural areas, their food security, income, and employment depend on successful food production. The *World Development Report 2008: Agriculture for Development* (World Bank, 2007) highlights the need to invest in agriculture in developing countries to reduce hunger and poverty, and the *International Assessment of Agricultural Science and Technology for Development* report (IAASTD, 2008) assesses agricultural knowledge and the role of science and technology for food and livelihood security. Recognizing the links between poverty, hunger, poor nutrition, health, and agriculture, the Bill & Melinda

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[1] South Africa is included in sub-Saharan Africa.

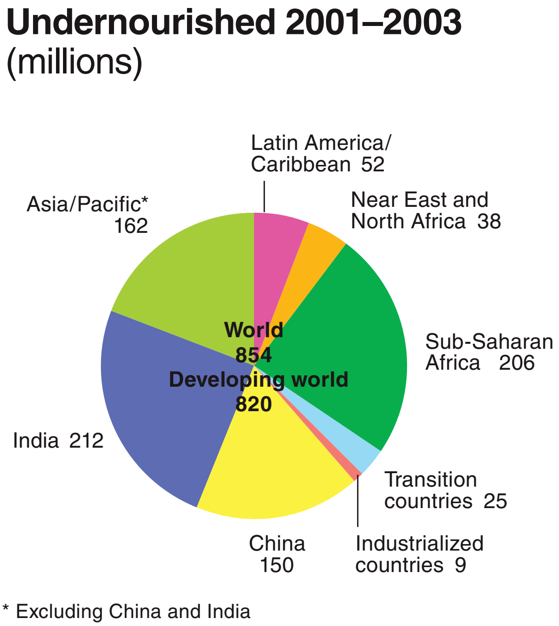

FIGURE 1-1 Distribution of undernourished people.
SOURCE: FAO, 2006. Reprinted with permission. © 2006 by the Food and Agriculture Organization of the United Nations.

Gates Foundation recently launched programs to improve agricultural productivity. The foundation's Agricultural Development initiative synergizes strongly with the foundation's global activities in other areas and brings new attention to a neglected segment of the social and economic structure of developing countries. Focusing on two areas where rural poverty and hunger are most prevalent—SSA and South Asia (SA)[2]—the foundation is supporting scientific research and the dissemination of technologies to improve crops, enhance soil fertility, increase the efficiency of water use, improve agricultural data, and promote market development.

As one of its guiding principles, the Bill & Melinda Gates Foundation has stated that "science and technology have great potential to improve lives

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[2] South Asia is defined as including India, Pakistan, Bangladesh, Sri Lanka, Afghanistan, Maldives, Bhutan, and Nepal; however, this report is much more heavily focused on agriculture as practiced in India, Pakistan, and Bangladesh because of their large populations.

around the world." Historically, innovations arising from research have mainly benefited agricultural systems in industrialized countries. In 2004, the output of U.S. agriculture was 167 percent higher than in 1948. This gain in productivity can be attributed almost entirely to greater resource efficiency and, in particular, to technological advances in crops, animals, and farming systems that are the results of substantial investment in public and private agricultural research over several decades. In contrast, in SSA, where support for agricultural research and development has declined in the last 20 years, most farmers produce barely enough food for subsistence and suffer from fluctuations of yield that often result in food shortage, a loss of income, and degradation of the local environment as farmers seek to cultivate marginal and sensitive lands. The exception is seen in South Africa, Ghana, Uganda, Kenya, Tanzania, and Zimbabwe with large-scale commercial farms where good soil, adequate rainfall, and the use of mechanized agriculture and advanced technologies have resulted in yields similar to those in the industrialized world. However, it remains true that the vast majority of farmers in SSA are small-scale subsistence farmers.

Given the historical success in applying science and technology to overcome agricultural constraints in the industrialized nations, it seems probable that identifying applications that address the needs of farmers in SSA and SA can also result in gains in crop and animal productivity. Existing knowledge and tools have a great deal to offer to farmers in the developing world, if they can be adapted and implemented.

THE SCIENCE AND TECHNOLOGY OF TOMORROW

Rapid advances are occurring at the cutting edge of plant, animal, and microbial sciences, propelled by the synchrony of molecular techniques with high-throughput chemistry and advances in engineering, miniaturization, and informatics. Dissecting the complexity of plant and animal traits and microbial communities is getting faster, easier, and more powerful because each revelation of nature's functions brings with it the potential to make those functions operate as technological tools for further exploring and manipulating biological systems. The ability to harness nature for mankind's needs has never been greater.

Beyond the fields traditionally associated with agriculture, advances in physics, chemistry, electrical engineering, materials science, remote sensing, and computer science are increasingly recognized as sources of novel ideas with implications for agriculture. One can imagine using innovations from those disciplines to develop tools for understanding and controlling the agricultural environment better and for managing soil, water, crop, and energy resources. Applications based on the new technologies may not yet exist, but the scientific foundations that will enable them in the future are steadily being built.

A STUDY OF EMERGING TECHNOLOGIES

The Bill & Melinda Gates Foundation's interest in those scientific advances led it to approach the National Research Council (NRC) for a study of emerging technologies that could benefit farmers in SSA and SA. Although it is probably safe to assume that research in the scientific fields mentioned above will move forward and eventually lead to agricultural applications in the industrialized world, it will take a concerted effort to direct the development of novel technologies (and investment in them) toward the specific needs of the world's poorest. The foundation requested the study to inform its long-term planning, advocacy, and partnerships for agricultural research support and to assess technologies that could be developed over the next 20 years to transform farmers in SSA and SA into successful agricultural producers.

With that goal in mind, the NRC appointed a committee of experts with knowledge of the constraints facing farmers in SSA and SA and of the newest advances in the agricultural sciences to conduct a study of promising innovations for agriculture. The committee was tasked with identifying *emerging* technologies, a term that captured two types of innovations: (1) applications that currently exist but have not been widely used or adapted in SA and SSA, and (2) innovations in the conceptual or developmental stages that hold promise for improving agriculture. A second charge to the committee was to develop a framework for prioritizing technologies most likely to transform the lives of farmers in these regions.

Because the foundation was interested in having a study that looked over the horizon to what might be *possible* in the future, the study committee focused primarily on the technologies themselves and their potential application to address relevant agricultural constraints or opportunities in SSA and SA but not on the complex socioeconomic environments into which they might someday be introduced. The study committee was acutely aware of the influence of the many factors in developing countries that can make a technology more or less practical; however, it was advised not to limit its thinking to what might be implementable under today's conditions but rather to think about what is possible for the future 15 to 20 years away.

This report is the result of the committee's exploration of scientific frontiers and of numerous technologies, applications, and research topics. The statement of task for the study is found in Appendix A, and biographical information on the committee members is contained in Appendix B.

STUDY APPROACH

The committee approached its task from several angles. Its first approach was to ask scientists in research institutions in SSA and SA to identify the three most acute constraints facing farmers that if overcome could transform their production capabilities. In general, scientists in the two regions produced remarkably similar lists of problems and issues, which are listed in Box 1-1 and roughly ordered according to how often they were mentioned by the local scientists. Appendix C contains the names of scientists from SSA and SA who provided input to the study. The same issues arose at a meeting of the Forum for Agricultural Research in Africa attended by two committee members, who led a discussion with scientists at that gathering.

Early in the study, the committee organized a meeting asking experts to envision and describe what the environment in the two regions might look like in the future and what resources and challenges would exist. A mix of technological innovators participated in the visioning exercise and

BOX 1-1
The Most Serious Agricultural Constraints in Sub-Saharan Africa and South Asia: Perspectives from Scientists in Those Regions

- Soil fertility, lack of fertilizer, and soil degradation
- Drought, insufficient water, and difficulties in managing water
- Animal nutrition, diseases, and arthropod vectors
- Insufficient markets and international regulation
- Weak government and institutions and finance for small farmers
- Germplasm of plants and animals
- Education of farmers, extension, and information systems
- Need for biotechnology and other new technologies to increase productivity
- Parasitic weeds, plant diseases, and arthropod pests
- Lack of infrastructure and manpower
- Energy and mechanization for small farmers
- Climate change and related problems
- Information and resources for local scientists
- Postharvesting technologies
- Population growth

SOURCE: Appendix C.

in a brainstorming session that allowed each of them to explore how the frontiers in different fields of science might offer tools that could be used for agriculture. Finally, the committee held a series of information-gathering meetings at which experts described the state of research on specific agricultural problems and novel ways to address them. The scientists who participated in these sessions are listed in Appendix D.

ORGANIZATION OF THE REPORT

Given that some of the technologies explored by the committee are in the early stages of development, the study's focus is on a point far upstream from the point of delivery to the farmer, where the existence of supporting infrastructure (physical, institutional, and human resources) and other practical considerations will be key determinants for the success or failure of an innovation. Some of those factors are acknowledged in Chapter 2 with a description of the key agricultural constraints, problems, and opportunities that serve as the context for exploring novel technological approaches.

Chapter 3 outlines considerations for plant breeding programs and describes the powerful new knowledge and capabilities emerging at the interface of plant science, genomics, and biotechnology. Chapters 4 and 5 examine technological possibilities for improving and conserving water and soil, respectively, as the cornerstones of agricultural productivity. Chapter 6 explores technologies to improve and protect animals, an increasingly important sector of agriculture in SSA and SA. Chapter 7 identifies innovations in off-grid energy production that could help to boost agricultural productivity and rural development. In Chapter 8, the committee presents its key findings, describes several ideas for increasing the capacity of agricultural research in the two regions, and highlights several technologies that merit high priority for further exploration on the basis of qualities such as time frame and breadth of impact.

The technologies described in this report range from those that are years from being turned into useful tools to those that are in hand but have not been applied to agricultural problems in the two regions. Some of the ideas may be carried forward for more detailed examination in a future NRC study.

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Constraints on Crop and Animal Productivity in Sub-Saharan Africa and South Asia

As the committee began its task—to identify technologies emerging in different fields of science and engineering that could be most helpful to poor farmers in sub-Saharan Africa (SSA) and South Asia (SA)—it quickly agreed that the first place to look for opportunities to transform agriculture was in the fields and pastures where conditions that constrain agricultural productivity are manifested. Any technology that could help a farmer to overcome the worst conditions would have a substantial impact on crop yields, improve food security, and increase the farmer's potential for income.

This chapter provides a broad sketch of crop and animal production in SSA and SA and identifies general and specific constraints that limit the ability of farmers in these regions to sustain reliable food production. The constraints were identified on the basis of the committee's own expertise and responses to the committee's request for input from scientists in the two regions, and the constraints provide the context for the rest of the report.

OVERVIEW OF CROP PRODUCTION IN SUB-SAHARAN AFRICA AND SOUTH ASIA

High-Priority Crops

As shown in Figure 2-1, there are substantial differences between the crops of SSA and the crops of SA. The major crops of the Green Revolution[1]—rice and wheat—still predominate in Asia. However, increases in

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[1] The Green Revolution of the 1960s and 1970s came as a result of scientific efforts to improve rice and wheat varieties—combined with the expanded use of fertilizers, other chemical inputs, and irrigation—and ultimately led to dramatic yield increases in Asia and Latin America (IFPRI, 2002).

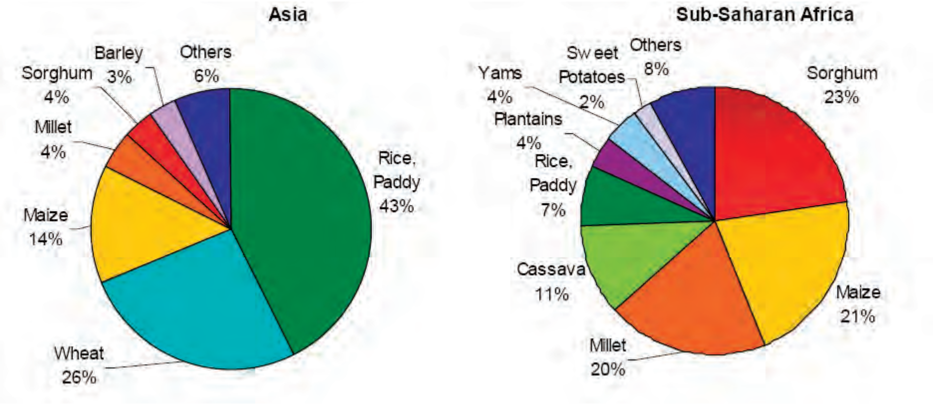

FIGURE 2-1 Major food crops of Asia and sub-Saharan Africa.
NOTE: Percentages refer to hectares harvested, averaged for 2000-2004.
SOURCE: FAO, 2006a; de Janvry and Byerlee, 2007.

productivity are tapering off in the classic rice-wheat cropping rotation that has been used for more than 1,000 years in Asia; it now encompasses about 24 million hectares in Asia, of which 13.5 million are in SA (Rice-Wheat Consortium, 2007). Sorghum and pearl millet are also widely grown, although they are on the decline, being replaced by maize in many areas, which is important for the burgeoning livestock and poultry feed industries (Joshi et al., 2005). The legumes that are important for nutrition are chickpea, lentil, pigeon pea, and groundnuts; they are less abundant as crops. The Indian government claims to be promoting diversification of crops away from the intense reliance on cereal grains with recommendations to increase growth of legumes, fruits, vegetables, and oilseeds and more emphasis on dairy, poultry, and fish and with concomitant strengthening of markets and the government's ability to meet health and safety standards. Cotton and tea remain important export crops, although the declining yields of tea plantations and competition from abroad still pose problems; unlike SSA, India has a strong textile industry that complements the widespread production of cotton.

The major crops of SSA are somewhat more diverse, and this makes priority-setting for improvement more challenging. Most of the crops shown in Figure 2-1 are also listed by DeVries and Toenniessen (2002). Among cereals, maize continues to emerge as the dominant crop, particularly in eastern and southern Africa, and sorghum and millet are important in drier areas of SSA. Rice has always been grown in the wetter areas of west Africa and is increasingly popular for consumption especially in the growing urban populations throughout SSA. Among the legumes, cowpea, pigeon pea, common bean, and groundnuts are important in many parts of SSA. Because of its ability to yield well despite stress and low inputs (externally supplied nutrients, pesticides, etc.), cassava is an important crop to millions of poor farmers throughout SSA, and yams also are hugely popular in countries such as Nigeria. Sweet potato is a major source of calories in some countries of eastern and southern Africa. An orange-flesh sweet potato that is rich in beta-carotene, the precursor of vitamin A, is being promoted to address the problem of nutritional deficiency (see Box 2-1) (Low et al., 2007). Banana has emerged as a major cash crop, and tissue-culture production of virus-free plantlets is becoming a viable business in eastern and southern Africa. The starchy east African highland banana is the major staple crop of countries such as Uganda, Rwanda, and Burundi. Forests are increasingly recognized as important in SSA, not so much as a crop (although they are now for biofuels) but rather for their benefits to the environment—in protecting watersheds and preventing land degradation—and as a major source of fuel and building materials for small-holder farmers, and for their potential to offer income in schemes involving trading of carbon credits.

Crop Yields

Data on yields in SSA and SA and in the developed world are relevant to food security and the relative health of the agricultural economy. Table 2-1 shows selected data on Kenya, Ethiopia, and India as representative of the regions in question. Yields are particularly low for maize and legumes, but yields of all crops listed are substantially lower in the three countries than in the developed world. Yields of cereals like wheat and rice showed striking rises in India in past decades but are now leveling off, and as previously mentioned, per capita yields of cereals in SSA are actually declining.

Most African crop and animal production is practiced under low-input agricultural systems, and the chances of substantial improvement under those conditions may be limited (IAC, 2004). Figure 2-2 (Henoa and Baanante, 2006) compares SSA and Asia with respect to agricultural productivity and land use. The data provide a striking contrast: almost all the yield gain in SSA has come from increased land use, whereas in Asia it has resulted largely from increasing the yield on the same land area.

The increased yield in Asia on the same amount of land can be attributed largely to three factors: the new Green Revolution varieties of wheat and rice, which continue to be adapted and improved; the widespread use of inorganic fertilizer and herbicides; and irrigation of large areas in India

BOX 2-1
Agriculture and Malnutrition

In the last decade, the number and proportion of malnourished children and mothers in sub-Saharan Africa has increased. Undernutrition—deficiencies in macronutrients, protein, and energy, as well as micronutrients, iron, vitamin A, zinc, and iodine—is the underlying cause of half of all child mortality (Chopra and Darnton-Hill, 2006). About 84 percent of children under 5 years old in Kenya have some level of vitamin A deficiency, 73.4 percent are iron-deficient (anemic), and 51 percent are zinc-deficient. Women, especially pregnant women, are among the most vulnerable, with a high risk of iron deficiency (60 percent of pregnant woman) and vitamin A deficiency (39 percent of women). An estimated 16 percent of men have iron deficiency. Approximately 4.5 billion people living in the developing world are chronically exposed to aflatoxin, a fungal toxin that is considered an unavoidable contaminant of foods that is a major cause of malnutrition (Williams et al., 2004).

At the same time as undernutrition persists in parts of the population, rates of obesity are skyrocketing in other parts, especially in urban areas, because of greater consumption of refined fats and carbohydrates and more sedentary lifestyles (Prentice, 2006). In South Africa, 56 percent of women are considered overweight, and 30 percent are obese. Interrelationships among micronutrients and age-sex biases dictate that solutions more complex than single-nutrient supplementation are required. Similarly, food-based solutions to malnutrition—such as the orange-flesh sweet potato (Low et al., 2007), biofortified rice (Haas et al., 2005), and meat and milk (Neumann et al., 2003)—although time-consuming to implement, can result in beneficial long-term dietary change.

The HarvestPlus program (*www.harvestplus.org*) of the CGIAR aims to address biofortification primarily through conventional breeding. Other efforts, including the Grand Challenge 9 Program, support biotechnological approaches to raise the concentrations of vitamin A, iron, and zinc in banana, rice, cassava, and sorghum beyond those possible through conventional breeding. The goal to raise micronutrient levels in those crops is attainable with today's technologies; the biggest challenges for the projects may well be in finding ways to deal with regulatory approvals for traits that have not yet been evaluated by any regulatory system. Folate (a form of vitamin B) deficiency is a global problem that leads to neural tube defects, and transgenic approaches have been successful in increasing folate levels in tomato and rice (Diaz de la Garza et al., 2007; Storozhenko et al., 2007). Because obesity is becoming more prevalent in the developing world, lowering the rate of starch digestion by altering the amylose-to-amylopectin ratio would be one way to address the issue.

TABLE 2-1 Cereal and Legume Yields in 2005

Crop	Kenya (kg/ha)	Ethiopia (kg/ha)	India (kg/ha)	Developed World (kg/ha)
Maize	1,640	2,006	1,907	8,340
Sorghum	1,230	1,455	797	3,910
Millet	580	1,186	1,000	2,010
Rice (paddy)	3,930	1,872	3,284	6,810
Wheat	2,310	1,469	2,601	3,110
Beans, cowpea	378	730	332	1,790
Chickpea	314	1,026	814	7,980

SOURCE: FAO, 2006a.

and Pakistan, because water has not at least until recently been a major limiting factor as it has been in the largely rain-fed agriculture of SSA. Quality seed, adequate nutrients, and water synergize to enhance yield, and lack of a combination of these three goes a long way toward explaining why yields of all major crops in SSA are among the lowest in the world.

GENERAL CONSTRAINTS ON CROP PRODUCTION

Poor Soil and Poor Soil Fertility

Not all soils are the same: soils arise from different geophysical processes that give them different characteristics. In Africa, soils are categorized in three groups. The first group includes highly erodible, weathered soils and low-activity clays with high acidity and aluminum phytotoxicity; these soils occur mostly in the subhumid tropical uplands and humid equatorial and coastal lowland regions. The second group includes the more moderately weathered, fertile soils derived mainly from basic rocks and volcanic materials in western Cameroon, Rwanda, Burundi, the Kivu region of Zaire, and parts of eastern Africa; this is where the most productive plantations of perennial crops—such as coffee, tea, and banana—are grown. The third group is the hydromorphic or ancient alluvial soils that predominate in the subhumid tropical uplands, where an underlying hardened plinthite (an iron-rich clay-quartz mixture) at shallow depths limits the downward growth of plant roots; these soils are easily compacted and eroded.

Many of the soils of SSA are less than ideal for agriculture, and the situation is made worse by the extensive nutrient mining caused by poor agricultural practices in the region. In addition to natural wind and water erosion, much of the soil erosion is caused by overgrazing, deforestation, and intensive row cropping. Erosion rates of 10 to 40 t/ha per year are

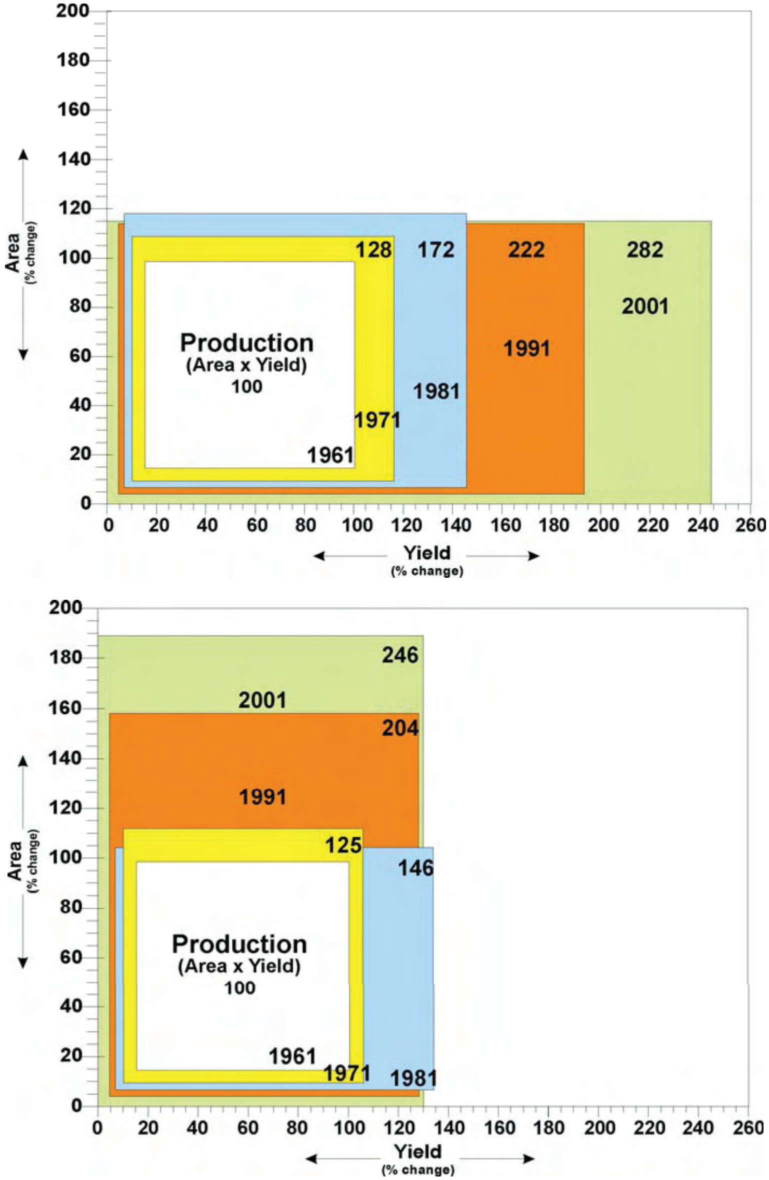

FIGURE 2-2 Changes in cereal production, 1961-2001, in sub-Saharan Africa and Asia.
NOTE: Increases in yields were due primarily to increased land use in sub-Saharan Africa but to increased production per unit of land area in South Asia.
SOURCE: Henoa and Baanante, 2006. Reprinted with permission. © 2006 by International Center for Soil Fertility and Agricultural Development.

common on crop lands, compared with annual soil losses of 5 to 10 t/ha per year in the U.S. corn belt (Lal, 1995, 1998).

The soils of SSA have also been robbed of their nutrient content. The Tropical Soil Biology and Fertility Institute has published an excellent review of challenges to soil management in the tropics (TSBF-CIAT, 2005). Most cropland soils in SSA are affected by negative nutrient balance: nitrogen-phosphorus-potassium (NPK) depletion occurs at 20 to 40 kg/ha per year throughout the continent (Smaling, 1993; Smaling et al., 1993; Sanchez, 2002). African farmers traditionally left lands fallow to restore nutrients and regain fertility, but because of food demand crops now grow continuously with little or no nutrient input. The result is extensive and sometimes irreversible soil degradation, as illustrated in Figure 2-3.

Fertilizer use in SSA is low (NPK at 8.8 kg/ha per year) (Henoa and Baanante, 2006). That situation is attributable to the inaccessibility and exorbitant cost of inorganic fertilizer—up to 4 times that paid by a farmer in the United States (Camara and Heinemann, 2006; Eilittä, 2006). Efforts to address the accessibility and cost of fertilizer were highlighted at a recent African Fertilizer Summit. In addition, the Alliance for a Green Revolution in Africa (AGRA)—established by the Bill & Melinda Gates Foundation and the Rockefeller Foundation—has launched a new program in soils that aims to increase sustainable use of fertilizers, organic matter, and soil management methods.

In contrast with Africa, fertilizer use in SA is high (NPK at 100 kg/ha per year). Fertilizer consumption in SA increased by a factor of 42 from 1961 to 2003 and accounts for much of the yield gain in the region during the period (Lal, 2007). However, there seem to have been recent widespread decreases in the responses of crops to agricultural inputs. For example, cereal production in India declined from a peak of 235 kg/ha in 1995 to a low of 205 kg/ha in 2002.

One possible reason for the decline, which also occurred in SSA, is the loss of soil organic matter as farmers strip off all plant matter. In SA, this includes weeds and roots, to use for animal feed or for cooking fuel (Eswaran et al., 1999). Lacking input of organic matter, degraded soils have low holding capacities, so they often do not respond to the addition of inorganic fertilizer. Numerous studies indicate that there can be strong synergism in the use of both organic and inorganic fertilizer. However, difficult tradeoffs with respect to organic amendments remain. In SA, manure is used for cooking fuel; in many parts of SSA, the poorest farmers use some crop residues as building material and might not have animals as a source of manure, and they are reluctant to use their small plots to grow crops that yield only green manures. Low organic matter may lead to a decrease in the abundance of important soil organisms, such as bacteria, fungi, termites,

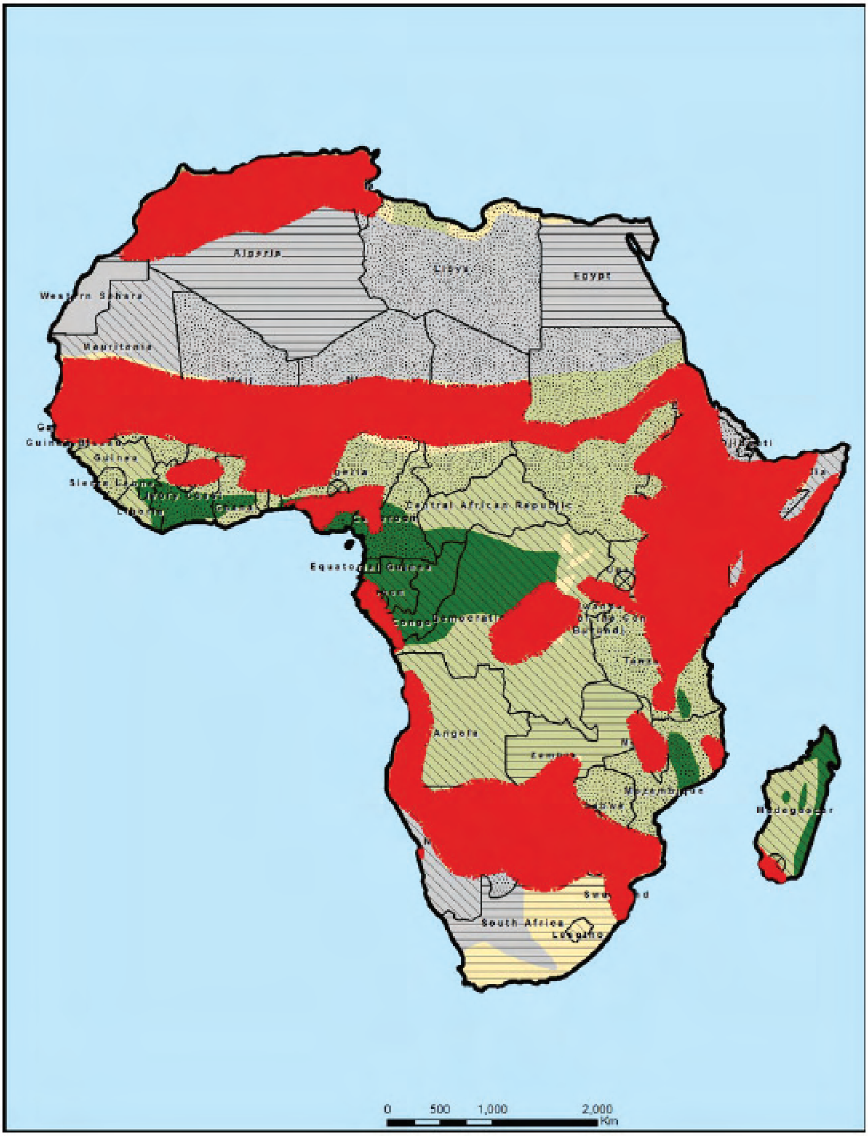

FIGURE 2-3 Areas in red are where current population exceeds agricultural capacity because of severe soil degradation and nutrient mining.
SOURCE: Henoa and Baanante, 2006. Reprinted with permission. © 2006 by International Center for Soil Fertility and Agricultural Development.

earthworms, insects, and small animals that inhabit the rhizosphere, an area of biological diversity whose importance continues to be studied.

Poor Water Use and Management

Water constraints intersect with issues of soil fertility, water-use efficiency, and climate change. As recently stated, "water may seem to be everywhere, but for a rising portion of the world's population, there may soon be hardly a drop to drink—or to use for growing food, supporting industries and cities, and preserving life-giving ecosystems" (Postel, 1997).

The climate of Afghanistan, Pakistan, and one-fourth of northwestern India is predominantly arid, and that of Bangladesh, Bhutan, Nepal, eastern India, and Sri Lanka is humid. In SA, the proportion of cropland under irrigation is among the highest in the world (Table 2-2), but the water resource is poorly managed. Overuse of water through inefficient canal irrigation systems led to increased salinization and serious rising of the water table. A transition to tube wells has lowered the water table, but poor water quality remains a serious issue. Estimates for Pakistan indicate that over 50 percent of the groundwater is saline and not fit for irrigation. Other problems include the discovery of arsenic in many groundwater sources, the gradual depletion of major aquifers in some regions, and pollution from runoff.

Wastewater could be an important source of water for agriculture, but it also carries health hazards. In Pakistan, for instance, it was found that hookworm is a major problem for those exposed to wastewater, and fear of contamination of vegetables is a major health issue for consumers (IWMI, 2003b). As an alternative solution, wastewater could be suitable for growth of bioenergy crops, which would not be associated with health issues.

In substantial areas of SA—areas where there is also widespread rural poverty—agriculture is carried out under rain-fed conditions. As pointed out to the committee by Bharat Sharma, of the International Water Management Institute (IWMI), the northwestern region of India (Rajasthan and

TABLE 2-2 Irrigated Areas in South Asia

Country	1975 (Mha)	1985 (Mha)	1995 (Mha)	1998 (Mha)	2003 (Mha)	Per Capita in 2003 (ha/person)
Afghanistan	2.4	2.6	2.8	2.8	2.7	0.09
Bangladesh	1.4	2.1	3.2	4.2	4.7	0.03
India	33.7	41.8	50.1	54.8	55.8	0.05
Nepal	0.2	0.8	0.9	1.1	1.2	0.04
Pakistan	13.6	15.8	17.2	18.1	18.2	0.11
Sri Lanka	0.5	0.6	0.6	0.7	0.7	0.03

SOURCE: Kaosa-ard and Rerkasem, 2000; FAO, 2006a; Lal, 2007.

Gujarat), the Sind and Baluchistan provinces of Pakistan, and Afghanistan constitute one of the largest blocks in SA confronted with frequent and devastating droughts. In contrast with drought-prone areas, flooding of the Indo-Gangetic plains is an all-too-common occurrence and of increasing concern in climate change scenarios.

Only 5 percent of agricultural land in Africa is under irrigation, compared with more than 60 percent in many parts of Asia, and most small-scale poor farmers in SSA suffer the vagaries of fluctuating weather conditions that are inevitable in rain-fed agriculture. In both SSA and SA, there is increasing use of low-cost bucket and drip irrigation systems and treadle pumps, even by the very poor (IWMI, 2003a; *www.acumen.org*; *www.kickstart.com*), but the general lack of irrigation in SSA is an obvious target for technological intervention. The recently published *Water for Food. Water for Life. Comprehensive Assessment of Water Management for Agriculture* (IMWI, 2007) regards the upgrading of rain-fed systems as one of the most important opportunities to both reduce poverty and increase productivity in the rain-fed regions of SSA and SA, as is indicated in Table 2-3.

Several reports (Camara and Heinemann, 2006; Rockstrom et al., 2006, 2007) emphasize that yields can be increased by a factor of 2-4 in many parts of SSA through better water management practices, such as adding organic matter to soils, preventing soil erosion, using water harvesting technologies, and increasing water retention with tied ridges, bunds, and terraces. The InterAcademy Council (IAC) report (2004) indicates that there is also an opportunity to improve current irrigation practices and to increase the amount of land under irrigation, inasmuch as current

TABLE 2-3 Regional Potential for Increasing Crop Water Productivity

Comprehensive Assessment Scenario Characteristics			
Region	Scope for Improved Productivity in Rain-Fed Areas	Scope for Improved Productivity in Irrigated Areas	Scope for Irrigated Area Expansion
Sub-Saharan Africa	High	Some	High
Middle East and North Africa	Some	Some	Very limited
Central Asia and Eastern Europe	Some	Good	Some
South Asia	Good	High	Some
East Asia	Good	High	Some
Latin America	Good	Some	Some
OECD countries	Some	Some	Some

SOURCE: IWMI, 2007. Reprinted with permission. © International Water Management Institute (*http://www.iwmi.org*).

estimates indicate that only 30 percent of what is potentially available has been reached in SSA, with the greatest opportunities lying in humid regions, such as the Congo Basin.

Lack of Plant Breeding Resources

The importance of plant breeding for the health of a modern agricultural system cannot be overstated. Even in the United States and Europe, where there is private-sector investment in crop-trait improvement, substantial public-sector and philanthropic resources are essential if for no other reason than that breeding is needed to cope with changing pathogens and pests that affect food production. Progress in crop improvement can be sustained over decades, but advances become more difficult when the environments are prone to change as a consequence of different temperatures, length of seasons, rainfall patterns, and pests and diseases. Thus, where climate change and associated factors pose additional threats to future crop production, more active breeding programs are needed so that crop selections can be responsive to expected environmental change; for example, crops can be selected for tolerance to higher temperatures.

National breeding programs in SA have been greatly enhanced since the onset of the Green Revolution, but progress in developing modern varieties of the major crops for SSA has been much slower. If they exist at all, national breeding programs for rice, wheat, tropical maize, sorghum, cassava, beans, banana, pearl millet, lentil, cowpea, pigeon pea, common beans, yam, groundnuts, banana, sweet potato, and various fruits and vegetables are generally small and modestly staffed. The poorest countries only have a few testing facilities to help local farmers to find better strains of the crops they grow. Some countries, such as Kenya and India, manage to adopt, and to a limited extent improve, germplasm developed elsewhere. In some cases, private breeding companies are paying more attention to crops in SSA and SA, but often the fruits of these endeavors are effective only for wealthy farmers. Advanced breeding programs of any important scale that focus on the needs of poor farmers are limited to the International Agricultural Research Centres (IARCs) of the World Bank's Consultative Group on International Agricultural Research (CGIAR). While these programs have been faulted by some for trying to "short-cut" germplasm improvement in SSA by transferring less than suitable varieties from Asia and Latin America (Evenson and Gollin, 2003), there are now positive signs with respect to yield increases for most major crops. The CGIAR system as a whole has made major contributions in terms of new varieties and crop improvement in a range of crops. CGIAR has been a pioneer of participatory breeding: germplasm developed by many of the centers found its way into national breeding programs and subsequently into the fields of small-scale farmers. In an ideal world, the IARCs would have strong capacity to serve national breeding programs by maintaining germplasm collections, developing knowledge about germplasm characteristics, and identifying superior traits and introducing them into relevant crops that the national programs could routinely introduce into locally adapted germplasm. The centers could also help to build technologies and systems that recognize the issues of intellectual property, ownership, and preferences of the recipient countries. Thus, it is unfortunate that funding for those centers, particularly for core activities as opposed to donor-driven research agendas, has not kept pace with the need.

Government and donor support for public breeding in the national breeding programs of SSA has also been sparse until recently. The development of capacity for conventional breeding approaches should be accelerated by the new Program for Africa's Seed System (PASS), which is part of the recently established AGRA.

Lack of High-Quality Seed

In India and South Africa, a number of private-sector seed companies are active in providing high-quality hybrid seed. India is unique in its use of hybrid cotton—partly because of the availability of cheap labor required for seed production. The seed is increasingly transgenic, incorporating genes for herbicide tolerance and insect resistance, and is widely used; in most cases, it provides increased yield and permits reduction in the use of pesticides, which benefits small-scale farmers (Delmer, 2007).

Hybrid maize and vegetable seed are also widely marketed in SA, which, unlike SSA, has a wide variety of hybrids available for sorghum and pearl millet. In SA, very poor farmers still rely heavily on open-pollinated varieties of these crops that are bred and distributed through public-sector efforts involving universities and national laboratories. In the maize-growing regions of eastern and southern Africa, several large multinational seed companies are active and business is largely driven by the existence of large farms using high inputs, but there is also substantial growth in small and medium-size African-led companies, a few of which have their own maize breeding programs. Fewer than 30 percent of smallholder maize farmers in SSA are buying and growing hybrid maize, but the number is rising (IFPRI, 1996; Smale et al., 2006). However, African farmers—especially women, who bear the responsibility for feeding their families—are very risk-averse: if they have indications of a bad year for rain or inadequate access to fertilizer, they will usually choose not to buy seed of the fertilizer-responsive, high-yielding hybrids. They increasingly recognize that such seed represents a good investment if seed and fertilizer can be purchased together. While farmer-saved seed will continue to be important for the very poor, it is counterproductive to suggest that it is the *only* good policy; farmers who wish to enter into a dynamic agricultural sector will need high-quality seed that has a high germination rate, is pathogen-free, and is clear of weed seed.

Land and Labor Availability

Almost 40 percent of the total land area of SA is used to grow crops—a reflection of the high population density of the region. Huge numbers of small-scale farmers and a sizable rural population of landless poor subsist among the fields. At the extreme is Bangladesh, where the land area per person is already limited and projected to be a mere 0.03 ha by 2050. All food, feed, fiber, and fuel demands of the present and future population in Bangladesh will have to be met on a very small land area, which may be reduced by projected sea level rise.

In SSA, about 6 percent (173 million hectares) of the total land area is used to grow crops, and another 24 percent (720 million hectares) is used for pasture (FAO, 2006b). However, there is a lack of agricultural labor in SSA, whereas in SA, there is a limitation of crop land but not a shortage of labor. Although Africa has the highest rate of population growth in the world (the projected population by 2025 is 1.5 billion), the population density in rural and urban areas of SSA is much lower than that of SA (FAO, 2005). That small-holder agriculture in SSA is constrained by labor shortages is counterintuitive, but cases of labor scarcity have been documented in Malawi (Alwang and Siegel, 1999), Burkina Faso (Fafchamps, 1993), and Ethiopia (Barrett and Clay, 2003). Farm workers are primarily female, and the woman with the hoe is the woman who raises children and cares for the sick and elderly. That is often unrecognized by nongovernment organizations and governments when they promote labor-intensive crop management or cultivation of crops that require extensive hand labor. The labor shortage is compounded by the impact of HIV/AIDS on the rural population in SSA (Du Guerney, 2002 and references therein). Malnutrition (see Box 2-1) and disease (including HIV/AIDS) in the rural poor sap crucial energy needed for labor-intensive work.

Lack of Fuel and Electricity

The largest concentrations of the “energy-poor” in the world live in SSA and SA. In most of the poorer countries, fewer than 25 percent of rural households have access to electricity, and only 5 percent of the rural population is connected to the national electric power grid. The primary region where the expansion of services has not kept pace with population growth is SSA, where the total number of people without access to electricity has increased steadily and is projected to continue to do so for the next several decades (IEA, 2002). Energy to support all aspects of agriculture is severely limiting; in particular, power-driven agricultural tools and the cold storage and transport to market of fruits, vegetables, fish, dairy, and meat are not available.

Poor farmers are seriously affected by rising prices of oil and gas, especially farmers who depend on diesel-driven pumps in the Indo-Gangetic basin, where 70 percent of irrigation depends on such pumps. As a result of the cost and lack of availability of power sources and equipment, only 1 percent of the land in Africa is cultivated mechanically (IAC, 2004). Use of animal traction and small diesel-powered devices is much lower in SSA than in SA, where small rototillers are widely used by small-holder farmers. For example, the availability of energy and power tools would transform agriculture in SSA. A woman can farm twice the area and farm with far less drudgery with a lightweight herbidicide sprayer than with hand tillage to control weeds, and the yields are greater (Carl Pray, Rutgers University, personal communication, 2007).

The rural poor rely on biomass or manure for cooking fuel and heat; on kerosene wick lamps, batteries, or candles for lighting; and on human-based or animal-based mechanical power for tilling and weeding the land, grinding or crushing grain, agroprocessing, and transport. The lack of access to improved cooking fuels is greatest in SSA, followed by SA, as measured by the direct use of solid biomass (charcoal, fuelwood, stalks and other farm waste, or manure). Some 575 million people in SSA (89 percent of the population) rely on traditional biomass for cooking and heating, compared with 713 million in SA (about 50 percent of the population) (IEA, 2002; Gordon et al., 2004). As a rule of thumb, biomass is the most important source of energy (largely for heating and cooking) for people who live on less than US$2 per day (this is an equity issue in that poor people pay proportionally more for basic services). As discussed previously, the cutting of forests for wood and charcoal and the burning of crop and animal residues for energy are necessities of life when other sources of energy are either scarce or too expensive. Those practices contribute to a loss of soil quality and to environmental degradation, and they create health hazards, so a critical challenge is to find alternative sources of energy that are affordable and healthier for humans and the environment. For all those reasons, new designs of cooking stoves and fuels for the poor are gaining attention (Kammen, 1995; Goldemberg et al., 2004; Utria, 2004).

BIOTIC CONSTRAINTS ON CROP PRODUCTIVITY

Diseases and insect pests rob humanity of over 40 percent of the attainable yield of eight of the most important food crops worldwide (Oerke et al., 1994), and invasive species threaten both crops and native biodiversity (McNeeley, 2001). Some of the major pests and diseases are described below.

Insects and Other Pests

There is no centralized source of data on crop losses due exclusively to pests, but all major crops of SSA and SA are attacked by numerous insects, and even birds pose a major problem. The red-billed quelea (*Quelea quelea*), with an estimated world population of 1.5 billion (Cheke et al., 2007), is a major pest in Africa, especially of the open-panicle cereals, such as sorghum, millet, and rice (Ruelle and Bruggers, 1982). Children in particular are given the job of protecting crops from those birds. One hectare of acacia scrub can have 50,000 nests, which produce 100,000 young, hungry birds that migrate with their parents; the birds each eat 20-50 g of grain per day (Doggett, 1988). In Somalia, grain losses of 80 percent have been reported. Crops within 30 km of a roosting area are in danger of being virtually destroyed by the birds, and much larger areas are subject to damage when the flocks migrate (Cheke and Walsh, 2000).

Lepidopteran insects, such as the stem borer and bollworm, attack maize, cotton, rice, eggplant, and other crops. Mealybugs are a major pest of cassava, and pod borers attack legumes, such as chickpea, pigeon pea, and cowpea. Nematodes are a scourge in banana, and weevils in both banana and sweet potato. Storage pests, such as the grain weevils and borers, are responsible for huge losses in SSA (Gressel et al., 2004). Vegetable producers in India suffer a US$2.5 billion annual loss to insect damage even while spending US$100-200 per hectare on insecticides (Padmanabhan, 2000).

Insecticides can control some pests, and biological agents have been used with mixed success, as in the control of cassava mealybug with parasitic wasps and of locusts with the fungus *Metarhizium anisopliae sf. acridum* (Calatayud and Le Rü, 2006). There has been little success in breeding plants that are resistant to the wide array of insects that affect crops in SSA and SA, because the germplasm available to breeders has limited genetic resistance. In contrast, there are many trials with transgenic crops (maize, cotton, banana, and eggplant) that have been engineered to express the *Bacillus thuringiensis* (*Bt*) toxin, and the crops have proved to be very successful where they have been adopted, primarily in maize and cotton (Ferry et al., 2006; James, 2006a; Delmer, 2007). Provided that intellectual property, regulatory, and other barriers are successfully addressed (Box 2-2), these technologies are predicted to be valuable new approaches for plant improvement in SSA and SA.

BOX 2-2
Overcoming Barriers to the Use of Genetically Engineered Crops

It is clear that modern agriculture has been transformed by the advent of genetically modified crops (James, 2006a,b), but in SSA and SA only South Africa and India are even beginning to benefit from them. Insect-resistant (*Bt*) and herbicide-tolerant cotton is being widely adopted in these two countries, yet South Africa is the only country in SSA where transgenic crops are grown by farmers, and it is one of many countries where *Bt* cotton and maize led the way (Eicher et al., 2006; Delmer, 2007). Other *Bt* crops—such as rice, cowpea, and eggplant—are under development in many countries. Transgenic maize that is resistant to the herbicide glyphosate has been released in South Africa and is increasingly popular among small-scale farmers because it has eliminated drudgery associated with hand weeding, allowed cultivation of larger areas, and substantially increased yields. It is obvious that many of the approaches to crop improvement for the poor discussed in this report could be transgenic approaches. An important point to emphasize is that transgenic techniques are important not only for the development of new crops but for the critical first steps of research because they can allow rapid testing of new genes for their potential role in altering crop productivity.

To benefit the poor, there needs to be a dramatic alteration of the barriers that have prevented the development and release of such crops in the developing world (Juma and Serageldin, 2007). Kent (2004) and Delmer (2005) analyzed some of the barriers in detail and suggested a few solutions. The major needs include improved transformation efficiency in several crops, new ways to control gene flow that are acceptable to small-scale farmers, robust ways to insert (“stack”) multiple genes and a path to getting stacked transgenics through regulatory systems, predictable methods for targeted gene insertion, and widely acceptable confined and contained research trials in SSA and SA so that local scientists can participate in the development of transgenic crops important to their own countries. Unfortunately, the high costs and long time frames associated with regulatory approval are a major constraint globally (Bradford et al., 2005; Kalaitzandonakes et al., 2007).

Weed Problems

Parasitic Weeds of Sub-Saharan Africa: Orobanche, Striga, and Others

Parasitic weeds present the most intractable weed problems throughout Africa. In northern Africa, *Orobanche* (broomrape) species attach to roots and devastate most vegetable crops, where they do the most economic damage. They also attack all the grain legumes and have thus become a food security problem; countries that were once self-sufficient in grain legumes are now net importers (Gressel et al., 2004).

In SSA, *Striga* spp. (witchweed) are the major problem (Ejeta and Gressel, 2007). Border countries, such as Ethiopia and Sudan, have both *Orobanche* and *Striga* problems. *Striga hermonthica* and *S. asiatica* attack and devastate maize, sorghum, millet, and upland rice throughout SSA. *S. gesnerioides* attacks grain legumes in western Africa but for unclear reasons has not spread to eastern Africa. *Rhamphicarpa fistulosa* is a related species that is becoming a problem in paddy rice (Ouedraogo et al., 1999).

Major Weed of Wheat in India: Phalaris minor

Wheat (*Triticum*) cultivation throughout the world relies on the use of herbicides, such as 2,4-D, which has been able to control broadleaf weeds without the evolution of resistance. But the absence of broadleaf weeds in the field left an ecological niche that was filled by grass weeds, and controlling them has posed a larger problem. In wheat, all selective graminicides (grass weed herbicides) except one can be detoxified by grass weeds. One in particular, *Phalaris minor*, has become the major weed in Green Revolution wheat in India, having evolved resistance to isoproturon, the sole graminicide used there. This herbicide-resistant weed now covers millions of hectares (Malik and Singh, 1995; Singh, 2007). Although isoproturon was replaced with other graminicides, the problem is worsening, and there is less control by these herbicides (Yadav and Malik, 2005; Singh, 2007).[2]

Major Weeds of Maize and Rice: Feral Rice and Echinochloa

Feral, weedy rice (sometimes called red rice), a rice that was once cultivated but has become dedomesticated, is becoming the major weed problem in rice production in SA (Vaughan et al., 2005). Two changes in farming practices are exacerbating the problem: The use of cheaper bulk rice seed that contains feral rice is replacing the planting of seed from hand-picked, elite germplasm from weed-free fields (the equivalent of certified seed); and rice production is moving away from the back-breaking, labor-intensive method of hand-transplanting rice seedlings into paddies to the direct seeding of paddies. The change in practices has encouraged the evolution and

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[2] In addition to the widespread problems in Haryana and Punjab, the development of new herbicides by major chemical companies is waning while there is a fairly rapid rise in emergence of weeds resistant to the most widely used and environmentally friendly herbicide, glyphosate (Powles, 2008).

establishment of feral rice. With the older production method, the hand-transplanted seedlings had a head start over the development of the weedy rice seeds.

Echinochloa species are major weeds of all grass crops. The International Maize and Wheat Improvement Center lists the weeds *Cynodon* and *Echinochloa* as the most serious pests of maize (Joshi et al., 2005). In southern China, nearly 2 million hectares of rice is infested with *Echinochloa* species that are resistant to two of the three most common inexpensive herbicides used to control the weeds (Huang and Gressel, 1997). In some parts of the world, *Echinochloa* has evolved resistance to the third herbicide, propanil, but compounds that suppress the propanil-degrading properties of the weed have been identified (Valverde and Itoh, 2001). No such solution has yet been reported to overcome resistance to thiobencarb or butachlor, the other two herbicides most commonly used in Asia.

Viruses

Geminiviruses

Two important crops—cassava in SSA and cotton in SA—are experiencing catastrophic losses because of viral epidemics. Both epidemics involve single-stranded DNA (ssDNA) geminiviruses in combination with satellites.[3] In SSA, there is a clear pandemic of African cassava mosaic disease (ACMD), which is spread by the whitefly *Bemisia tabaci* (Mansoor et al., 2003, 2006; Legg and Fauquet, 2004). This problem is compounded by increases in whitefly vector populations that may be due to evolved resistance to pesticides and to global warming (Seal et al., 2006). The outbreak began in Uganda in the 1990s and over the last 2 decades has spread to cover more than 3 million square kilometers in nine countries in eastern and central Africa.

The consequence has been devastating to the largely subsistence agricultural communities affected. It is now known that the ACMD is caused by a number of variant viral strains that are highly mutable and can recombine and that are influenced by the presence of additional satellites (Legg et al., 2006). To make the situation worse, the RNA virus called Cassava brown streak virus, once confined to the coastal areas of Kenya, Mozambique, and Tanzania and now spreading further into eastern Africa, almost certainly synergizes to reduce yields further, to near zero in many areas.

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[3] Satellites are short nucleotide sequences that are distinct from the virus but part of the viral system. Satellites are dependent on a helper virus for replication. Their function is often unclear; they have been shown in some cases to exacerbate symptoms and in others to ameliorate them.

Some progress in breeding for tolerance (but not true resistance) to Cassava brown streak has been recently reported. The CGIAR centers of the International Institute of Tropical Agriculture and the International Center for Tropical Agriculture have also worked to deploy varieties of cassava that are resistant to ACMD, and it is encouraging that molecular markers that segregate with resistance to ACMD have been developed and widely distributed in western Kenya and Uganda and have already contributed to averting a major food insecurity disaster (Okogbenin et al., 2007). However, resistance has been observed to break down in the presence of some newly discovered satellites (Akano et al., 2002; Ndunguru, 2005).

On the Indian subcontinent, a serious threat has emerged in the form of another geminivirus complex—the cotton leaf curl virus, which has re-emerged as a complex with two DNA satellite viruses (Amin et al., 2006; Briddon and Stanley, 2006; Mansoor, 2006) and has caused disastrous losses of the cotton yield. The threat is true especially in Pakistan, but a similar (although distinct) complex is now found to be emerging in SSA. Indeed, the emergence of satellites that form complexes that lead traditional forms of resistance to break down is one of the most serious issues of these DNA viruses. Another ssDNA virus, banana bunchy top, is problematic throughout Asia, causing more than a 50 percent decrease in production in Pakistan. It has now also been identified in SSA, where it is creating worries that it could constitute yet another constraint on banana production in the region. Another geminivirus, tomato yellow leaf curl, whose vector is the whitefly *B. tabaci*, affects the tomato crop worldwide, including in Africa.

ssDNA viruses present a major constraint on production of maize in SSA, and their effects on many common vegetables continue to worsen globally (Rybicki and Pietersen, 1999; Mansoor et al., 2006; Vanderschuren et al., 2007). Maize streak virus (MSV), another geminivirus, is spread by leafhoppers and can cause widespread yield losses in maize; MSV is found only in Africa, so MSV resistance has not been a target for most of the major international seed companies. A few genes that confer some resistance are available and have been used in breeding programs in eastern and southern Africa, and large growers are able to afford insecticides to control the leafhoppers. Although breeders commonly say that MSV is under control, the recent reported loss of up to 80 percent of the maize crop in one region of Tanzania (Joseph Ndunguru, Mikocheni Agricultural Research Institute, Tanzania, personal communication, 2007) is characteristic of many reports from farmers throughout eastern and central Africa. MSV shows much less variability than African cassava mosaic viruses, but recent work indicates that recombination between viral strains does occur (Owor et al., 2007), and little is known about how current resistance loci respond.

RNA Viruses and Retroviruses

In addition to Cassava brown streak virus, a single-stranded RNA virus of importance is rice yellow mottle virus (RYMV); there are at least five regional RYMV variants in eastern and western Africa. The virus limits yields particularly in western Africa, where rice is grown more intensively. Few sources of resistance exist, but some mutations of a rice gene—eukaryotic translation initiation factor 4G (eIF(iso)4G)—confer high resistance to the virus (Albar et al., 2006). Knowledge of that resistance allows both conventional breeding and the possibility of genetically engineering susceptible varieties with the mutant rice gene. Banana streak virus is a retrovirus that can integrate into the banana genome. It is now being spread and activated by some tissue-culture operations in SSA that lack proper viral-indexing capacities (James Dale, Queensland University of Technology, Australia, personal communication, 2007). The latter problem illustrates another serious constraint on disease control: the almost total lack of capacity, infrastructure, and coordination needed to create a comprehensive diagnostic network in SSA. Such a network is critical for monitoring viral, fungal, and bacterial diseases and insects that vector disease, and for identifying and monitoring animal diseases.

Fungal and Bacterial Pathogens

Fungal diseases cause serious yield losses in SSA and SA. The fungal stem rust (*Puccinia graminis*) of wheat was effectively controlled decades ago through introgression of the Sr31 resistance gene by Norman Borlaug and colleagues in one of the key achievements of the Green Revolution. However, a resistant strain of the rust has recently emerged in Uganda and spread to Yemen, and in this age of globalization it poses a potential worldwide threat (Kolmer, 2005; Wanyera et al., 2006). Although it will take time, breeders are identifying sources of genetic resistance in wheat germplasm with help from DNA molecular markers.

Soybeans in Africa, Asia, and Latin America are severely affected by rust (*Phakospora*). According to the International Potato Center, the late blight of potato (*Phytophthora*) is the most costly biotic constraint on global food production. Powdery mildews affect a wide array of crops, including such major cereals as wheat, sorghum, and millet; fungal anthracnose affects crops such as sorghum, beans, and cassava; angular leaf spot and root rots plague beans and other important crops; turcicum and gray leaf spot diseases are serious pests of maize in SSA; and black sigatoka limits banana production worldwide.

Similarly, bacterial diseases cause large crop losses. Particularly deadly are diseases caused by the genus *Xanthomonas*, which include blights of rice and cotton and, more recently, banana wilt blight, a serious disease of the east African highland banana, the major staple crop of Uganda.

Small farm environments are susceptible to the development of fungi that lead to mycotoxin (aflatoxin or fumonisin) accumulation. Mycotoxins are highly toxic metabolites produced by a number of fungi, especially in drought-prone or unseasonably rainy environments or as a consequence of high moisture before harvesting, during harvesting, and in storage (Widstrom, 1996). Many toxin-producing fungi have been found in stored food products, but two in particular have major impacts on tropical economies: aflatoxins produced by *Aspergillus flavus* and fumonisins A and B produced by *Fusarium*. Research in Asia and SSA has shown that mycotoxin contamination is widespread on staple crops. Aflatoxins are routinely found in maize, groundnut, sorghum, cashew, cassava, yam chips, pistachio, almond, and chili pepper; *Fusarium* toxins occur in maize, wheat, and sorghum; and ochratoxin (produced by some *Aspergillus* and *Penicillium* species) occurs in cocoa and cashew (Ortiz et al., 2008). Mycotoxins are also present in some processed food and feed and even in milk and meat products when animals are given contaminated feed. The presence of mycotoxins in agricultural products renders them unexportable (see Box 2-3).

An estimated 4.5 billion people are chronically exposed to mycotoxins in the developing world (Williams et al., 2004). Mycotoxins get some public attention when people die after acute exposure to them, as in the aflatoxin poisoning in Kenya where 125 deaths were recorded in 2004 (Probst et al., 2007). But effects of chronic exposure are also widespread and often more insidious and therefore do not cause the alarm expected.

OVERVIEW OF ANIMAL PRODUCTION IN SUB-SAHARAN AFRICA AND SOUTH ASIA

Livestock

Globally, livestock production is in a period of rapid transition. Since 1995, more meat has been produced in developing countries than in developed countries. Most livestock is owned by farmers who work on mixed crop-livestock farms. In Asia, more than 95 percent of the ruminants and many swine and poultry are raised on such farms. Worldwide, 57 percent of the 687 million poor who own livestock work in mixed crop-livestock systems (Devendra et al., 2005). The animals in these systems have multiple purposes: they provide milk, meat, fiber, hides, manure (soil amendments), traction, and a means to accumulate assets. In Africa, 70 percent of the poor farmers own animals, and the animals represent about half their assets.

Most African livestock are raised in the subhumid and semi-arid re-

BOX 2-3
Meeting International Food Safety Standards

The entrance of small-scale farmers into global food markets is prevented by their inability to meet the high standards of food safety set by the developed world. A classic example is the stringent standard for mycotoxins in imported foodstuffs imposed by the European Union. With the rise of supermarkets in SSA and SA, such standards are increasingly being set even locally and can lead to lost opportunities for such farmers to find markets in the growing urban populations of their own regions (see Weatherspoon and Reardon, 2003; Brown, 2005; and the many references in both).

Poor farmers lack the tools to prevent mycotoxin problems—clean water; rapid and cheap diagnostic kits; an array of improved postharvest technologies, including local access to cold storage, solar drying, and improved packaging; and rapid and efficient transport systems. The good news is that when projects are in place to upgrade small-scale farmers' ability to meet all those challenges, the large supermarket chains appear eager, at least sometimes, to have them participate.

Some examples of success stories have been outlined by Page and Slater (2003) and Weatherspoon and Reardon (2003). In Zambia, the Luangeni project is using various actors (donors, the government, nongovernment organizations, and retailers) to help small-holders to meet quality, safety, and cost standards in conjunction with the South African retailer Shoprite. Dave Weatherspoon, of Michigan State University's Partnership for Food Industry Development Project, funded by the U.S. Agency for International Development, is helping to connect small producers in South Africa's Eastern Cape Province with Pick 'N Pay, the country's second-largest supermarket chain. The farmers have agreed to a 3-year growing project in which they supply squash products and sweet corn to the chain. Pick 'N Pay specifies what varieties the farmers must plant, the farming practices and processing methods they must use, and when they must deliver the produce. In return for participating in this rigorous program, the farmers gain access to a profitable and reliable market.

gions that extend in an inverted "L" from South Africa north to the Sudan and west across the Sahel (Figure 2-4) (Thornton et al., 2002).

Of poor farmers who own animals, 20 percent operate in extensive systems (Devendra et al., 2005). They include livestock owners in eastern Africa (Ethiopia, Somalia, Eritrea, Kenya, and Sudan), in western Africa across the Sahel region, and in India (the Rajasthan). In those areas, which represent about one-fourth of the world's land mass, millions of nomadic herders and pastoralist herders and their families tend livestock on lands that otherwise would probably be agriculturally unproductive because of

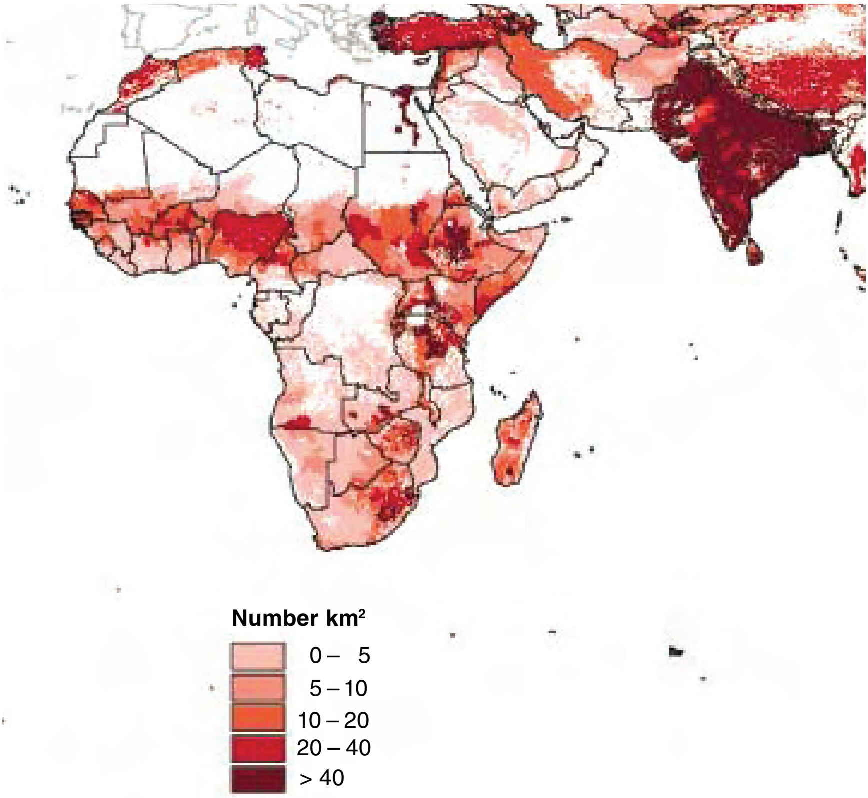

FIGURE 2-4 Tropical livestock unit density in sub-Saharan Africa and South Asia.
SOURCE: Excerpted from Thornton et al., 2002. Reprinted with permission. © 2002 by International Livestock Research Institute.

low rainfall. About 10 percent of the global meat supply is produced in those areas, and livestock production is the primary food- and income-generating activity for the people living there. Up to 88 percent of agricultural income of farmers in the regions is derived from livestock (Winrock, 1992). Enormous social, economic, and environmental pressures threaten those pastoral systems.

Dairy

In 1998, India became the world's largest milk producer, outstripping the United States (FAO, 2006b). Small-holder farmers predominantly operate forage-based dairy production systems. The continued success of small-holder dairying in India is due, in part, to Operation Flood, a long-term (1970-1996) national program to promote dairying and to support more than 72,000 village milk cooperatives that purchase milk from small-holders. Lagging behind efforts in SA, the lack of ability to market dairy products represents an even more serious constraint in SSA. In China, India, Brazil, and other parts of Latin America and southeastern Asia, changes in the supply chains for milk and meat have led to more reliance on centralized processing and supermarkets (Reardon et al., 2003). Processing and marketing advances have provided outlets for livestock products and improved food safety, but these technology-linked benefits often are inaccessible to the poorest farmers.

Aquaculture

The Asia-Pacific region is the world's largest producer of fish (over 80 percent of total world production) by both aquaculture and capture fisheries. Each sector is approaching 50 million tons per year. As might be expected, artisanal fishing is a major driver of the economy of island states, such as the Maldives, and is important in all the coastal regions of SA. Fishing is especially important in Bangladesh, a country of rivers and coastal flood plains where inland capture fisheries provide both income and important sources of protein for the poor. However, small pond sizes and their seasonal drying remain large constraints on this industry. Fishing is also important in SSA (although on a smaller scale than in SA), with a total production of about 7 million tons per year divided equally between marine and inland fisheries. The Food and Agriculture Organization of the United Nations (FAO, 2003) estimated that 20 percent of dietary protein in SSA comes from fish. Capture fishing predominates in many coastal communities of Africa, although the IAC report (2004) indicates that the per capita supply of such fish is declining, and capture fishing in some areas, such as Lake Victoria, is judged to be near its maximum. Assuming an average annual population growth of 1.9 percent, just maintaining the current production level in SSA up to 2015 will require that fish production increase by 27.7 percent over this period (World Bank, 2004; WorldFish Center, 2005).

Globally, most forecasts are for a decreasing supply from capture fisheries and an increasing proportion from aquaculture, with an annual increase of 8.9 percent making it the fastest-growing food production sector (Hill, 2005). Thanks to visionaries like Mondadugu V. Gupta, winner of the 2005 World Food Prize, aquaculture, including co-cultivation of fish in rice paddies, has increased throughout SA and is judged still to have strong growth potential. FAO projections show that by developing only 5 percent of the suitable areas available for aquaculture use, Africa could meet its fish production target (FAO, 2003). That points clearly to the benefits that might accrue if aquaculture were more extensively developed in SSA using sustainable practices.

Poultry

Another fast-growing segment of the agricultural sector in SA is the poultry industry, with an average growth rate of 8 to 10 percent and production of 44 billion eggs and 1.6 billion broilers per year in India alone. At the National Seminar on Poultry Research Priorities to 2020, held in 2006 at the Central Avian Research Institute (*http://www.icar.org.in/cari/index.html*), a number of priorities for research were outlined. It provided a rich source of information on new directions for the poultry industry on issues such as the use of molecular tools for poultry breeding; disease management, including biosecurity and control of emerging zoonoses; and processing (Kannaki and Verma, 2006). The poultry industry in SSA is still lagging compared with that in other parts of the developing world.

GENERAL CONSTRAINTS ON ANIMAL PRODUCTION

Poor nutrition, diseases, and poor genetic potential are the three major constraints on animal production in SSA and SA (CAADP, 2003; IAC, 2004), but there are several ancillary constraints, such as the lack of animal identification and tracking measures for disease status, competition from imports, the need for mobile milking machines and chilling tanks, the need for reliable animal and meat transportation and storage, and alternatives to fish meal for aquaculture.

The interactions between wildlife and domestic animals also contribute to important factors affecting the ability of poor farmers in SSA and SA to increase the productivity of their animals. One is the effect of wildlife on competition for land resources and land use, and another effect is the transmission of diseases between wildlife, domestic animals, and humans. The legal and illegal trade of bushmeat also has a tremendous impact on the sustainability of livestock and ecosystems in both SSA and SA (Loibooki et al., 2002; Rowcliffe et al., 2005).

Water is another constraint. Production of meat from animals requires about 8 times the amount of water needed to produce the same amount of vegetable protein. Lack of water for grazing animals severely limits animal production in pastoral areas. On the basis of the goal of having 20 percent of all food come from animal sources, about 1,300 m^3 of water per person will be required each year to produce animal protein for a balanced diet of 3,000 kcal/person per day (FAO, 2003).

Lack of Nutrition and Reliable Feed Supply

Livestock nutritional inadequacy is a severe seasonal constraint in dry areas, but improvement of extensive pasture systems is extremely difficult. Farmers lack the equipment and improved forage varieties needed for pasture establishment, and free-ranging animals often consume newly planted pasture. To minimize losses to pests and diseases, pastoralists tend to overstock their herds, and this can lead to overgrazing and loss of forage diversity.

Forage in the tropics is often deficient in protein, energy, and micronutrients, and these deficiencies sharply reduce animal productivity. Although considerable effort has gone into improving the quality of *Brachiaria* spp. in the humid and subhumid tropics, relatively little attention has been given to other grasses and legumes. *Pennisetum purpureum* (Napier grass), which is widely used in the eastern African highlands and elsewhere and is susceptible to *Ustilago kamerunensis* smut, deserves particular attention, as do the herbaceous legumes that can simultaneously improve soil fertility and the nitrogen status of animals. A forage-breeding program that could improve the nutritive value and disease resistance of grasses and legumes is needed. Molecular breeding approaches could be used in combination with regional trials to assess the adaptability of germplasm for different ecozones.

Many forage-fed animals in the tropics grow slowly and produce small amounts of milk because their diets are inadequate in protein, energy, and micronutrients. In regions where mixed animal-crop systems prevail, there seems to be a great opportunity to address poor nutrition by strengthening fledgling animal feed industries. Not only would that promote a more stable source of food for animals, but it would also present an opportunity to stabilize output markets and add value to crops such as maize, sorghum, cassava, and legumes. Protein is often scarce in many regions: many ruminant animals have nothing but wheat straw to eat in the dry season.

Animal Diseases

Animal diseases have an extraordinary impact on livestock productivity and livestock production, especially in SSA and SA where the control of animal diseases has been more challenging with limited resources. The consequences of animal diseases range from direct economic costs, such as the loss of animal production and products, to indirect costs related to a disease outbreak, such as the loss of trade markets and job losses (OIE, 1999; Le Gall, 2006). In the 1980s, a foot-and-mouth outbreak caused the Kenyan dairy farming sector to suffer a 30 percent loss of milk production (Le Gall, 2006). In 1997-1998, abortions caused by Rift Valley fever virus impacted birth rates and milk production, and East Africa experienced a 75 percent decline in exports (Le Gall, 2006). The 2003-2004 outbreak of highly pathogenic avian influenza in Southeast Asia resulted in more than 140 million dead or destroyed birds and losses exceeding US$10 billion (World Bank, 2008). Even though poor countries in SSA and SA may not be ready to export some of their agricultural commodities, many countries are finding a market niche for some of their animal products and are facing significant obstacles in reaching international markets because of animal diseases in their countries.

Some major animal diseases in SSA and SA include African swine fever, peste des petits ruminants, sheep and goat pox, hemorrhagic septicemia, foot-and-mouth disease, contagious bovine pleuropneumonia, blue tongue disease, clostridial diseases, and vector-borne diseases, such as heartwater, East Coast fever, Rift Valley fever, trypanosomiasis (animal and human), parasitic diseases, classical swine fever, highly pathogenic avian influenza, and Newcastle disease. Zoonotic diseases pose a continuing threat (see Box 2-4).

The types of disease vary considerably among western Africa and eastern, central, and southern Africa, but ticks, worms, and the tsetse fly are common everywhere (Perry et al., 2002). Most of potentially productive SSA is infested by the tsetse fly and affected by human and animal trypanosomes. According to the International Livestock Research Institute, the 300,000 cases of animal trypanosomiasis in Africa (40,000 new cases each year) result in annual losses of over US$4.5 billion.

East Coast fever and Rift Valley fever take a heavy toll on cattle, and Newcastle disease severely limits poultry production by poor farmers (Gueye, 2000). Internal parasites of livestock, notably haemonchosis and fascioliasis, are also major constraints, as internal and external parasites have a severe impact on animal health and productivity at the level of poor farmers in SSA and SA. Many of these parasitic infections are easily controlled with low-cost medications and can be used with existing technologies—such as ear tags with insecticides and slow release anti-parasitic boluses that can be given to ruminants—to control parasitic burdens. There have been considerable advances in the development of vaccines for important parasitic diseases but little commercial interest in developing and marketing them. Endemic viral diseases often occur as focal or widespread outbreaks that cause immediate and short-term economic effects because of morbidity and mortality and restrictions on international trade and movement. Viral diseases constitute a particular problem in aquaculture (Hill, 2005).

CONSTRAINTS THAT CANNOT BE SOLVED BY SCIENCE AND TECHNOLOGY ALONE

One of the striking features of the list of constraints identified by scientists in SSA and SA (see Box 1-1 in Chapter 1) is the number of non-

BOX 2-4
Zoonotic Diseases

The World Health Organization defines zoonoses as diseases caused by infectious agents that are naturally transmitted between animals and humans. Some well-known zoonoses are salmonellosis, swineherd's disease (caused by *Leptospira* spp.), brucellosis, hepatitis E, HIV, bovine spongiform encephalopathy (BSE) and its zoonotic form the variant Creutzfeldt-Jakob disease (vCJD), Rift Valley fever (RVF), anthrax, adult meningitis (caused by *Streptococcus suis*), and influenza.

Of most interest today are the so-called emerging zoonoses, which include SARS, West Nile virus, and highly pathogenic avian influenza. Increasing population, globalization, trade in exotic pets, and the close intermingling of animals and humans in urban settings have all contributed to outbreaks of emerging zoonoses. The diseases are especially threatening to the fragile economies of SSA, where livestock, dairy, and poultry industries are just emerging and could be seriously affected. In Africa, movements of domestic and wild animal populations are important in the spread of the diseases. A very serious emerging zoonotic disease in SA is Nipah Virus Disease, which is transmitted by *Pteropus* bats and the disease results in high levels of fatality in humans and in pigs.

There are many opportunities for modern science and technology to contribute—through development of better and cheaper diagnostics, better surveillance, and rapid-response systems, including vastly enhanced capacities to rapidly create and deliver new vaccines. There is also much to learn about the mechanisms by which viruses recombine and create new and more deadly strains. Although the conventional wisdom is that mutations and recombinations are random and not predictable, novel approaches by, for example, Henry Niman and his company, Recombinomics (*www.recombinomics.com*), suggest that greater understanding will make these events more predictable. If so, there will be possibilities to create vaccines in advance of the recombination events.

agricultural issues, such as insufficient markets, weak governments, and lack of infrastructure. Some of those issues have long been blamed for holding back social progress and blunting the impact of technical solutions to agricultural problems. It now seems remarkable that few anticipated the "perfect storm" of rising food prices worldwide due to a convergence of events only partly related to agricultural productivity: a rising middle class in the developing world demanding more grain for direct consumption and for feed to satisfy a growing desire for animal products, the high cost of energy for agriculture, diversion of food crops to biofuels, and long-term droughts in major cereal producing regions such as Australia.

Weak Government and Policy Environment

Many of the challenges are of a political, social, or economic nature: poor governance, corruption, tribal rivalries, and intense civil strife continue to hinder development in many countries of Africa. Tribal customs can play a role in SSA, and remnants of the caste system in India still strongly reduce opportunities for the poor. Poor governance can create excessive roadblocks to the development of business enterprises and decrease the pace of rural economic development. Particularly in SSA, the lack of good policies to support agricultural trade and lack of credit for the poor at fair interest rates are common problems. Weak legal structures related to women's rights and land tenure provide little incentive for long-term farm improvement and, when coupled with the high death rate from HIV/AIDS, create instability in the rural sector. Outdated treaties on water rights that date from colonial times also impede development of sound water policies in some SSA countries, and inattention of SA governments to control the worsening depletion of major aquifers and the pollution of rivers is predicted to have disastrous consequences for agriculture.

In SSA, imposition of protective tariffs on needed inputs such as high-quality seed, fertilizers, and pesticides—coupled with the lack of specific government support systems for help with such issues as targeted subsidies for agricultural inputs—are also major constraints. The policies of international donors that prefer to donate surplus food from abroad as opposed to purchase food grown in African countries with surpluses and transfer of such to countries with shortfalls increase price volatility, distort markets, and discourage farmers from trying to be productive.

Not all government policies have adverse effects. A recent Malawi government investment in seed and fertilizer for poor farmers (and favorable weather) doubled maize yields, bringing some food security where famine had been rampant. Such approaches are clearly needed but with some caveats. One danger is that government "giveaways" of seed and fertilizer can compete unfairly with the fragile emerging private-sector seed companies and agrodealers—a danger that in the Malawi case was mitigated by the use of vouchers.

Insufficient Investment in Agricultural Research and Development

Most governments in SSA have not invested even a small percentage of gross domestic product in agricultural R&D, and even the recently set goals for boosting agricultural productivity by 6 percent per year in Africa (CAADP, 2002) appear to be quite inadequate in light of the rate of population growth and the dramatic rise in food prices worldwide. World grain prices, which by 2008 were roughly 75 percent higher than in 2005, are expected to remain high at high levels through 2017 (USDA, 2008), offering a unique window of opportunity to assist poor farmers in transferring from subsistence to production agriculture if productivity in SSA and SA can be increased.

Lack of Extension Services

A major constraint to agriculture is the woefully inadequate extension services in both SSA and SA that are so critical for transferring new knowledge and technologies to farmers. Many countries in SSA and SA maintain a large number of agricultural extension agents on government payrolls, but they do not have sufficient resources to get into the field or to develop and provide the information needed to support farmers. In addition to local radio, the growing access to the Internet, particularly in SA, might be used to great advantage to transform those services. SA is in a much better position than SSA with respect to infrastructure for information technology; however, with the completion of fiber-optic cables that can surround SSA and efforts to connect the interior regions to them, one can expect rapid adoption of this powerful means of communication just as cellular phones have been adopted.

Lack of Cash and Financing

It is often not recognized that farmers live in a cash economy with little means to generate cash. Purchase of day-to-day necessities—such as clothes and food not grown at home, school fees, and costs of health services, weddings, and funerals—limit a farmer's ability to purchase high-quality inputs, including seed, fertilizer, and irrigation and other farm equipment. For those and other complex reasons, the creation of dynamic rural enterprises depends on the availability of credit at manageable interest rates to small-scale farmers. The need for such credit impinges upon all efforts to increase agricultural productivity. Through the ability to purchase critical inputs that can increase primary productivity, excess yields of staple crops (beyond household needs) could be processed into higher-value commodities and sold in local and regional markets. Alternatively, with higher productivity, the land devoted to staple crops could be decreased to allow production of higher-value cash crops, such as fruits and vegetables, which contribute to both better nutrition and income.

Need for Basic Infrastructure

The lack of adequate roads in SSA severely limits the development of strong output markets; even in India, the Finance Minister in 2005 stressed in a speech the importance of further development of rural roads, electrification, and increased access to markets that would be critical for rural development. Particularly in SSA, poor roads and lack of transport mean that farmers are also isolated from key inputs, such as improved seed, fertilizer, irrigation and other farm equipment, and information services. A recent push to promote farmer collectives (*www.sacredafrica.org*) and to create a much larger number of small local agro-dealers to provide the inputs and services has helped in some small way to mitigate the problem in a few countries in eastern Africa (Eilittä, 2006). On the output side, both in SSA and SA, poor storage conditions for grain, fruits and vegetables, fish, milk, and meat and lack of transport and roads limit a farmer's ability to sell excess produce in years of abundance. The lack of roads coincides with the critical lack of energy, both on the farm and in the transportation sector. Together, the lack of these two critical aspects of infrastructure essentially ensures that efforts to modernize agriculture cannot succeed unless these two major limitations are addressed in a serious way.

A FUTURE UNCERTAINTY: CLIMATE CHANGE

A 2007 report by the Intergovernmental Panel on Climate Change leaves little room for doubt that the world is getting warmer. By the end of the century, average temperatures could increase by up to 6°C. Higher latitudes will experience greater temperature increases than coastal and lowland regions. The effects of climate change can also impact plant and animal disease patterns and prevalence. Increased carbon dioxide concentrations decrease stomatal conductance and reduce water loss from plants under both irrigated and rain-fed conditions and can result in higher yields, although the results can vary seasonally in ways that are not completely understood (Bernacchi et al., 2007). On a larger scale, the decreases in plant evapotranspiration have been shown to increase continental water runoff to the seas and thus affect global hydrology (Gedney et al., 2006). The magnitude of any feedback loops in those systems locally, regionally, and globally is complex and deserves further study; genomic approaches that facilitate adaptation of important crop species is part of this research (White et al., 2004; Li et al., 2007).

It is quite clear that, in terms of overall effects on world agriculture, there will be winners and losers as the climate changes. For example, it is predicted that southern and northern Africa will become drier and the tropics wetter (with regional variations), and there remains much controversy over how the Sahel will be affected. It is more certain that Africa and parts of Asia (Naylor et al., 2007) will be greatly affected by El Niño and that in general Africans, like most of the rest of the world, should expect more violent extremes of weather (DFID, 2004; IPCC, 2007). A recent study based on statistical crop models and climate projections for 2030 indicates that wheat in SA and maize in southern Africa are the most likely to suffer adverse effects of climate change (Lobell et al., 2008).

Farmers in SSA have millennia of experience in dealing with the vagaries of weather (Giles, 2007), and it has often been pointed out that annual variations in weather can be more extreme than the changes predicted for the long term. As noted previously, poor farmers in SSA are conservative when faced with uncertain conditions. Therefore, enhancing the accuracy of seasonal weather predictions could have a profound effect on agriculture in SSA. If a cropping season for bumper crops could be reliably foretold, farmers would be much more willing to risk the purchase of high-quality seed and fertilizer or to make reasoned decisions about what percentage of maize vs. the more drought-tolerant sorghum to grow.

It seems apparent that changing weather patterns will also affect the distribution and movements of pathogens and their vectors. Changes in the patterns, prevalence, and competency of arthropod vectors of infectious and parasitic disease agents are already having a serious impact on the emergence of vector-borne human and animal pathogens. Studies so far indicate that, in general, plants will be more predisposed to diseases as global warming proceeds (Chakaborty, 2005), but there are many complex feedback loops in the interactions (Harvell et al., 2002; White et al., 2004; Burdon et al., 2006; Garrett et al., 2006; Yamamura et al., 2006; Ziska and Goins, 2006; Zvereva and Kozlov, 2006). The roles of crop plants (such as rice) and animals in greenhouse gas emissions are coming into focus, but how the emissions might be mitigated, including soil carbon sequestration, is still an open question (Lal, 2004; Wassmann et al., 2004; Kerdchoechuen, 2005).

Finally, how will rising sea levels affect the livelihoods of those engaged in agriculture and fishing in coastal areas? The situation could be so severe in some island countries, such as the Maldives and the coastal regions of Bangladesh, that relocation of people might be the only worthwhile option. Rising sea levels and as well as more violent storms will certainly affect coastal ecosystems, including the mangroves that harbor rich fishing grounds, and lead to salinization of coastal aquifers (IPCC, 2001). Changes in sea level, temperature, and concentrations of CO_2 and O_2 can also lead to changes in population dynamics for all species. IWMI (2006) has provided an excellent summary of the challenges that global warming will probably create for both artisanal fishing and aquaculture. Efforts are needed to anticipate the changes and take adaptive actions before the adverse effects on agriculture occur.

LACK OF QUICK FIXES

The Comprehensive Africa Agriculture Development Programme emphasized that "there should be no illusion of quick fixes, or miracle paths, towards African self-reliance in food and agriculture. Achievement of a productive and profitable agricultural/agro-industrial sector will require Africa to address a complex set of challenges" (CAADP, 2002).

Because agriculture in SSA and SA is so *relatively* unproductive, almost any well-chosen effort to address some of the constraints in these regions might bring about substantial improvement in a short period of time, although one has to understand that such improvement is relative. For example, the yield increases experienced in Malawi after government financing of fertilizer and seed purchase were still only about two-thirds the world average. Therefore, more progress is needed. In the industrialized world, the implementation of a novel technology provides a marginal benefit to the production system, but no coherent production "system" exists in most places in the developing world. A whole suite of approaches, some technological and some not, must come together for farmers to realize the benefit of any innovation. For example, addressing the nutritive component of a crop will be of little use if the numerous other constraints that limit the crop's productivity are not tackled.

The opportunities suggested in the succeeding chapters must be viewed in that light—that at best they offer new approaches that can synergize with each other and with the many other activities supported by governments and donors worldwide to transform subsistence agriculture to productive agriculture in SSA and SA.

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3

Plant Improvement and Protection

ENHANCING CROP PERFORMANCE

Crop performance is affected by a combination of many factors, not the least of which is the collection of genes (or variants of individual genes, referred to as alleles) that provide the plant with the potential for high yield in a given farming environment. The right genes or alleles to overcome the constraints identified in Chapter 2 and enhance desirable traits in a crop are brought together by plant breeding, a complex process that, broadly defined, uses all the tools of modern plant science, including agronomy, field trials, propagation, tissue culture, genomics, molecular biology, biochemistry, and plant physiology. This chapter describes existing and evolving tools for improving and protecting crops. The first and largest part of the chapter focuses on plant-based applications; the second part addresses plant protection using biological control methods.

For many crop species, sources of germplasm that are able to overcome particular constraints have been identified, and conventional breeding techniques can be used to bring together the desired genes or alleles (Pingali, 2001). Within the range of germplasm available to breeders, crops contain alleles that can improve performance with respect to a variety of traits, but in many instances they do not. This is where the potential for genetic engineering of crop plants can make a tremendous contribution. Novel genes for improving a crop can come from plant, animal, or bacterial species, and molecular techniques are used to introduce them into a candidate crop. Once they are introduced into a plant, conventional plant breeding approaches are used to incorporate them into the local, elite germplasm.

Conventional and transgenic approaches to enhance crop performance are complementary and rely on many of the same molecular and informational tools.

Box 3-1 contains a list of plant traits of which variants are selected by breeders (sometimes inadvertently) as targets in the process of creating improved plants for various environments. Many of the traits are linked by biochemical interactions that influence the expression and control of gene products. Sometimes the genes controlling the different traits are ge-

BOX 3-1
Examples of Traits Targeted for Improvement

- Architecture—height, number of leaves, tillers, branches, leaf angle, number of flowers and seeds, seed size, root structure, surface area.
- Optimal planting density.
- Flowering time and photoperiod responses.
- Growth rates and regulation of hormones: brassinolide, auxins, gibberellins, cytokinins, ethylene.
- Growth responses to light quality and quantity.
- Photosynthesis rates and overall carbon fixing during growing season, chloroplast number and positioning, C_3 vs. C_4 metabolism, pathway regulation.
- Heterosis (hybrid vigor) and male sterility for hybrid production.
- Fertility, inbreeding and outbreeding.
- Nitrogen and phosphorus uptake, use efficiency, translocation, storage, reduction, portioning between plant parts.
- Water use efficiency: uptake, storage, transpiration rates, loss, tolerance of chronic drought and transient drought.
- Heat or cold shock and sustained tolerance to heat, cold, freezing.
- Seed germination in cold.
- Flooding tolerance.
- Oxidative stress tolerance.
- Heavy-metal and salt tolerance.
- Biosynthesis of key metabolites.
- Nutritional composition—seeds, roots, leaves, fruits, stems.
- Digestibility (by humans and animals).
- Root endosymbionts.
- Resistance to viral, fungal, and bacterial pathogens.
- Resistance to weeds and to herbicides that control them.
- Resistance to insects and other pests and predators.

netically linked and do not undergo recombination in meiosis. Failure to understand these associations leads to inefficiency in the breeding process and to poor crop performance. These relationships exist even when a new, transgenic trait is introduced into a plant genome, which emphasizes the need to continue improving germplasm even when transgenic solutions are available for some traits.

It is beyond the scope of this report to describe a strategy for every trait that would be worth targeting. Examples of opportunities with potentially high returns are discussed throughout the chapter, which focuses on opportunities to overcome some of the major problems that constrain agricultural productivity in sub-Saharan Africa (SSA) and South Asia (SA).

Essential Features of Breeding Programs

Because the success of every trait modification project depends on the competence of breeding programs, it is worth drawing attention to the quality of the breeding process itself. In particular, two essential features of modern breeding programs should be emphasized. First, successful crop improvement is based on a foundation of knowledge that informs all the intellectual and physical efforts of plant breeders in the laboratory and in the field. The different types of information needed are likely to be generated by a variety of sources, so the task of plant breeders is to draw the information together as the basis of a breeding strategy. With relevant information, breeders can consider options for genetic and operational tactics to resist disease, weed, and pest damage; to enhance yield traits; and to begin a science-based, comprehensive breeding program to generate candidate germplasm.

Among the types of knowledge important to plant breeders are the following:

- An understanding of the appropriate crop for breeding and its fundamental genetics. This knowledge comes from extensive analysis of the needs of specific human societies (including farmers and consumers) and of the relevant production constraints on a crop that have the potential to be genetically manipulated.
- An understanding of the markets for and uses of crops and the types of improvements that can add value to the crops.
- Knowledge of the genetic and phenotypic diversity in the available crop germplasm (enhanced by similar information on other crops).
- Knowledge of the biology of relevant pests, weeds, diseases, and stresses that routinely limit yield in the crop.
- Knowledge about the specific processes that result in yield loss in farmers' fields.

The second feature of a successful breeding program involves understanding that in evaluating germplasm, trials and selections take place in environments similar to those in which the crop will be grown. Therefore, crop yield trials in these regions are essential, requiring trained local manpower. The international agricultural research centers of the Consultative Group on International Agricultural Research have endeavored to establish consortia with national programs to achieve this testing, but an expansion of the effort is needed. Trials can be carried out under favorable conditions to estimate yield potential, but such conditions are not usually encountered area-wide. Additional realistic trials need to be conducted to select tolerance traits relevant to the major constraints under conditions encountered by small-scale farmers.

Similarly, a fundamental tenet of plant breeding is the ability to assay the trait in question. For example, during breeding and selection, plants have to be subjected to the most common strains of pests, weeds, and diseases that will challenge them in the farmer's field. That is not a simple task, because given that pests, weeds, and diseases are not prevalent every year, breeding and selection processes need to be coupled to tests for tolerance and sensitivity to the specific strains of indigenous or potentially indigenous pests, weeds, and diseases. Local and emerging diseases need to be precisely identified for each crop; the involvement of local farmers in the selections and tests could increase the likelihood that the final products will be adopted, and additional local knowledge can be incorporated into the selection processes.

The establishment and scale-up of modern plant breeding programs in SSA and SA should have high priority in any organization looking to improve agricultural productivity. Plant breeding is rapidly evolving as an integrative technology supported by increasingly powerful molecular tools. Most of the expertise and knowledge needed to carry out this work is already available somewhere in the world. The message to the international development community is that crop improvement ultimately needs to be understood as a local and regional effort that is assisted by tools and knowledge developed by a broader community.

EXISTING TOOLS FOR CONVENTIONAL PLANT IMPROVEMENT

Annotated Sequences of Crop and Model Species for Comparative Genomics

Some of the knowledge that plant breeders need to improve crops in SSA and SA already exists or is rapidly being generated. The sequences of the genomes of corn, sorghum, rice, and poplar have been or soon will be published. The cassava genome is currently being sequenced by the U.S. Department of Energy Joint Genome Institute. The genomes of tomato, the legume *Medicago truncatula* (barrel clover), and many other species are in line to be started or completed, although more attention to important legumes such as the common bean, cowpea, and pigeon pea, as well as other crops important to the poor such as species of *Musa* (e.g., banana and plantain) would certainly be welcomed. Nevertheless, the complete sequences of several genotypes of many additional crops will be known in 5 years; nearly every gene will be identified, variants for many important genes found, and the most relevant genes' associations with traits established. The patterns of expression of co-regulated genes will become linked to phenotypes (the expression of the collection of genes that make up a trait in a given environment). Easily scorable genetic markers for every small chromosomal segment of much of the relevant germplasm will be known, and determinations of which chromosomal variants to select for in different environments will begin to emerge. All that will usher in a new platform for genomics-based breeding in which the needed genomes exist in the crop or in interbreeding relatives. Transgenic technologies will be needed to transfer the genes from other species where that is not the case.

Two plants in particular are important models of the major species grown in SSA and SA. One is *Arabidopsis*, the most-studied reference plant; over the last 20 years, a detailed understanding of the molecular, biochemical, and cellular basis of pathways and circuits in *Arabidopsis* has been developed, and it will remain the leading source of knowledge on the biological systems of plant traits in the coming decade. The other is rice, the model plant of the grass species, including maize, wheat, pearl millet, sorghum, and others. Progress in understanding the biology of rice traits will be slower than in that of *Arabidopsis*, but it will be more directly relevant to cereal crops in the developing world. Research tools and genetic stocks available to address the fundamental questions concerning potential constraints on rice yield are rapidly increasing and are being used by a growing consortium of scientists around the world. Moreover, because of their common ancestry, the grasses have retained the same general order of genes along chromosomal segments (synteny), so mapping of genes on chromosomes of one species can be helped enormously by knowledge of a reference genome, such as that of rice or maize (Bennetzen and Ma, 2003). Diversity in gene order sometimes exists between these genomes over short distances, but this does not eliminate the value of synteny in aiding comparisons between crop genomes. It also helps in finding truly orthologous (similar) genes between species.

DNA Markers

DNA markers—sequences of DNA shown to be associated with particular genes or traits—have great potential to assist plant breeders (Jena et al., 2006; Steele et al., 2006), but for various reasons they have been underused in breeding programs. The use of qualitative phenotypic information with markers to determine the optimal crosses and offspring can shorten the cycle of crop improvement from 5 to 2 years (Jannink et al., 2001; Arbelbide and Bernardo, 2006). Methods for assaying genetic variants are readily available and improving each year. When the contribution of a variant gene to a trait is known, the variant can be used as a marker of the trait. A candidate plant for breeding can be identified by the presence of a marker in its genome without the need to test it for its phenotypic expression. That can help in choosing diverse parents for specific traits; in reducing the number of breeding generations by making it possible to select homozygotes more efficiently; in accelerating backcrossing of a trait to an elite parent, especially when the desired trait is recessive; and in selecting desirable progeny while rejecting poorer genotypes without the need for complex assays, such as assays of tolerance to diseases.

The use of molecular markers has highlighted the importance of genes from wild relatives for crop improvement (Tanksley and McCouch, 1997; Koornneef et al., 2004). As evidenced by recent work on tomato, the results of introgressing ancestral genes can sometimes be spectacular (Frydman et al., 2004). Another example of the richness that diversity can provide is New Rice for Africa, NERICA. African farmers are showing enthusiasm for these new inter-specific hybrids that combine the best of Asian and African rices (Jones et al., 1997). Better knowledge of the genetic diversity of indigenous tree species, particularly those of central Africa, could be applied to forest improvement (Juma and Serageldin, 2007).

Genetic markers that link DNA sequences to traits are increasingly available in rice, maize, cassava, cowpea, wheat, and sorghum, and these crops are becoming better understood genetically (Buckler and Thornberry, 2002; McCouch et al., 2002; Somers et al., 2004; Duputie et al., 2007; Huang and Wu, 2007; Timko, 2007). Box 3-2 provides one example of the value of such markers.

In general, however, tropical forage plants have received little attention from molecular and conventional plant breeders with a few notable exceptions: alfalfa (which is grown in some tropical highlands), *Brachiaria* spp., *Pennisetum purpureum* (elephant or napier grass), and *Panicum maximum* (Guinea, colonial, or Tanganyika grass) have been studied (Jank et al., 2005). Characterization of forage traits that need improvement and studies of genetic markers for those traits have just begun, and temperate forage still receives far more attention than that grown in the tropics (Spangenberg et al., 2005; Smith et al., 2007). The burgeoning interest in biofuels, including use of switchgrass, should complement and accelerate our understanding of processes related to those occurring in forage digestion by ruminants. However, the collections of germplasm of tropical forage are poorly funded, and loss of current accessions (separate populations) is a distinct threat.

BOX 3-2

Molecular Breeding and Transgenic Approaches Can Be Combined to Offer New Approaches to Crop Improvement

A recent publication offers a striking example of how use of the tools of molecular breeding can be coupled with transgenic technologies for crop improvement. Using knowledge gained from extensive breeding efforts that had identified a number of quantitative trait loci (QTLs) in rice that related to number of grains per panicle, plant height, and heading date, Xue et al. (2008) used map-based cloning to identify the gene underlying one such major QTL. The gene was identified as a CCT domain protein that plays a key role in regulating photoperiod-controlled flowering and may also control a number of other functions in growth and differentiation. The superior allele for the gene identified by this technique was then inserted and overexpressed in a recipient rice cultivar, leading to dramatic alteration in yield potential, plant height, and heading date. This information can now allow breeders to introgress this trait into other locally adapted rice cultivars.

Mutation Breeding and Mutant Analysis

TILLING (targeting induced local lesions in genomes) is a method whereby natural or induced mutations in known genes are created in large populations of plants and the populations are screened for the mutation with sensitive molecular biology methods (Henikoff et al., 2004). When plants with a mutation in a selected gene are found, their phenotype can be studied in detail, and relationships between the gene and a trait can be assessed. Most mutations are not beneficial, but if mutating a gene leads to a specific phenotype, its relationship to a trait can be inferred. In the rare cases in which a mutation is beneficial, the approach can be used to identify useful mutant alleles that can be introduced into a crop plant by conventional breeding (see Box 3-3); this constitutes a nontransgenic method for altering deleterious traits or modifying biochemical pathways. Many approaches to mutant analysis and control of gene expression have been used in *Arabidopsis* and rice. Making mutant analysis relevant to crops in SSA and SA will require high-throughput assessment of the phenotypic consequences of overexpression, underexpression, or mutation of candidate genes in the crops as identified in functional genomics studies of *Arabidopsis* and rice.

BOX 3-3
Nontransgenic Herbicide Resistance in Maize for *Striga* Control

Breeding for *Striga* resistance has been somewhat successful in sorghum, a plant that is native to Africa with different strains and wild relatives whose germplasm carries modicums of resistance to *Striga* (Ejeta, 2005; Ejeta and Gressel, 2007). If and when such genes are isolated, they might be transgenically transferred to other crops such as maize. Recently, a non-transgenic approach has been developed for maize that is showing good promise in the fields of Western Kenya. Unlike sorghum, maize did not co-evolve with *Striga* and is expected to have fewer genes for resistance, and all breeding efforts (of which there have been many over 3 decades) have given rise to lines that at best work in certain locales but not others. At present, the only technology that seems to work over large areas is mutant-based resistance to systemic herbicides, which has been back-crossed into local elite germplasm (Kanampiu et al., 2003). The herbicide is applied to the seed and requires far less chemical (one-tenth) than is typically sprayed, and this does not require spray equipment. Because the herbicide remains in the maize root zone, legumes can be interplanted and not affected (Kanampiu et al., 2003). This technology is also appropriate for other crops affected by *Striga*. Three groups are generating mutant sorghums resistant to the same groups of herbicides. With the mutant sorghums there is the inevitability that the resistance gene will flow to major sorghum weeds, namely shattercane and *Sorghum halepense* (Ejeta, 2005). This will not give an advantage to those weeds as long as only seed treatments of herbicide are used and the seed is certified to be weed-free.

EXISTING AND EVOLVING TOOLS FOR CONVENTIONAL AND TRANSGENIC APPROACHES TO PLANT IMPROVEMENT

Studies of the commercialization of discoveries in many disciplines often reveal that 2 decades pass before consumers see the results from discoveries translated into products. In plant innovation, the timescales are often especially long because the long generation times of plants and the requirement to test an innovation in multiple versions of a plant in multiple environments add years to the process. In addition, public-sector laboratories responsible for plant breeding in SSA and SA rarely have the means to adopt new technologies rapidly and on a sufficient scale to achieve the high impact that is possible.

Using the pace of a multinational plant breeding company as a benchmark, obtaining a research finding and testing it in a model plant might require 5 years, and deploying and optimizing a trait in elite germplasm for SSA and SA another 5 to 10 years. Production, testing, and distribution of a crop for consumers could then take another 5 to 10 years, especially if the crop is transgenic and therefore has a longer regulatory testing phase under current regulatory regimes. The development of such transgenic technologies would need to be done in conjunction with the development of crops that are appropriate for SSA and SA.

This section highlights frontier, paradigm-changing technologies that show promise for agriculture but need further development. Creative, world-class research will be needed to move them into practice if they are to be incorporated into plant breeding programs and production agriculture. And the technologies will require education and training for users, from the breeder to the farmer and consumer.

Technologies for Rapid Sequencing and Annotation of Crops of Sub-Saharan Africa and South Asia

The most fundamental tool in modern plant breeding is a complete and annotated genome sequence of a crop of interest coupled with the ability to probe the DNA of selected germplasm to look for favorable gene combinations. Because that tool does not exist for many of the crops of importance to farmers in SSA and SA, the sequencing of the genomes of these crops is identified as an emerging and essential tool for plant improvement.

For example, temperate maize (or corn), the focus of U.S. studies, is different from tropical maize. How? And what genes are involved in the differences? U.S. and European crop improvement programs in both the public and the private sectors tend to target temperate crops, so understanding how many genes control the temperate vs. tropical phenotype would seem to have value in connecting the “northern” efforts with the “southern” and in looking at the effects of global warming on agriculture (for example, for maize, see CIMMYT, 2007).

High-quality reference sequences and genome annotations of all the relevant major crops in SSA and SA can be built on the sequences and annotations of rice and sorghum already available, the emerging sequence of maize, and the reference sequence of *Arabidopsis*. Breeders in SSA and SA also need resequencing capacity to complement their efforts in assessing and understanding the genetic diversity in the available germplasm of these major crops. Much of the sequencing work could be accomplished wherever there are adequate facilities and staff.

A number of radically new sequencing technologies have become commercially available within the last few years and have resulted in a dramatic increase in the speed of DNA sequencing and a decrease in the cost. State-of-the-art machines now generate up to 500 million bases per day. At least six companies are in a race to deliver "a complete human genome sequence for $1,000." The agriculture sector has an opportunity to capitalize on this race. Gaining help from world-class sequencing centers that are likely to test and purchase machines is essential for securing early opportunities for application to the germplasm of SSA and SA.

Large efforts are also being made in developed countries to obtain the sequences of major insect pests, pathogens, and weeds. These are necessary for determining weak points that might be targeted and determining whether to try to find new insecticides, fungicides, and herbicides or to try to use RNA interference (RNAi) or other technologies for control. Such information is not being garnered for SSA-specific and SA-specific constraints, so these areas are at a disadvantage.

Information Technology and Computational Biology

One of the single most important activities for improving breeding efforts across SSA and SA will be in unifying available information, especially from national programs. This will involve data curation, germplasm genotyping, and breeding value estimates based on markers. Crop varieties will need to be evaluated in tens to hundreds of locations to make rapid progress so that a wide range of environmental fluctuations are experienced in a single year. When DNA is sequenced quickly and at low cost, it probably will no longer be a bottleneck in plant science and breeding. However, managing all the data generated on each crop to create the reference genome sequences and to define genetic diversity with a high degree of accuracy will require substantial attention from researchers in the biological sciences and information technology (IT).

There is tremendous opportunity to apply 21st century bioinformatics —which merges techniques from applied mathematics, informatics, statistics, computer science, artificial intelligence, chemistry, and biochemistry—for effective plant breeding. In many regards, breeding efforts in developing countries are not unified and trials are not well replicated, and much of the agricultural efforts are similar to in situ breeding efforts of the late-19th and early-20th centuries in the United States that provided almost no yield increase for maize. Therefore the potential to leapfrog and breed more effectively is great if researchers in SSA and SA are able to implement some of these existing techniques for plants with user-friendly computer programs to access and use genomic information. IT and software innovations will be needed to enable the agriculturally oriented programs that can help breeders to profit from knowing the sequence and position of all the genes in the chromosomes of SSA and SA species. Accurate and easy annotation of all the genes in a genome sequence is still beyond the ability of the scientific community. As soil, climate, weather, and remote sensing data and models continue to advance, these parameters combined with genomics and informatics could be especially helpful for adapting crops for specific environments. Computational biology and IT should be a special focus of an effort to bring the power of data acquisition to the practice of plant breeding and crop production.

Technologies for Determining Genetic Variation in Key Crops

Plant improvement is based on and necessarily exploits genetic variation. Thus, being able to characterize the variation in every gene in the plants of a breeding nursery can bring the most powerful knowledge to the breeder. The breeder's dream would be to know and understand the genetic diversity of equivalent chromosomal segments in the crop germplasm. Such knowledge would revolutionize the ability to pick parents successfully and select progeny more successfully. However, few breeders recognize the potential importance of that information and are content to focus on "good x good" crosses, ignoring the major benefits that might be hidden in other, less adapted germplasm.

Equivalent chromosomal segments evolve independently in different populations but can be brought together in new combinations in breeding programs. It is desirable to know how many substantially different versions (haplotypes) of each chromosomal segment are present in the germplasm of a species and what the differences are. Answers to such questions are provided initially by the use of markers that measure sequence differences in chromosomal DNA (McCouch et al., 1997; Mohan et al., 1997; Bernado and Yu, 2007).

The commercial technologies for using markers are advancing rapidly, to the point where tens of thousands of data points can be gathered in a day. The technologies for measuring polymorphisms are many and are evolving rapidly in synchrony with the DNA technologies described above because high-throughput sequencing technologies are excellent for revealing sequence differences. With efficient sequencing technologies, it is possible to reveal variants of the same gene or allele between hybrids or different accessions. It can be accomplished for thousands of genes at a time in genomic DNA, in libraries of complementary DNA (cDNA), or in selected regions of the genome. With high-throughput sequencing technologies, fragments of copies of messenger RNAs can be sequenced to reveal rarely expressed genes. When the fragments of genes are assembled, they can be aligned with genomic DNA sequences to define the correct gene structure. By sequencing copies of mRNAs from different accessions, one can identify single nucleotide polymorphisms (SNPs) between allelic genes and use them as markers. That is now the fastest way to obtain polymorphic markers (Barbazuk et al., 2007; Emrich et al., 2007), and crops in SSA and SA could be brought to that state of knowledge rapidly. Other technologies rely on hybridization of DNA or RNA to reference DNA sequences that have been attached to solid materials and then analysis of the differences between test and reference sequences (Kirst et al., 2006). Separation of polymerase-chain-reaction (PCR)-amplified DNA sequences from different genomes and fractionation to reveal size differences, which are often due to variation in the number of short repeats in or around a gene, is another commonly used technique (McCouch et al., 2002).

The technologies discussed above, such as DNA sequencing, are being driven by the need to describe associations between genetic characteristics of humans and their healthcare needs. They can also be used by the plant science community, but they will need to be applied on a much greater scale for the relevant germplasm and breeding programs of SSA and SA. Plant breeding depends on assessing large numbers of progeny, and large-scale applications are essential. A major goal should be to have haplotype maps (see "Analysis of Gene-Trait Associations" below) globally available for all the germplasm of a crop, easily accessible in databases, and with full phenotypic descriptions and details of the phenotyping protocols and of all the plant accessions that have each of the haplotypes. That will enable many more scientists to become involved with the problems and opportunities in crop improvement.

Just as with the DNA sequencing described above, the generation of large datasets needs to go hand in hand with IT and software innovations and with the development of user-friendly databases to enable breeders to obtain the benefits of all new information. Achieving that goal will require the help of world IT experts, most of whom work outside the agricultural community.

Proteomics

DNA sequences alone do not provide sufficient information on how genetic information is transcribed or translated into functional proteins. Proteomics is emerging as a powerful method for annotating structural and functional aspects of the genome, and it complements DNA-based technologies. Direct measurement of protein identity and quantity was not possible on a genome-wide scale until recently, but advances in chromatography, electrospray ionization of peptides, tandem mass spectrometry, bioinformatics, and computer architecture have made it possible.

A method called multidimensional protein identification technology (MudPIT), supplemented with a conventional two-dimensional gel approach for identifying proteins, was used to create the most complete description of a plant proteome; it identified more than 2,400 proteins in rice (Washburn et al., 2001; Koller et al., 2002). The method was later used to demonstrate that the genomic complement of proteins of a plant species on which little or no DNA sequence information is available can be identified by relying on the expanding sequence database from other plant genomes. Nearly 200 proteins of wheat amyloplasts were directly identified with that method (Andon et al., 2002). It is now possible to observe 8,000 or more proteins of whole plants with highly reproducible quantitative comparisons between samples.

Peptide mass spectrometry can reveal the exon-intron composition of genes, including which splice isoforms are present, amino acid sequence polymorphisms, and post-translational modifications. Proteins and their subcellular compartments can be identified by using mass spectrometry in conjunction with cell fractionation. These kinds of information cannot be obtained reliably from genomic DNA sequences alone. Peptide mass spectrometry analysis of a single human cell line showed that hundreds of human gene models were wrong. The data allowed the previous models to be corrected and validated gene predictions regarding hundreds more hypothetical proteins. In all, peptides from 39,000 exons and 11,000 exon-spanning junctions were observed (Tanner et al., 2007a,b); this made clear how much value genome-wide proteomics can bring to genome annotation, including cases in which little or no supplementary information, such as cDNA sequences, is available.

Peptide mass spectrometry also permits the identification of single amino acid polymorphisms arising from allelic DNA sequence differences. About 20,000 peptides can be routinely observed in a plant sample analysis, and this facilitates the detection of thousands of genetic markers. In the data on the human cell line described above, more than 300 known SNPs were confirmed as single amino acid polymorphisms. The level of polymorphism in plant breeding populations would most likely be greater. It is possible that antibodies that discriminate between single amino acid polymorphisms could be used to enable high-throughput, low-cost enzyme-linked immunosorbent assay (ELISA) for genotyping breeding populations. By combining discovery of polymorphic peptides with mass spectrometry and low-cost, conventional ELISA detection, it should be possible to deploy robust assay systems that accelerate breeding.

Peptide mass spectrometry also has recently enabled the genome-wide discovery of all post-translational modifications (Tanner et al., 2007b). Fractionation methods have recently been combined with fluorescence-tagged proteins to assign selected proteins to subcellular locations. That approach is low-throughput, therefore the locations of very few proteins are known. Combining fractionation methods with peptide mass spectrometry has the potential to establish the subcellular locations of all proteins. Many proteins change locations during their function cycle. For example, protein products of plant disease-resistance genes migrate from the cytoplasm, where they are activated by pathogen attack, to the nucleus, where they induce a defense response (Wirthmueller et al., 2007). Every case of relocation has been discovered after years of painstaking research. Peptide mass spectrometry has the potential to reveal all the relocation dynamics of the proteome and to associate changes with performance traits.

Despite the exceptional opportunities for discovery in and practical benefits of peptide mass spectrometry research, there is little grant funding to support it and few people have the training required to do it.

Systems Biology for Analysis of Complex Traits

Breeders are well aware that key traits—such as drought tolerance and durable resistance to diseases and pests—are complex and involve many genetic loci, and it is a major goal in biology to have an integrated understanding of these dynamic, complex traits, their regulation, and how they create form and function. Gaining that understanding requires many observations and the development of computer-based simulations of the processes. These tools provide new ways of designing experiments to test hypotheses. Besides static models of how plants function, dynamic models of the developmental programs of plants can build in the plant's responses to environments. Such progress will probably first come from *Arabidopsis* and other species such as yeast, *Caenorhabditis elegans*, and bacteria. For example, scientists studying the yeast *Saccharomyces cerevisiae* have constructed a predictive mathematical model for specific signaling pathways and use oscillatory stimuli as a surrogate for environmental conditions to demonstrate how networks of proteins and genes are engaged by a living system to control physiological behavior (Mettatal et al., 2008).

That physiological behavior will be expressed not only in the form of gene products (proteins) but also in the dynamic levels of small molecules (metabolites) produced as biochemical pathways ramp up and down according to different environment conditions, such as nutrient levels or temperature. Metabolomics, the high-throughput, comprehensive analysis of metabolites in the tissues of an entire sample (or even an entire plant), will provide important data for the models of biochemical pathways used in systems biology (Allwood et al., 2008).

A systems approach can also facilitate better strategies to manipulate multiple transcription factors that regulate the biochemical pathways that control complex traits. Recent very promising results demonstrate that altering the expression of even one such master regulator of a single pathway can alter the responses of plants to drought in maize (Nelson et al., 2007), resistance to disease in rice (Zhang et al., 2008), or control of developmental programs that control architecture, plant growth rates, and yield potential in rice (Xue et al., 2008). One can only anticipate that understanding the interactions among various transcription factors will lead to even better approaches for the control of complex traits (Century et al., 2008).

Work on *Arabidopsis* in the next 5 years will encompass the sequencing of its many variants, mapping of quantitative trait loci (QTL), and the discovery of the genes behind the QTLs. The expression patterns of every gene, the role of microRNAs and small RNAs, and the levels of mRNAs in development and environmental responses will be understood (Lu et al., 2006; Maher et al., 2006). There will also be greater knowledge about the epigenetic control of genes and their processes during development and in different genetic backgrounds, about biochemical pathways and the relationships between metabolites and physiological states, and about the control of growth by multiple factors, especially hormones. The genetic basis of some examples of hybrid vigor (Springer and Stupar, 2007) will probably be understood. Although the information will come first from noncrop species, it will have enormous value for crops in SSA and SA (see Box 3-4). The information will reveal the genetic, biochemical, and physiological basis of traits at the cell, tissue, organ, and whole plant levels. It will hopefully lead to new insight into how to improve the traits for specific crops and purposes.

Analysis of Gene-Trait Associations

Geneticists have made great progress in locating, on genetic maps, the loci that are linked to particular traits (Mohan et al., 1997; Steele et al., 2006). The use of polymorphic genetic markers covering all the chromosomal sets allows the linkage of a marker in a chromosomal segment to a trait in populations in which the trait is segregating. The existence of huge datasets of mapped sequence polymorphisms means that finding genetic markers of traits is not rate-limiting.

What *is* rate-limiting is the measurement of phenotypes. In plant breeding, the phenotype needs to be ascertained for hundreds or thousands of progeny from a large number of crosses for each species to reveal which loci move together in heritable associations. It is also desirable for the strength of the phenotypes to be measured in multiple environments. To measure traits that affect a disease, the plants being tested must be exposed to the disease—an enormous task.

An alternative to that laborious process is to compare markers and traits in as large a number of unrelated accessions of a crop as possible (Yu and Buckler, 2006; Ersoz et al., 2007). It might be possible to infer a close and possibly causal relationship between a marker (or gene) and a trait by seeing whether they are inherited together at a higher frequency than would occur randomly. The process of "association mapping" and the development of haplotype maps are being studied in maize in detail (Yu and

BOX 3-4
Understanding Lignin Synthesis for Improving Tropical Forage

In many cases in SSA and SA, forage-fed animals lack nutrients to sustain growth or lactation and are struggling to meet their basal requirements The C_4 grasses (so named for the metabolic pathway used to fix carbon dioxide) that typically predominate in the tropics are about 15 percentage units less digestible than are temperate C_3 grasses (Van Soest, 1994) and have low forage energy. In C_3 grasses, highly digestible mesophyll cells accumulate during development; in C_4 grasses, parenchymatous bundle-sheath cells form between the vascular bundles and reduce digestibility (Wilson and Hatfield, 1997). Differences in the hemicellulose and lignin fractions of C_4 grasses and C_3 legumes also affect digestibility. The lignin-hemicellulose cross-linking (ester linkages in grasses vs. ether bonds in legumes), lignin monomer composition, and functional groups render grass lignin more soluble in alkali than lignin in legumes (Van Soest, 1994). In addition to better understanding of cell-wall chemistry in model plants, including maize (a C_4 grass), progress has been made in understanding the genes that control lignin biosynthesis and their regulation (Ralph et al., 2004), and lignin content has been modified and digestion improved, not only in the model plant tobacco (Spangenberg, 2005) but also in alfalfa (Chen and Dixon, 2007) through engineering of the expression of key enzymes. The next steps involve application of those results to the understudied tropical forage and genomic research on pasture species that are well-adapted to stressful environments (drought, low soil fertility, and salinity) to identify novel genes. Using a systems biology approach to understand plant chemistry and lignin synthesis could help plant breeding programs to improve the nutritional value of forage and would also complement ongoing efforts to enhance the accessibility of cellulosic residues in crops targeted for biofuels.

Buckler, 2006) but could be promoted for many more crops important to the developing world.

QTL analysis uses statistical frequencies of alleles to suggest the strength of relationships between loci and quantitative or continuous traits. QTLs in rice, maize, and other crops have been studied extensively (Young, 1996; Steele et al., 2006; Szalma et al., 2007). Many QTLs have been mapped, and candidate genes responsible for them are being nominated. All this information on multiple species can be brought together to establish hypotheses for one crop species using results on another.

In the field of functional genomics, many gene-trait associations have been established by adding new genes, or upregulating or downregulating existing genes in plants and examining their effects on a trait. In the course of such studies, genetic changes that cause changes in a trait imply that a transgene controls a step that is connected with regulation of the trait. Such genes are likely to be especially interesting and of special significance in plant breeding. Because the functions of new genes are being discovered rapidly in model plants, it seems important to promote efforts to carry out surveillance of the results with an eye to identifying and testing in crop plants the genes that may have particular relevance for international agriculture.

The work involved in establishing the genetic variation that is present in a crop and which genes contribute to which traits is massive. It will be a huge undertaking but will gradually transform plant breeding into a more directed, efficient process driven by technologies different from and more powerful than those of today.

Hyperspectral Imaging and Digital Capture

Since the mid-1980s, various groups have been developing remote sensing technologies capable of collecting hyperspectral images from high-altitude aircraft and orbiting platforms. Hyperspectral images provide high-resolution spatial and spectral data (in the visible and infrared light spectrum) that can discriminate small differences between objects, such as crops and weeds. The images are collected by charge-coupled devices (CCDs) that have been developed to permit high-resolution imaging with broad wavelength capability and very fast signal readout. Typical CCDs can record 200-plus spectral channels for each pixel over a range of 0.4 to 2.5 µm. Differences between the spectral reflectance curves of plant parts can distinguish differences in species and genotype, surface structure, and chemical characteristics (Liew et al., 2008). In addition, light penetrates leaves to a depth of some 50 to 200 µm, so spectra of internal structure and chemistry can also be gained, reflecting changes during plant development, during senescence, and in response to stress, disease, variation in nutrient-use efficiency, water-use efficiency, and photosynthetic activity.

Just as it is possible to make remote hyperspectral measurements and compare them reliably with reference spectra in the field, it is also possible to develop automated spectral tools coupled with methods of multivariate spectral calibration to assess the physiological state and some internal chemical composition characteristics—those of seeds, leaves, fruits, and so on—by direct spectral measurements. More research is needed to learn how to understand the variation in a subject plant's spectra during the day, in different environments, and in different physiological states.

Initially, such spectrometers could be deployed by hand in the field and linked to a GPS, but remote sensing is also possible. The data could be sent instantly to warehouses and analyzed by experts with suitable software support. The technology is not in place today, but it could revolutionize the phenotyping of plants for genetics and breeding programs and could support agricultural production. The ability to capture and transmit the images electronically would allow scientists around the world to conduct plant breeding and development studies much faster and more efficiently.

EXISTING AND EVOLVING TOOLS FOR TRANSGENIC CROP IMPROVEMENT

Biological limits on the genetic diversity of a crop's germplasm mean that some traits cannot be readily (if at all) produced without incorporating genes from other species (referred to as transgenes) into the crop genome. Surveys of the literature show that hundreds of transgenes that affect one or more of the traits listed in Box 3-1 are known, and many of them have been field-tested. For a variety of reasons, few have been commercialized. The most common reason is that the studies have been done by academic researchers seeking to identify gene function rather than to make a commercial product.

The most widespread commercial uses of transgenes have been to make crops resistant to insect pests (primarily lepidopterans), such as the European corn borer and the corn root worm, and to make crops tolerant to herbicides, such as glyphosate, so that field treatments with the herbicides can take place after the crop plants have emerged from the soil.

Bt Toxins

Cotton that expresses a toxin protein from the bacterium *Bacillus thuringiensis* (*Bt*) is widely grown in SA and in South Africa and results in higher yields with fewer insecticide applications and fewer worker poisonings. In China, transgenic rice crops containing *Bt* resistance to insects of the order Lepidoptera coupled with a variant of the (non-*Bt*) Xa 21 gene, which provides resistance to strains of the genus *Xanthomonas*, are awaiting release by the government (Huang et al., 2005).

Trials of *Bt* cotton are proceeding successfully in Burkina Faso, and expectations are that this country maybe the first in SSA, after South Africa, to adopt a transgenic crop (ICAC, 2007) and trials are also in progress in Kenya. *Bt* maize for stem borer control has been commercialized in South Africa and is being field-tested in Kenya. *Bt* rice is now in field trials in India and China for stem borer control, and *Bt* eggplant is showing strong resistance to the fruit and shoot borers in trials in India, replacing up to 80 sprays per year for control. *Bt* genes also hold potential for control of the pod borers that attack legumes such as chickpea, pigeon pea, and cowpea.

BOX 3-5
Directed Evolution of Genes

In recent years, a number of approaches have been developed that allow scientists to carry out "evolution in a test tube." Through use of techniques that allow rapid shuffling of domains of genes or generation of random mutations in specific gene sequences at high frequency, scientists have been able to enhance the rate of catalysis or alter the specificity of enzymes or other proteins encoded by the altered genes (Kaur and Sharma, 2006; Babushok et al., 2007). Several recent examples relevant to agriculture are the directed alteration of an activase of Rubisco that resulted in enhanced photosynthesis and plant growth rate under moderate heat stress (Kurek et al., 2007), and the directed optimization of a bacterial *N*-acetyltransferase that, when transferred to plants, conferred resistance to the herbicide glyphosate (Siehl et al., 2007). Use of such technologies might also lead to broadening of the effectiveness or altering the specificity of *Bt* and other toxins important for control of insects.

The Rockefeller Foundation and the U.S. Agency for International Development have been supporting projects in SSA to test the efficacy of such genes for control in SSA of lepidopteran and non-lepidopteran pests, such as pod borer in cowpea, weevils in sweet potato, and burrowing nematodes in banana. There are a wider range of *Bt* toxins available against lepidopteran pests compared to those for the coleopteran and other non-lepidopteran pests, but there may be opportunities to use directed gene evolution (see Box 3-5) to generate new variants with altered toxicity profiles.

Herbicide Resistance

Transgenic crops resistant to herbicides have been widely adopted in North America and South America, especially soybean, cotton, maize, and oilseed rape. In South Africa and India, some herbicide-resistant cotton has now been released as a trait stacked with *Bt*. Box 3-6 describes possible opportunities for controlling weeds by engineering other forms of herbicide resistance into crop plants.

Transgenes in Metabolic Pathways

Although genes for insect and herbicide resistances are the most common transgenes in use today, a growing understanding of metabolic path-

BOX 3-6
Opportunities to Control Weeds in SSA and SA Through Engineered Herbicide Resistance

Phalaris minor, Echinochloa, and Feral Rice

In India, where graminicides are no longer able to control *Phalaris minor* (canary grass) in wheat, and other countries that cannot control feral rice and *Echinochloa* in rice, the most effective alternative is transgenic herbicide-resistant wheat and rice that use resistance genes that are not normally found in Gramineae. Such technologies are useful in wheat without fail-safe mechanisms to contain gene flow wherever there are no weedy *Triticum* (wheat) or *Aegilops* (goat grass) species (Weissmann et al., 2005). Wherever there are related *Aegilops* or *Triticum* weedy or ruderal species, fail-safe mechanisms to prevent gene flow will be essential. Containment or mitigation systems will be needed in rice to prevent the transgenes from crossing in to feral rice (Valverde and Gressel, 2005).

Striga

Comparative genomics has been successfully used to develop genetic markers for breeding resistance to *Striga* in cowpea (Timko et al., 2007) and sorghum (Ejeta, 2005). A gene from rice that confers partial *Striga* resistance also has been isolated (Scholes et al., 2007). When the genes from cowpea and sorghum are isolated and stacked with the rice gene, it could prove useful in engineering *Striga* resistance in other crops.

It has been demonstrated that Orobanche (broomrape), a parasitic weed similar to *Striga*, can be controlled when the crops are transformed with genes that confer herbicide resistance at herbicide target sites of action (Joel et al., 1995; Surov et al., 1998; Aviv et al., 2002). The herbicide must be systemic and move from the site of leaf or seed application into the parasitic plant.

Transgenic herbicide resistance would also be useful in sorghum, but because of feral sorghum (shattercane), it is imperative to develop and use fail-safe mechanisms that prevent gene flow where it is expected that herbicides will be widely used in the future.

ways in plants suggests that it will not be long until many new transgenically enabled traits are introduced (see Box 3-7). For example, Golden Rice 2 (a variety of *Oryza sativa*), contains three transgenes—one from the bacteria *Erwinia uredevora*, one from maize, and one from the daffodil *Narcissus*—that together form a biosynthetic pathway for producing substantial concentrations of beta-carotene (provitamin A) in the rice endosperm. Although testing is still in progress and consumer acceptance of this bright

BOX 3-7

Engineering Plant Pathways to Decrease Postharvest Losses and Degrade Mycotoxins

Isolation from major markets limits small-scale farmers in many ways, one of the most critical being the large postharvest losses incurred because of delays in getting products to markets—a challenge that is even more severe in hot tropical regions. In addition to the use of better technologies for storage and transport, plants can be bred to show reduced senescence or delayed ripening. We now recognize that senescence and ripening of fruits and vegetables involve processes akin to programmed cell death (PCD). Genes that are involved in control of PCD or of ethylene production, which also promotes ripening, will therefore need to be further tested for control of postharvest losses.

A number of recent patents suggest that private enterprises are investigating the possibility of producing transgenic plants that degrade mycotoxins. An amino-oxidase active against fumonisins has been isolated and cloned from black yeast, and its activity has been enhanced with mutagenesis (Duvick, 2001) and gene shuffling (Zhao et al., 2004). Human genes that express glutathione transferase, aldehyde reductase, and epoxide hydrolase, which degrade aflatoxin, have also been cloned (Bandman et al., 2003, McGlynn et al., 1995). They could be engineered into plants in different combinations to determine which, if any, have practical utility for suppressing toxin production. Such research may well elucidate the importance of the toxins in fungal pathogenicity.

yellow rice remains in question, the rice offers a health benefit if eaten regularly in sufficient quantities (Enserink, 2008). A similar strategy is now being tested for development of golden cassava, sorghum, and banana that might also be enhanced for other nutritional traits such as elevated levels of zinc or iron or enhanced digestibility. Knowledge of the pathways for synthesis of oils in seeds is also leading to new crops with more beneficial oils, both for nutritional purposes and for use in biofuels (Dyer et al., 2008).

The transferability of disease resistance genes is also of interest for crops like bananas, which are difficult to reproduce sexually. Transgenic varieties containing a resistance gene to *Xanthomonas* wilt from sweet pepper are in trials in Uganda (Tripathi et al., 2006, 2008).

Plant-Based Gene Silencing

One of the most exciting developments in plant biology in recent years has been the discovery of small RNA molecules that play key roles in plant development and resistance to stresses. The discovery has led researchers to create vectors containing genes that encode for small RNAs that target and down-regulate or interfere with critical processes governing plant development, metabolic pathways, and also processes related to the interactions of plants with plant pests. It is probably the case that genes designed to function by making RNAs with sequences that are antisense to specific target genes function via the small RNA pathways and processes to down-regulate (or “silence”) natural messenger RNAs. Although promising, the development of RNA interference (RNAi) technology is still in a very preliminary stage, especially for application in large-scale agriculture where consistency of action is essential. However, some current research strongly suggests that plant-mediated delivery of small RNAs can be used to control fungi, parasitic plants, nematodes, and possibly many insects, such as aphids, white fly, and the bollworm or boll weevil (see Box 3-8).

Site-Specific Gene Insertion Systems

Homologous Transformation

A long-standing goal of plant scientists and breeders is to be able to exchange alleles precisely in a directed way, which is almost impossible with standard breeding approaches. The ability to replace one allele with a more favorable one at a specific site would have a great impact on plant improvement and make it possible to study the functions of specific genes. Directed targeting to known sites that minimize deleterious effects and optimize gene stability and levels of expression can also greatly facilitate the more rapid movement of transgenic plants through regulatory systems.

It is possible to replace an existing allele with an orthologous transgene in the laboratory, but this has not been efficiently reduced to practice in crops, because our understanding of the natural processes of DNA repair that plants use to replace and recombine alleles is insufficient. Those processes cause the transgenes to be inserted into chromosomes seemingly at random. Thus, breeders are usually obliged to screen hundreds of transgenic plants to find the optimal insertion event because the random locations of insertions result in large variations in expression. It would be desirable to identify the optimal insertion sites and target gene insertion there every time in the process of homologous recombination. Recent experiments and the development of novel systems to achieve homologous recombination suggest that this goal is within reach for crops. Homologous recombination can be used to insert genes, discover genes, and disrupt existing genes (Wright et al., 2005; Kumar et al., 2006; Hu et al., 2007; Lyznik et al., 2007; D’Halliun et al., 2008).

Zinc Finger Nucleases and Meganucleases

Efficient homologous recombination relies on the existence of a double strand break in the chromosome. Thus, the challenge has been to learn how to create double strand breaks at the desired sites of insertion. Zinc finger nucleases (ZFNs) and meganucleases are tools that have been designed to achieve that. A ZFN consists of a DNA-binding zinc finger domain covalently linked to the nonspecific DNA-cleavage domain of a restriction endonuclease. A ZFN binds to a specific DNA site, and the nuclease catalyzes a double strand break. ZFNs have been shown to facilitate site-specific gene replacement in plants, but the major challenge is to learn how to make and select ZFNs that are specific for any gene that the geneticist or breeder wishes to replace.

A "zinc finger consortium" has taken on the challenge, and publications describing standardized reagents and protocols for engineering ZFNs by modular assembly have appeared (Wright et al., 2005). In addition, meganucleases that cleave at different sites have been isolated from different organisms (Fajardo-Sanchez et al., 2008). One company, Cellectis S.A., has also developed a high-throughput screening platform to produce a large number of different meganucleases.

The further development of this technology will bring a new and powerful genetic approach to plant breeding. In addition to inserting genes precisely, it will enable promoters to be exchanged, and this will make it possible to directly alter the expression of genes. One can envision many novel applications (see Box 3-9 and Box 3-10).

Recombination Systems

In addition to zinc fingers, transgenes can be integrated into chromosomes at particular locations by site-specific recombination systems (Lyznik et al., 2007). These systems rely on proteins that specialize in recombining two identical specific sequences. That enables, for example, multiple novel genes to be inserted at a target site. The so-called Cre/lox recombination system derived from bacteriophage P1 has been used for site-specific integration of DNA into tobacco and rice (Day et al., 2000) and has been successfully used in wheat and rice to target single-copy insertions into lox sites placed in the genome (Srivastava et al., 2004). The lox target (a small 34-base pair DNA) is inserted into a chromosome at random. The Cre recombinase then inserts the desired transgene into this genomic target. Another system, FLp/frt, involves the flippase recombinase derived from yeast. Flp recognizes a pair of frt target sequences that flank a genomic region of interest. The flp recombinase system has been used in maize (Lyznik et al., 2003) and rice (Hu et al., 2007), as have the lambda and PHIC31 integrases (Suttie, et al., 2008) and (Ow et al., 2004), but there is concern

BOX 3-8

Opportunities to Apply RNAi to Agricultural Constraints in SSA and SA

Control of RNA and ssDNA Viruses

RNA viruses—including cassava brown streak, cucumber mosaic virus (CMV), and single-stranded DNA (ssDNA) viruses, such as African CMV in SSA and cotton leaf curl in SA—cause major losses to crops grown by small-scale farmers. Because there seems to be no strong resistance to some of the viruses available in germplasm of conventional breeding programs, the most promising strategies for addressing the pests involve the introduction of transgenes into the host plants.

Strategies to overcome the RNA viruses can build on the basis of an effective transgenic approach used to control ring-spot virus in papaya—a success story that virtually resurrected the growing of papaya in Hawaii (Gonsalves, 2006). That approach, first demonstrated in tobacco against tobacco mosaic virus, involves engineering the host plant to overexpress the relevant virus coat protein gene. It now appears to be effective for many such viruses (Beachy, 1999). An alternative approach that has been shown to be useful in the laboratory uses RNAi constructs to silence key RNA viral genes (Vanderschuren et al., 2007). But when multiple viruses infect a plant, a strategy is needed to prevent one virus from producing genes that suppress the RNAi directed at silencing another. The solution might lie in the recent design of small RNAs that target viral-suppressor sequences (Niu et al., 2006). More research is needed on the mode of action of all types of suppressors of silencing.

For the ssDNA viruses, RNAi that targets genes that encode a protein required for viral replication, called *rep*, has proved to be partially effective and is being tested against CMV (Vanderschuren et al., 2007), but the possibility remains that viral-suppressor genes may overcome the effects of the RNAi.

Control of Other Pathogens, Pests, or Parasitic Weeds

The promise of RNAi technology was recently extended significantly by the demonstration of its use to control the bollworm in cotton. In this case, plant-mediated RNAi was used to silence a bollworm P450 monooxygenase that resulted in lowered tolerance of the bollworm to the toxic gossypol produced by the transgenic cotton (Mao et al., 2007). Small RNAs can pass from crops to parasites, as is well-documented on the basis of technology used to control root-infesting nematodes (Huang et al., 2006). At least three groups are testing RNAi molecules that are targeted at *Striga* genes, or parts of *Striga* genes, that have no sequence homology with crop genes (de Framond et al., 2007). So far, no major success has been reported, but this new research warrants attention. The knowledge base of fungal genomes is growing rapidly, and the information offers opportunities for creating mechanisms to enhance aflatoxin resistance. One possibility is to interfere directly with the metabolic pathways that lead to mycotoxin production, inasmuch as the responsible genes have been elucidated (Yu et al., 2004; Wen et al., 2005). Gressel (2008) has suggested using the information to generate RNAi constructs to inactivate one or more of the mycotoxin biosynthesis genes; these could be delivered via viral pathogens of the fungi or by expression in the plant genome.

Reducing Apigenin in Fonio and Pearl Millet with RNAi

The high consumption of fonio and pearl millet is associated with goiter. At its worst, endemic goiter leads to endemic cretinism, a severe form of mental retardation. In an interior area of Guinea, 70 percent of the inhabitants had goiter (Konde et al., 1994). Goiter was also found in one-fifth of children tested in the southern Blue Nile region of Sudan, an iodine-sufficient area, and the syndrome was correlated with the consumption of pearl millet (Elnour et al., 2000). Livestock eating pearl millet also suffer from hypothyroidism (Gadir and Adam, 2000).

The culprit in fonio was discovered to be the flavonoid apigenin (Sartelet et al., 1996), and in pearl millet its glycoside, vitexin (Gaitan et al., 1995). Both are potent inhibitors, at low concentrations, of thyroid peroxidase, a key enzyme controlling thyroid hormone biosynthesis. If the specific flavonone synthase genes of fonio and pearl millet responsible for apigenin biosynthesis can be cloned, it might be possible to reduce apigenin in fonio and pearl millet through RNAi technology. Orthologs of those genes from Apiaceae have already been cloned, so if there is sequence similarity, it may be simple to isolate the gene from the Gramineae species involved in goiterism (Martens et al., 2003; Gebhardt et al., 2005). An RNAi construct might be made with a seed-specific promoter, turning off apigenin production only in the grain so that consumers of the grain would be protected while the stalks would retain apigenin, conserving its (probable) role as a deterrent of insect pests of the crop.

On the basis all of these promising results, further exploration of the possibility of use of RNAi for control of a wide variety of important plant traits is certainly warranted. The potential to control critical pests like whitefly, aphids, or weevils could also be explored. In addition, necessary fundamental research to better understand how RNAi might be used in crop plants includes studies to determine how and where movement of small RNAs occurs, whether plants discriminate between different small RNA molecules that move between the plant and the pest, and what size of small RNA molecules can move. We also need to know whether a target organism can evolve resistance to RNAi and, if so, at what rate.

BOX 3-9
Disrupting Plant-Virus Replication

The ssDNA viruses, particularly geminiviruses, have high rates of mutation and recombination that make it difficult to target specific viral sequences (Legg et al., 2006; Arguello-Astorga et al., 2007). New technologies might have a role to play in controlling these deadly, highly variant viruses, such as the African cassava mosaic virus that is causing the current pandemic in cassava (Mansoor et al., 2003, 2006; Legg and Fauquet, 2004; Vanderschuren et al., 2007). For viruses in the *Mastrevirus* genus, such as the one that causes maize streak, maize engineered to overexpress a transdominant mutant *rep* protein holds a great deal of promise (Shepherd et al., 2007). Three other approaches worthy of exploration for control of geminiviruses are the use of peptide aptamers that target conserved regions in *rep* proteins (Lopez-Ochoa et al., 2006), expression of a gene that encodes a nonspecific ssDNA-binding protein (Claude Fauquet, Donald Danforth Plant Science Center, personal communication), and the use of an artificial zinc finger protein that can be designed to be inserted into and disrupt the origin of replication of the virus (Sera, 2005). Even stronger control might come from targeting the origin of replication of the deadly satellites and thus controlling the emergence of new complexes.

about damage caused by the action of recombinases on cryptic excision sites in the genome.

An approach previously applied to animals was adopted by Agrisoma Biosciences, using sequences homologous to ribosomal DNA in the transformation vector, alongside the genes of interest. After insertion of the vector into plant cells, scientists stimulated recombination of the novel genes into the host ribosomal DNA, where the genes reside in an amplified structure in the regenerated plants. Additional genes can be added at the same general sites by similar homologous recombination events.

Those approaches facilitate the stacking of new traits at valuable loci in a modular fashion and can integrate new genes at a site in the genome that has already been found to support strong constitutive expression, avoiding disruption of existing genes and adverse agricultural effects. If brought into routine use, the methods will reduce the amount of work needed to stack multiple transgenes or to introgress them between lines in a breeding program and may ease regulatory approval since there is often a requirement in many jurisdictions to provide the DNA sequences flanking the insertion sites, which will be the same whenever site-specific integration is used.

BOX 3-10
Potential Transgenic Approaches to Protect Sorghum Against Birds

Birds have been chemically controlled with an organophosphate insecticide, fenthion, applied with back-pack sprayers (Mundy, 2000; van der Walt, 2000), but there are better biotechnology alternatives. A white, non-tannin containing sorghum variety, Ark-3048, is not attacked by birds (York and Daniel, 1991). Its seeds are high in dhurrin, a natural cyanogenic glycoside often found in seedlings and stalks of sorghum (Kahn et al., 1997). The cyanogenic compound dissipates by maturity, when the birds no longer find the seeds palatable (Alkire, 1996). Breeding with Ark-3048 has not advanced, because derived progenies have yield penalties (Gebisa Ejeta, Purdue University, personal communication, December 11, 2006). It might be possible to generate a sorghum that makes dhurrin only in the developing seeds, so that livestock that eat sorghum forage will not be poisoned. There might be less yield drag if the dhurrin genes were put under a high expression seed-specific promoter and not expressed in other tissues.

The relatedness of sorghum species and the existence of weedy feral forms of the crop (Ejeta, 2005) present a gene-flow hazard. A morphological solution would be to put the grains closer together on the stalk, make them harder to peck apart, and ensheath the grain heads to make them less conspicuous. The Mexican Amerindians did that in maize without genetic engineering by selecting genes that turned teosinte, with its open head, into maize, with its less accessible cob (Doebley, 2004). The open inflorescences of sorghum are reiteratively branched like maize ramosa mutants (Vollbrecht et al., 2005). In sorghum, delayed production of spikelet pairs correlates with a protracted onset of *ra1* expression (Vollbrecht et al., 2005). One might ask what would appear on a sorghum plant if the native ramosa were transgenically replaced with the maize genes; the answer would require extensive genomic and biological research, which might yield a bird-proof sorghum.

Meiotic Recombination

During meiosis in plants, the homologous chromosomes of egg-forming and pollen-forming cells undergo recombination in a process that results in new combinations of genes (alleles). A high rate of recombination at many places in chromosomes leads to a greater number of new gene combinations. A low rate of recombination maintains existing gene combinations. If the rate of recombination (Kitada and Omura, 1984) and the positions of recombination along the chromosomes could be controlled and directed to create desirable recombinant genomes, plant breeding might be more efficient.

It has already been learned by comparing recombination maps with physical maps that recombination occurs more often near the ends of chromosomes (See et al., 2006). Recombination involves cleavage of DNA molecules and repair processes that can lead to resynthesis of the parent strand or to a crossover and a recombinant chromosome (Wijeratne and Ma, 2007). The multistep processes are complex and involve many proteins. Before processes can take place at the level of DNA, specific polynucleotides in the DNA molecules have to be accessible to the protein complexes and to each other.

It now appears that one level of control of recombination involves the regulation of chromatin condensation and the coordination of the condensation between different chromosomal regions. That is the basis of variation at the *Ph*1 locus, which affects recombination between similar chromosomes in wheat (Griffiths et al., 2006). The genetic control of chromosomal condensation into heterochromatin is now known to involve small RNAs and epigenetic changes in histones and DNA. As research proceeds along this path, it may become possible to fathom how to locally control the degree of chromatin condensation during meiosis and so direct the places and frequency of recombination during meiosis. It will not be easy to implement in a single crop or to apply to all crops, so this should be seen as a long-term opportunity.

The *Ph*1 gene that regulates recombination frequency between chromosomal homologs in wheat is useful because recombination between the more distantly related homologous chromosomes occurs when it is absent (Griffiths et al., 2006; Wijeratne and Ma, 2007). This allows additional alleles to be brought into wheat from wild relatives of cultivated wheat. This illustrates another potential use of manipulating recombination: the incorporation of new genetic material into crops via wide hybrids. That use has had little success for many reasons, including its bringing many unwanted and deleterious genes in addition to those desired, but it should be revisited when new understanding and tools are available. As discussed earlier, it may be possible to insert into a chromosome sequences that preferentially undergo recombination at specific locations that is catalyzed by specific nucleases and in this way direct meiotic recombination events to some positions and away from others.

Artificial Chromosomes

Crop improvement involves combining the best alleles for key genes in a single variety. In a transgenic approach, that is accomplished by the stacking of various genes, preferably at a single locus so that the introduced genes do not segregate from each other in later generations. Homologous recombination and site-specific integration are beginning to offer breeders the potential to bring multiple genes together at a single site, making it easier to control their expression or to delete them selectively, but another novel approach has recently been pioneered by such companies as Chromatin.

Chromatin has developed a method of synthesizing a mini-chromosome by linking genes of interest to a large piece of maize DNA that encodes satellites, retroelements, and other repeats commonly found in maize centromeres. Other groups have developed artificial mini-chromosomes using telomeres (Lamb et al., 2007; Yu et al., 2007; Birchler et al., 2008). Those elements of DNA confer on a chromosome the ability to be divided regularly between daughter cells at mitosis and meiosis. When such artificial chromosomes were introduced into maize cells by particle bombardment, the new chromosomes were shown to be regularly inherited in plants regenerated from the cells (Carlson et al., 2007).

The technology is new, and there are technical issues to be satisfied, including the stability and fidelity of gene expression and the reliability of inheritance over the many generations associated with agricultural seed production. Other concerns are the stability, rearrangement, and expansion or contraction of the repetitive sequences in the centromere regions and the possibility of epigenetic silencing of gene expression over generations and in other genetic backgrounds (Dawe and Henikoff, 2006; Talbert and Henikoff, 2006; Carlson, 2007).

Species-specific systems for the major crops of SSA and SA would need to be developed to use the technology. As the availability of valuable genes for crop improvement increases, it will be necessary to address questions of where and how to insert multiple genes for long-term utility. Given the potential power of this technology, a large number of projects using artificial chromosomes could be envisioned. Nitrogen fixation (discussed in greater detail in Chapter 5) would be one such project. Conceivably, it would be possible to develop transgenic, nitrogen-fixing crops—such as rice, wheat, and maize—by adding an artificial chromosome with 20 or so genes known to play a role in fixing nitrogen. There is debate, however, in the scientific community about the metabolic and yield costs to the plant that would occur by adding this trait, so a project of this nature would be considered highly experimental.

Apomixis

Hybrid seed is more expensive to produce than certified seed and must be purchased every season because of segregation of properties in the offspring of the hybrids. Farmers who cannot afford to buy hybrid seed every season and opt instead to plant seed saved from a previous harvest forgo the benefits of heterosis—the vigorous performance of hybrid seeds—that include higher yields and greater resistance to pests and diseases. If it were possible to maintain the hybrid genotype in seed from one generation to the next, those benefits also would be preserved, so certified weed-free and pathogen-free seed could be produced at a much lower cost or farmers could save seed from one year to the next.

In many wild plant species, the perpetuation of the hybrid genotype is accomplished through apomixis, a process in which progeny seed produced in a plant without the sexual fertilization of cells give rise to embryos (Koltunow and Grossniklaus, 2003). The asexual event leads to the propagation of hybrid genotypes in the following generations. The genetic basis of the different forms of apomixis in wild plants is complex, but it is conceivable to harness this mechanism as a technology (Grimanelli et al., 2001).

Research to understand the process is proceeding (Grimanelli et al., 2001; Catanach et al., 2006). There is evidence that one or two dominant genes are involved in some systems with a large chromosomal segment that does not recombine. With additional research, it might be possible to design transgenes and insert them into crop plants to change the mode of plant seed production from sexual fertilization to apomixis. Whether it is possible to find genes that provide such a switch and to deploy them while maintaining high seed yields is an open question. Many believe it sufficiently important to continue research toward that goal.

Alternatives to *Bt*

Controlling insects that feed on crops can reduce not only losses from pest damage but the incidence of disease. For example, stem borers are vectors of *Fusarium* spp., and grain weevils, especially the lepidopteran ear borers, carry *Aspergillus* spp. Those two genera of fungi are responsible for the production of mycotoxins. Crops that have been genetically engineered to produce *Bt* insecticidal proteins experience less insect damage. The effect of *Bt* is greatest in seasons when fumonisin concentrations are the highest because of heavy infestations with stem borers (Munkvold et al., 1999; Munkvold, 2003; de la Campa et al., 2005). To further reduce mycotoxins, plants will need to have stacks of multiple genes that encode activities that kill the fungi and the coleopteran and lepidopteran insects that are vectors of the fungi in the field and in storage. It might be even better if genes are stacked that encode enzymes that degrade the mycotoxins.

Toxins from other pathogens carried by insects are a potential source of novel insecticidal compounds. *Photorhabdus* spp. are bacterial symbionts of entomopathogenic nematodes that are lethal to a wide array of insects and were effective when expressed in *Arabidopsis* (Liu et al., 2003). Other major foci for research could include genes from plants (such as genes that produce enzyme inhibitors and lectins) and animals, including insects (such as genes that produce biotin-binding proteins, neurohormones, venoms, and enzyme inhibitors). Fungi have been underexploited, particularly with respect to pathogens carried by insects, even though they are exceptionally rich sources of novel biologically active substances (Isaka et al., 2005).

The nearly 1 million arachnid toxins could probably be a major resource for genetically modified plants and biopesticide delivery systems (Edwards and Gatehouse, 2007; Whetstone and Hammock, 2007). They include toxins specific for many organisms, including microorganisms, and their potential appears virtually limitless if they can be provided with suitable delivery systems. As the history of insect control teaches, resistance to almost all interventions evolves eventually. Thus, although the effectiveness and specificity of *Bt* toxins in transgenic plants are extremely important for the future (Federici, 2007; Uneke, 2007), a multitude of stacked genes will make it harder for insects to evolve resistance.

Sentinels of Drought, Disease, and Deficiencies

Skilled farmers can readily recognize deficiencies in their crops, but it is often too late to supply a remedy and retain the yield, because the crops have already reorganized their internal chemistry to cope with the stress and consequently have suppressed growth or initiated senescence or irreversible death pathways. It is, however, possible to detect internal shifts in chemistry long before signs of the stress appear. The question is how to get such information to the farmer. Can the exquisitely sensitive and specific molecular sensing mechanisms of plants be harnessed to tell farmers the conditions of their fields, their soils, their ecologies, and their crops daily and at low cost?

Research with *Arabidopsis* has shown that it is possible to design transgenes and insert them into plants so that the plants serve as sentinels or reporters that can be observed by the farmer and indicate, for example, deficiencies in soil or water levels or an early stage of disease (Jefferson, 1993; Liew et al., 2008; Mazarei et al., 2008). Such genes consist of a promoter that responds specifically to the deficiency or stress of interest and is connected to a reporter that stimulates production of an easily visible product, for example, a pigment. The color or amount of pigment would help the farmer to decide how to best use available resources and when to take precautionary action to protect the crop. Signals could help a farmer to determine, for example, the most and least productive areas of land and which nutrients should be added to the soil and how much. That could prevent the wasteful use of nutrients, which is uneconomical and polluting. Early signs of water stress would be revealed in the field, and water could be applied to parts of the field that need it. The reporter plants could be non-crop plants that do not interbreed with the crop but are physiologically matched to the crop. Ideally, they would be scattered across the field in strategic places and not harvested with the crop.

Sentinels could also be useful to plant breeders, who face a major problem in simultaneously comparing different genotypes for many characters. Use of sentinels in breeding materials would, for example, make it easier to know whether one plant used water or nitrogen more efficiently than another. Reporter genes could be left in the commercial variety or crossed out later in the breeding program.

Chemical-Induced Switching

A forward-looking type of crop is one with qualities that can be modified on the basis of weather, market conditions, or local need. One can imagine that sorghum, for example, could be grown for its seed, as now, or for its biomass for energy purposes. Specialized crops can exist for the two kinds of applications, but what if farmers could stop flowering and seed production, and instead, produce more vegetative biomass, in light of accurate market or weather predictions that would favor biomass? A farmer might seek to turn a carbohydrate crop into a protein-enriched crop because of failure to obtain protein from other sources, or it might be desirable to accelerate flowering to meet an off-season demand or to enable a different crop rotation. Many such scenarios can be envisaged for SSA and SA.

Today's science is producing knowledge that is making such possibilities more realistic. Genes that can stop flowering, bring flowering on earlier, and control major pathways leading to different end products are being found. Breeders will learn how to manipulate them to the extent that useful genetic variation is available. However, transgenes that can create such shifts in traits can be placed under the control of promoters that respond to specific chemicals, and these chemicals would be applied by a farmer to initiate the changes (Box 3-11). For such transgenic crops to become practical, it would be essential to discuss their possible value with a farmer and then to seek promoters that can respond specifically to easily obtained chemicals that can be sprayed on crops without damaging people or the environment. Such chemicals exist, and it has been shown that promoters that respond to them can be found (Girke et al., 2005). In general, the public sector could benefit from having available a much broader suite of tissue-specific or inducible promoters than is available today.

CURRENT BOTTLENECKS IN CROP IMPROVEMENT

Transformation and Regeneration

The ability to introduce new genes into plants depends on many factors, especially the frequency with which transformed cells can be induced to divide, form embryos, and then form plantlets. The genetics of the host

BOX 3-11
An Inducible Suicide Gene for Weed Control?

The crop-parasitic weed *Striga hermonthica* is an obligately outcrossing species and must be cross-pollinated. If this species were transformed with a multicopy transposon bearing a lethal (suicide) gene under the control of an inducible promoter, a small number of such plants could be introduced into fields. With a dominant gene, only half the progeny from crosses would bear the transgene; because of the nature of a multicopy transposon, virtually all progeny of all generations would bear the potentially lethal transposon. After about five generations, when the whole population bears the gene the inducible transgene can be turned on, killing the *Striga* (Gressel and Levy, 2000). The concept of using multicopy transposons bearing inducible lethal genes was first elaborated for insects (Grigliatti et al., 2001), but it could be applied to any obligately outcrossing weed (Gressel, 2002). Two kinds of inducers would be ideal for this situation: a chemical inducer emanating from a crop root and a radio-wave-inducible system, which is still in the realm of science fiction. The required genetic systems might come from bats, which perceive radio waves in their echolocation systems.

plant are influential; many elite cultivars are among the most difficult to grow in tissue culture and to induce to form new embryos. Being able to easily regenerate crops from tissue culture would speed the process of plant improvement (Gelvin, 2003; Shrawat and Lorz, 2006). It is now possible to add cell division-promoting genes to the transformation vectors used to introduce genes into a plant, and there is evidence that this can substantially boost regeneration efficiency.

For example, scientists at Pioneer took a repA gene from wheat dwarf virus and put it into maize. The gene stimulates the cell cycle and results in many rapidly growing colonies per embryo; the effect is greater when the gene is under the control of a more active promoter. The method was able to substantially increase the number of maize transgenic lines (Gordon-Kamm et al., 2002). The *LEC1* gene from *Arabidopsis* produces a similar effect (Lowe et al., 2002).

Some plants, e.g., cowpea, regenerate with reasonably high frequency but only a low proportion of such can be transformed, and the challenge is to facilitate transformation in regenerable tissues. In this regard, worthy of further investigation is a recent report that the use of an anti-apoptosis gene from animals prevented death of banana cells transformed with *Agrobacterium* and led to a large increase in transformation efficiency (Khanna et al., 2007).

If such technologies were deployed in the germplasm of SSA and SA crops, the production of transgenic crops would much more efficient. That would enable scientists and breeders to make and evaluate many more transgenic plants from which to select optimum forms with the probability of better products as a consequence. The advances could be beneficial in early research phases and in product development. For regulatory and other reasons, genes that stimulate regeneration might have to be deleted from commercial crops. That can be done by placing the regeneration-stimulating genes and the desired trait genes on separate vectors, selecting elite progeny, and then deleting the regeneration-stimulating genes by screening progeny with only desired genes in later generations; or the regeneration genes might be expressed only transiently during the early stages of transformation and selection.

Shortcomings of Transgenics

The many issues and problems associated with the science and commercial deployment of transgenes include the following:

- Variable expression and instability over generations that requires screening many events to obtain both stability and required level of expression.
- Cost of regulation and the additional time required for transgenic processes.
- Silencing of transgene expression by other genetic elements in the plant.
- Regulatory demands to remove selectable markers associated with transgenes.
- Inefficient transformation processes for certain genotypes.
- Consumer and political acceptance, even when improvements are valuable.
- Outcrossing to nontransgenic relatives.
- Intellectual-property and freedom-to-operate issues.
- Costs, if crops have to be kept separate from nontransgenic versions.

In spite of all those challenges, it would be short-sighted to continue trying to solve crop production constraints and breeding inefficiencies decade after decade without using transgenes. A strategic plan is needed to incorporate transgenes into SSA and SA crops for the sole purpose of relieving or removing the constraints that contribute to poverty. Because the plant science community has made a major investment in the use of transgenes to evaluate gene-trait associations, there will continue to be a large supply of potentially useful transgenes worthy to consider for applications in SSA and SA crops.

Moreover, many of the challenges listed above are slowly being addressed. The Public Intellectual Property Resource for Agriculture (PIPRA) is an example of an effort actively engaged in enhancing the freedom-to-operate (to use patented genes) in specialty crops and crops developed for humanitarian purposes. Some of the scientific approaches discussed in this chapter could help to speed the regulatory process. For example, the ability to integrate genes in specific, pre-determined, optimized sites in the genome should reduce significantly the number of events that need to be generated and tested. Site-specific gene integration might also make it more acceptable to approve a particular gene construct that could then be used for transformation of many related varieties (as opposed to event-specific regulation)—something that is critical for vegetatively-propagated crops such as cassava, banana, and sweet potato where back-crossing a transgene into other varieties is not feasible. Studies on gene silencing are also leading to the design of constructs that avoid problems with silencing of transgenes. Finally, as discussed in the next section, technologies are emerging to eliminate gene flow and the problem of outcrossing with other plants.

Control of Gene Flow from Transgenic Plants

Fail-safe mechanisms are needed to contain gene flow and mitigate the effects of a transgene's escape to wild and weedy relatives of the crop (Valverde, 2005). Various containment procedures have been proposed, but all seem to be unidirectional or leaky, and none has been tested in the field (e.g., see Daniell et al., 2002). For crops which are sterile—the classic one being banana—gene flow is simply not an issue. For other cases where the flower or seed does not add significant value to the product, such as cassava or some trees, techniques are available to repress flowering and seed production through down-regulation of key flowering genes. Another approach is to introduce the transgene into the chloroplast DNA so that the pollen will not carry the gene (Daniell et al., 2002). While this can work in some cases, there are cases where genes may be transmitted through the pollen, but the relative of the crop can be the recurrent pollen parent, allowing gene transfer albeit more slowly. Other approaches may involve fruit-specific excision of transgenes or development of strategies in which the fitness of the resulting hybrid is compromised. These latter technologies have been suggested as a means to control feral rice (Valverde and Gressel, 2005); this idea has been validated with tobacco (Al-Ahmad et al., 2004) and oilseed rape (Al-Ahmad et al., 2006) but not yet with rice. Examples of mitigation genes that could be used to render hybrids between rice and feral rice noncompetitive include those responsible for dwarfism, non-shatter of seed, and lack of secondary dormancy (Gressel, 2008).

Understanding DNA Satellites Associated with Geminiviruses

One of the greatest challenges in controlling ssDNA viruses, such as the geminiviruses, is the emergence of DNA satellites associated with the viruses that, in some cases at least, are believed to serve as extremely effective suppressors of silencing and thus enhance disease symptoms. The emergence of two such satellites is responsible for the breakdown of crop resistance of cotton in cultivars that were developed to be resistant to cotton leaf curl virus in Pakistan (Amin et al., 2006; Briddon and Stanley, 2006; Mansoor et al., 2006). The existence of DNA satellites in cassava may help to explain the rising pandemic in SSA of cassava mosaic disease (Ndunguru, 2005). An intensive research effort to determine the fundamental nature of those DNA satellites is needed so that the products they encode and how they overcome resistance alleles in the target crops can be understood. The research should be coupled with strong support for development of regional diagnostics to develop baseline information and carry out surveys that can follow the emergence of new disease threats, especially emerging satellite DNAs—information that will need to be communicated rapidly to breeders so that they can test all their resistance alleles for effectiveness in the presence of newly emerging viral sequences.

PLANT PROTECTION WITH CLASSICAL AND GENETICALLY ENGINEERED BIOCONTROL AGENTS

The previous sections of the report focused on manipulating the plant to introduce improved traits, including resistance to diseases and pests. This section explores the potential for other organisms to be used to protect plants from insects, weeds, and other pests.

Biological Control of Insects

Use of Natural Predators

Insect biological control (biocontrol) consists of the release of specific natural enemies, usually from the place of origin of an exotic pest. Parasitoids are the most frequently used natural enemy group for biocontrol. The long history of plant breeding as the focus of plant protection efforts in Africa (Hahn et al., 1989) has meant relatively weak support for biocontrol initiatives. However, most food in Africa is produced from exotic crops that originated in South America, southeastern Asia, or SA. With foreign insect species invading Africa at an increasing rate and threatening agriculture and conservation, biocontrol is increasing relevant.

Although biocontrol is not a quick fix and is usually doomed to failure if there has been no preliminary research, Africa has seen some of the most successful examples of classical biocontrol, in part because the introduced agents have not been exposed to pesticides, given the low application rates common in subsistence farming. The data in Table 3-1 demonstrate the effects of three biocontrol technologies. In terms of yield, they offer benefits comparable with those of long-term breeding programs for maize and cassava.

The use of biocontrol agents can help to preserve the biodiversity of crop varieties inasmuch as the agents can be used with all varieties whereas conventional or transgenic breeding of varieties with insect-resistance traits usually involves a small number of varieties. Some possibilities are described below.

Control of Whitefly. The world's most destructive whitefly pest, *Bemesia tabaci*, is a target worthy for biocontrol. Its genetic diversity, its wide range of host crops and other plant species that lead to its ability to transmit more than 70 disease-causing viruses, and its environmental adaptability make this pest particularly challenging, and control will require multicomponent, integrated pest management (Legg and Fauquet, 2004; Legg et al., 2004). Cassava, an important crop in Africa, is being severely affected by

TABLE 3-1 Economic Impact Analysis of Current Biocontrol Projects in Africa

Pest Species and Time of First Occurrence	Losses in Yield	Control Agent and Time of Start of Campaign	Area	Reduction in Loss
Cassava mealybug, 1973	40%	Encyrtid wasp, 1981	27 African nations	90-95%
Cassava green mite, 1971	35%	Phytoseiid mite, 1983	Nigeria, Ghana, Benin	80-95%
Mango mealybug, 1980s	90%	Encyrtid wasp, 1987	Benin	90%

NOTES: Estimated savings from the biocontrol projects in millions of U.S. dollars were 7,971-20,226 (cassava mealybug), 2,157 (cassava green mite), and 531 (mango mealybug). Estimated saving were achieved for costs far below 1% of research costs.

SOURCE: Neuenschwander, 2004. Reprinted by permission from Macmillan Publishers Ltd: Nature (Neuenschwander, 2004), © 2004.

the spread of two virus groups by *B. tabaci*: CMV disease, caused by geminiviruses, and cassava brown streak, caused by an ipomovirus.

Little has been done to address the whitefly situation. Control of the highly fecund B biotype has been achieved in the United States and elsewhere through a process of conserving and augmenting natural enemies and introducing new ones from other locations with similar environments (Goolsby et al., 2000; Hoelmer et al., 2000). Although the B biotype is not the form of the pest that is causing problems in the main tropical zones of SSA, the strategy used to control it elsewhere provides a model for a potential biocontrol program in Africa. A concerted effort is needed to characterize the genetics and biotypes of *B. tabaci* in Africa, to explore interactions of the pest with natural enemies and host plants, and to test the extensive fauna of *B. tabaci* parasitoids worldwide to examine the possibility of introducing additional parasitoid species.

A smaller but important adjunct to the effort would be a program to tackle alien invasive whitefly species. One of the most destructive of these is the spiralling whitefly, *Aleurodicus disperses*, major infestations of which occur on a wide array of annual and perennial crops in eastern Africa. Fruit trees are an important source of income for farming communities in this coastal zone, and coconut, papaya, guava, and avocado are all seriously affected. Occurrences in both northern and southern coastal zones mean that spread is continuing, but in the absence of trained observers it is probably being missed. Inasmuch as effective control has already been achieved in western Africa through the spread of parasitoids, an effective solution could be possible in a relatively short time.

Control of Pests of Cowpea. The cowpea aphid originated in the Middle East and south Central Asia, where it is seldom recorded as reaching pest status because a multitude of parasitoids of *Aphis craccivora*, such as *Trioxys* spp. in Pakistan and India, control this pest in a variety of environments and on different crops (Singh and Agarwala, 1992). Considering that no parasitoids attack this pest in SSA (Soukossi, 2001), introduction of climatically adapted strains might reduce aphid numbers below the damage level (Manuel Tamo, IITA-Benin, personal communication). A potential biocontrol agent for cowpea bruchids is the parasitoid *Dinarmus basalis* (Amevoin et al., 2007). Similarly, the cowpea pod borer, *Maruca vitrata*, is controlled in Asia by three braconid wasps, three ichneumodids, and a tachinid fly (Huang et al., 2003). Preliminary studies suggest that among these *Apanteles taragamae* and *Nothura maculosa* (with up to 63 percent and 40 percent parasitism, respectively) are promising candidates to exploit as biocontrol agents against the pod borer in western Africa, where it has few natural enemies.

Biocontrol with pesticides based on natural pathogens is one method for replacing chemical insecticides (Uneke, 2007). Biocontrol of insects has relied mainly on the bacterium *Bacillus thuringiensis* (*Bt*) and the Cry (for crystal) protein (protoxin) it produces that is highly toxic to some species of insects after ingestion but safe for most nontarget organisms. The success of using whole *Bt* is due to the relative ease of mass-producing products based on it (Federici, 2007). However, a problem of toxin resistance is emerging in some insect species (Poopathi and Tyagi, 2006; Federici, 2007). Genetic engineering has been used to develop more potent recombinant bacteria to produce multiple toxins that are more cost-effective and less prone to resistance (Federici, 2007).

Some of the major insect pests of cowpea can be controlled with inundative applications of the entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* (Tamò et al., 2003). Fungi are the most common pathogens in nature that attack thrips and aphids, and their mode of action—direct penetration of the cuticle—makes them suitable candidates for controlling these pests (St. Leger and Screen, 2001). Such fungi may also be useful for controlling storage pests, such as the bruchid beetle, which is able to cause losses of 60 to 80 percent (Glitho and Nuto, 1987). The application of *B. bassiana* was able to protect stored cowpea for up to 6 months (Cherry et al., 2007).

Viruses also have the potential to be used as biocontrol agents for biting insects. A hitherto unknown nuclear polyhedrosis virus (MaviMNPV) was found to infect the cowpea pod borer (*Maruca vitrata*) moth larvae in Taiwan (Lee et al., 2007) and was later exported to Africa for trials. Preliminary observations indicate that the virus can control *M. vitrata*, and an effort is under way to conduct surveillance of the pest with pheromone-based traps in different cowpea cropping areas. Once that is achieved, the traps could be used to derive an intervention threshold for spraying with MaviMNPV.

Genetic Engineering for Biocontrol and Biopesticides

An advanced approach could remedy the perceived deficiencies in naturally occurring biological pesticides by molecular manipulation to improve virulence (speed of kill), restrict or widen the host range or reduce inoculum loads, and alter saprophytic competence. Such technology has been used to produce hypervirulent viruses and fungi (Zlotkin, 2000; Wang and St. Leger, 2007).

Classical insect biocontrol is being challenged to improve its success rate, robustness, and reliability. The use of genetics to enhance efficacy of natural enemies has attracted a lot of discussion but delivered little thus far (Poppy and Powell, 2005). It might be possible in the future to use transposable elements that allow insects to be engineered with a variety of traits, making genetic engineering of parasitoids likely (Atkinson et al., 2001; Grigliatti et al., 2001). Parasitoids show remarkable phenotypic plasticity because of associative learning. Understanding the genetic control of learning and the ability to select parasitoids for learning ability is an exciting prospect if research on gene-environment interactions can be studied.

Suicide-Inducing Genes

An emerging approach to pest management is genetic modification of the insect pest to target it for biocontrol. A possible biological pest management system, dubbed TAC-TICS (Grigliatti et al., 2001), proposes to transform the whitefly pest with a multicopy deleterious transposon bearing an incapacitating gene with an inducible promoter. The transformed insect would be released into the population for dissemination of the transposon; after spread, a chemical switch would turn on the incapacitating gene. Progress in insect sciences makes each of those steps feasible, but the scheme would require considerable research to implement in the field. Recent successes have been achieved in transforming mosquitoes to make them unable to transmit the malaria parasite and fitter than wild-type mosquitoes (so that they replace them) (Marrelli et al., 2007). It might be possible to produce transgenic whiteflies that carry a lethal gene under the control of a promoter that is turned on by the presence of plant pathogenic viruses so that only whiteflies carrying the viruses die.

Biological Control of Weeds

Insects are not the only organisms for which there are applications of biocontrol. For example, fungi have been isolated that control *Striga* in limited inundative biocontrol trials. There has been considerable success in applying fungal inoculum as a seed treatment, but support has not been available for testing and developing it on a large scale (Beed et al., 2007). It has been suggested that transgenic fungi with hypervirulence genes could be used to further increase efficiency, and there has been laboratory-scale success with this approach using *Orobanche* as a model for *Striga*. If the transgenic hypervirulence approach is used, genes would have to be added as a fail-safe mechanism to prevent spread and mating with other fungi (Gressel et al., 2007). Similarly, highly specific pathogenic fungi that attack *Echinochloa* have been isolated and tested in rice paddies (Zhang and Watson, 1997; Yang et al., 2000); these, too, could be genetically enhanced to increase virulence (Vurro and Gressel, 2007).

Cultivating the perennial legume *Desmodium* between crop rows has been somewhat successful in controlling *Striga*. It secretes *Striga*-killing allelochemicals. The technology is limited to where *Desmodium* will grow and to where farmers have livestock that will eat the legume, but no livestock are kept in the poorest and densest parts of Africa. The nature of the allelochemicals is known, and the genes responsible for their synthesis are being sought (Pickett et al. 2007). If only a few unique genes are involved, then these genes might be engineered directly into *Striga*-susceptible crops and potentially eliminate the need for growing *Desmodium*.

Some rice varieties generate allelochemicals that dampen but do not kill neighboring weeds (Ma et al., 2006; Khanh et al., 2007). Presence of the chemicals is polygenically inherited with low heritability (Olofsdotter, 2001), so conventionally breeding the genes into elite material would be a daunting challenge and might reduce the crop yield. However, the approach might be more practical if transgenes could be found that encode root-emitted allelochemicals and do not reduce yield.

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4

Water Resource Availability

Water is essential to human survival and critical to the success of agricultural systems. This chapter examines what is known about the quantity of water available to farmers in sub-Saharan Africa (SSA) and South Asia (SA) and the projected impact of climate change on water availability in these regions. Technologies for increasing the quantity of water available to agriculture and for increasing the ability to manage and conserve water resources are discussed in this chapter. Water and soil are tightly linked and conservation of those combined resources is addressed in Chapter 5.

WATER RESOURCES IN SUB-SAHARAN AFRICA

SSA is a region of diverse climate, from tropical humid to arid, and much of the continent is influenced by the monsoon season. The continent and its climates are criss-crossed by numerous rivers (Figure 4-1). In the humid regions, rivers and groundwater networks overlap. In arid regions, groundwater resources are not connected with surface rivers, so groundwater recharge (by rain) is more important than in humid areas. The base flow of rivers in the arid regions is also low, and evaporation is very high. Thus, some countries have less water flowing out than flowing in.

In SSA, a horizontal band of countries forms the Sahel, an arid transitional zone between the desert to the north and the tropical regions to the south. Water resources in the Sahel are limited and unevenly distributed. The Nile River flows through the east Sahel; the west is served by the Niger. The Niger is also the major river system of the tropical, monsoon-influenced climate of the Gulf of Guinea on Africa's west coast, an area that makes up

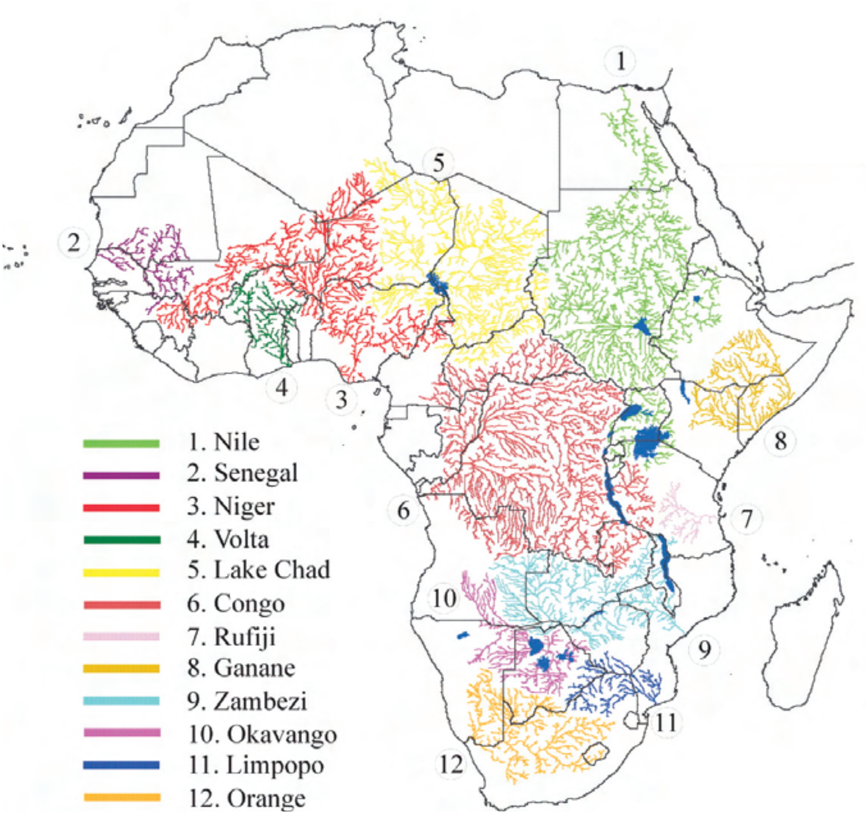

FIGURE 4-1 Major rivers of Africa.
SOURCE: From de Wit, M., and J. Stankiewicz. 2006. Change in Surface Water Supply Across Africa with Predicted Climate Change. Science 311:1917-1920. Reprinted with permission from AAAS.

one-fourth of Africa's water resources. East of the Gulf of Guinea, the countries of humid, tropical central Africa are served by two major rivers—the Congo and the Ooguué—that make up almost half the continent's water resources. In eastern Africa, the climate ranges from semi-arid to tropical humid, and the major river in this subregion is the Nile. Although the water resources in this region are limited, Africa's largest lake, Lake Victoria, is there. The climate in southern Africa is diverse, from subtropical humid to arid. The Zambezi, Limpopo, and Orange Rivers serve the region, but the water resources are modest, and some groundwater reserves are not renewable (FAO, 2003), although two large inland lakes, Lake Malawi and Lake Tanganyika, are in the region.

WATER RESOURCES IN SOUTH ASIA

SA is also a region of diverse climate and water resources. The western parts of SA—Afghanistan, Pakistan, and northwestern India—are characterized by dry climates, whereas very humid climates prevail in eastern India, Bangladesh, Bhutan, Nepal, and Sri Lanka (Figure 4-2). Rainfall in the entire region comes primarily during the annual monsoon, when rain falls for a period of 3 months or less, often very intensely, and leads to severe runoff over sloping land and inundation of flat terrain. The variability and unpredictability of the monsoon rains in time and space create great difficulties for farmers, who base their planting, fertilizing, and other production decisions on their expectations of the timing and amount of rain.

Vastly more water falls on the humid and subhumid regions of India and Bangladesh during the monsoon than on the arid regions of the west. The annual precipitation in India, including snowfall, is nearly 4 trillion cubic meters, and 75 percent of that is from the monsoon (Mohapatra and Singh, 2003). In contrast, the arid regions of northwestern and western

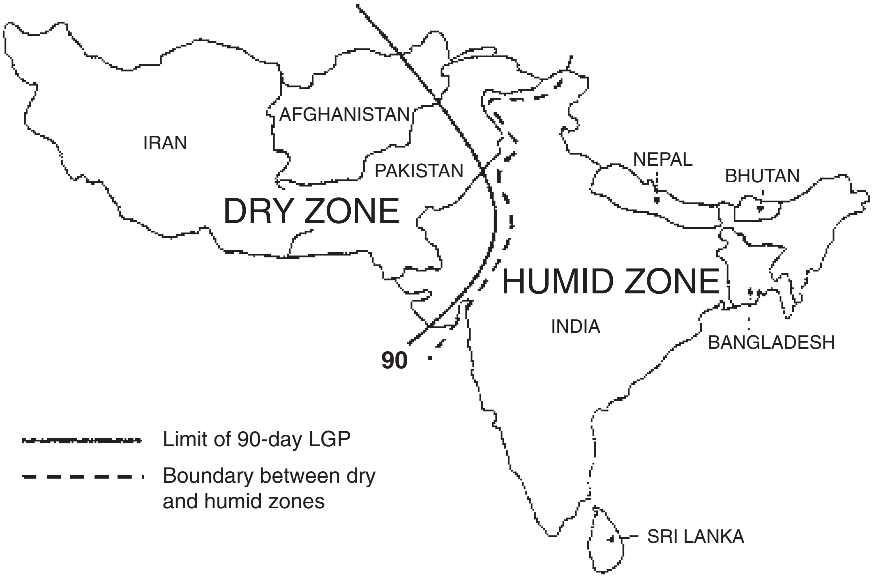

FIGURE 4-2 The South Asia region showing the approximate boundary line at which rainfall or soil moisture is adequate to support a 90-day-long growing period for crops.

SOURCE: Food and Agricultural Organization, 1994. Reprinted with permission. © 2006 by the Food and Agriculture Organization of the United Nations.

SA, which experience severe water shortages during the 9-month-long dry season, receive 80 percent of their water from the seasonal melting of snow in the Hindu Kush mountain range. Most of the entire SA region has high temperatures during the summer, when soil temperatures exceed 45°C at a depth of 1 cm (Gupta and Gupta, 1986). Thus, the rate of water evaporation is high (Lal, 2006).

DEMAND ON WATER RESOURCES IN SUB-SAHARAN AFRICA AND SOUTH ASIA

Having a sense of the water resources of a region is important, but it is more relevant to know how accessible the water is and how rapidly it is used relative to the rate at which it is recharged. SSA and SA are very different from each other in both regards. Since the 1960s, SA has emerged as the world's largest user of groundwater for irrigation (Shah et al., 2006). Indeed, groundwater is used in over 75 percent of the irrigated areas in some parts of India, Pakistan, the Terai region of Nepal, and Bangladesh. In contrast, only 6 percent of Africa is under irrigation, and far fewer wells and irrigation systems exist to bring water to crops. Not surprisingly, the limited accessibility of water makes a huge difference in agricultural productivity. Grain yields are linked to rainfall in countries where almost all the agriculture is rain-fed. In Ethiopia, the interannual oscillations of national grain production mirror variation in rainfall, and so does the gross domestic product (see Figure 4-3).

The huge irrigation demands on water resources in SA are competing with industrial and other uses, and excessive withdrawal of groundwater is leading to reduction in water levels, drying up of wells, and increase in problems of water quality, including the problem of arsenic in groundwater (Reddy et al., 2000). It is estimated that as many as 25 percent of farmers in India are overtapping the aquifers and withdrawing water faster than it is being recharged (Pearce, 2006; Postel, 2006).

From 20 to 30 percent of the renewable water resource in SA is withdrawn each year for various uses, in contrast with SSA, where total water withdrawal as a percentage of renewable water is only around 3 percent (Table 4-1).

Water availability can also be described as a function of the size of the population. The total renewable water resource per capita in South Asia is about 1,591 m^3/year. Given population growth and other demands, renewable per capita freshwater resources in SA are likely to be severely constrained in the future, especially in Afghanistan, India, and Pakistan.

In contrast, Africa has only 13 percent of the world's population, and its total renewable water resource per capita is 5,000 m^3/year. Because of low population density, even countries in the Sahel, *on the average*, have

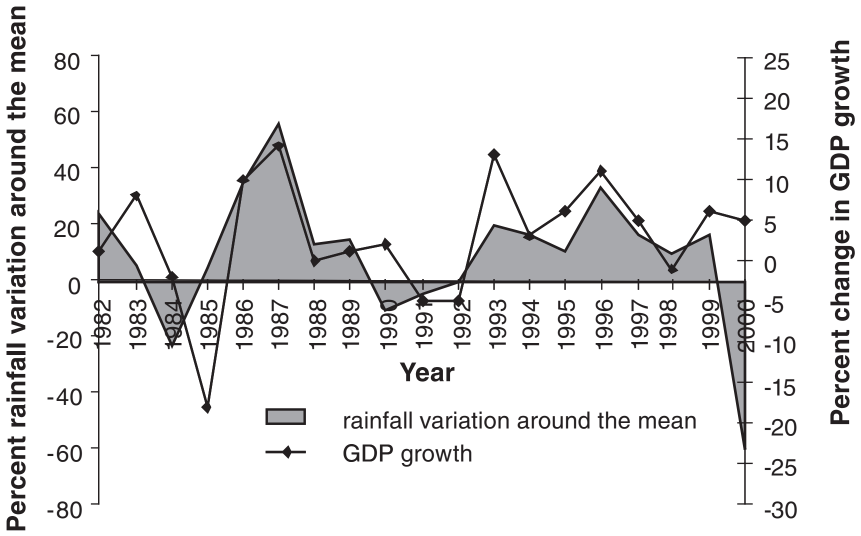

FIGURE 4-3 Rainfall and growth in gross domestic product in Ethiopia, 1982-2000.
SOURCE: World Bank, 2006. Reprinted with permission from D. Grey and C. Sadoff.

adequate per capita renewable water resources. The problem is that the water is not always accessible to the population. Of the 47 countries of SSA, six (Comoros, Eritrea, Lesotho, Malawi, Somalia, and Zambia) experience a moderate deficit of renewable water resources of about 1,500 m^3/year per capita, and six others (Burkina Faso, Cape Verde, Djibouti, Kenya,

TABLE 4-1 Total Water Withdrawal by Volume and as Percentage of Renewable Water

	Water Withdrawal (km^3)			Water Withdrawal (% of Renewable water)		
Region	1995 Baseline	2010 Projection	2025 Projection	1995 Baseline	2010 Projection	2025 Projection
India	750	750	815	30	33	36
South Asia (excluding India)	353	391	421	18	20	22
Sub-Saharan Africa	128	166	214	2	3	4
World	3,906	4,356	4,772	8	9	10

SOURCE: Rosegrant et al., 2002. Adapted and reproduced with permission from the International Food Policy Research Institute (*www.ifpri.org*) and the International Water Management Institute (*www.iwmi.cgiar.org*).

Rwanda, and South Africa) have severe deficits of 1,000 m^3/year or less per capita (UNESCO, 2006).

WATER RESOURCES AND CLIMATE CHANGE

Climate change models predict scenarios for SSA and SA that may drastically affect the availability of water in parts of these regions. In most climate change projections, most of SSA will probably be warmer than today, and the rate of warming will be more than the global average. In fact, Africa has already been getting warmer, at the rate of about 0.05°C per decade (IPCC, 2001).

Projected changes in rainfall are much less clear. Two analyses of how a theoretical 10 percent decrease in rainfall would affect the flow of Africa's surface waters found that the flow in rivers in Africa's wettest regions would decrease by 17 percent (Nyong, 2005) and that the semi-arid zones would experience a disproportionately larger decrease of 25 to 77 percent, with the most severe decreases in southern Africa and the Sahel (de Wit and Stankiewicz, 2006). If those projections are realized, the change in water availability will be devastating in some regions.

In SA, climate change promises to be just as ominous, although most climate change models predict that central and eastern Asia will become wetter. However, irrigation systems in Pakistan and India are served by four rivers (Indus, Ganges, Brahmaputra, and Yamuna) that originate in the glaciers and snow of the western Himalayas. About half the annual snow and glacier melt from the high mountains is used in irrigation (Winiger et al., 2005). Therefore, it is of great concern that snowfall amounts in the Himalayan region have been progressively declining while melting has increased and caused floods. Quantitative comparisons of satellite images of 1972, 1989, and 2000 reveal a decline in the annual average surface snow rate and the deposition of dust over the snow and glaciers. From 1972 to 2007, the observed surface temperatures have increased by 8 kelvin (Prasad and Singh, 2007). The more than 700 million people who live in the Indo-Gangetic Basin are likely to face a future with less water (Brown, 2001).

To add to the gloomy picture, severe weather events are expected to increase in both SSA and SA and to result in floods and droughts in an unpredictable pattern. Recently, more than 340,000 people were displaced in southern Africa because of flooding that began in December 2007. Erratic monsoon rains have led to the loss of crops, livestock, property, and human lives throughout SA. The average area annually inundated by floods is 7.6 million hectares, and 33 million people are affected in India alone (Mohapatra and Singh, 2003). The problem is even more serious in the densely populated deltaic region of Bangladesh. Joining the rivers of the north to those of the south and west has been considered a long-term solution to the flooding, but an objective and careful analysis of such a plan is necessary.

TECHNOLOGIES FOR WATER MANAGEMENT

Anticipating changes in water resources, planning for shortages (or excesses) of water, managing the use of the resource, and finding ways to increase the availability of water in SSA and SA should have high priority for nations in these regions. In the industrialized world, a great deal of activity is under way to deal with anticipated constraints on water resources. The technologies described here are some that are worthy of exploration in the context of SSA and SA.

On-Farm Integrated Water Management

As noted earlier, SSA and SA differ dramatically with respect to irrigation. In SA, large areas of cropland are irrigated, from 30 percent of cropland in Afghanistan to 80 percent in Pakistan (WRI, 2005; Lal, 2007). India uses water at 200 km^3/year for irrigation, the equivalent of 3 times the flow of water in China's Yellow River. But the water-related productivity of irrigated rice in India is comparatively low, averaging grain yields of just 0.4 g/kg of water used compared with up to 7 g/kg of water in the Philippines (Kar et al., 2004).

In contrast, only about 5 percent of the potentially irrigable land in SSA is under irrigation, and two countries (Sudan and Madagascar) account for about 60 percent of the irrigated land. However, if irrigation in SA is inefficient, so are the rain-fed farms of SSA, where evaporation and runoff lead to large losses. In SSA, the priority need is to expand the land area for water capture and irrigation.

The integration of techniques to manage water on the farm is one of the most important set of technologies that exist to transform agriculture in SA and SSA. On-farm water management includes techniques for water capture, storage, pumping, transfer, field application, and drainage technologies. On the scale of the small farmer in Africa or India, water capture has typically involved small dams to pool and store surface water. An important development for small farmers has been the drilling of small-scale, individual tube wells, typically powered by treadle pumps, and the development of small lined reservoirs for local storage of water.

The delivery of water to plants via irrigation is a critical step in water and soil conservation. Flood or furrow irrigation, the predominant method in India, is the most inefficient form of irrigation, although land leveling (essentially the removal of high and low spots of land) using animals or tractors tied to a leveling bucket that is dragged across the earth, can improve irrigation efficiency (Jat et al., 2006).

Over the last decade, micro-irrigation, primarily drip irrigation, has been increasingly adopted because of the availability of low-cost tubing and pipe systems (Wallace, 2000; Panigarhi et al., 2001; Viswanathan et al., 2002; Aujla et al., 2005). Studies comparing drip irrigation to conventional surface irrigation in a variety of cropping systems revealed water productivity gains ranging from 91 to 149 percent (Molden, 2007).

Water can be used most efficiently if it is applied to the active root zone of plants. Subsurface drip irrigation (SDI), which consists of buried plastic tubes containing regularly spaced, embedded emitters (pores), is a technology with some potential for farmers in arid regions of the world, if the costs of the technology could be addressed. Although SDI has existed for over 20 years in the United States, SDI has been used on less than 25,000 hectares, primarily in Arizona and California. One of the reasons that SDI is not used more widely is that until recently, design requirements to match system characteristics with soils and crops had not been well defined. The initial use of SDI has been to irrigate annual row and field crops and permanent crops, like citrus. Drip tubes have been typically located 130 to 210 cm apart, and 15 to 25 cm below the soil surface. However, emerging design standards will permit SDI to be used for any crop, including those that are planted neither in beds nor in rows. SDI can be adapted to grow any crop (e.g., corn, wheat, rice, sorghum, soybean, cassava, yam) and can produce the "ultimate" in water use efficiency for open field agriculture, resulting in water savings of 25-40 percent in comparison with flood irrigation. The typical efficiency of SDI is 90 percent compared with 60 percent for conventional furrow 80 percent for furrow with valve and also for low-pressure sprinkler.

However, SDI also has limitations, primarily its cost and the possibility of clogging over time. Work is under way to make a low-cost SDI system, but its installed cost will probably be about \$0.20/m^2 as opposed to \$0.084/m^2 for a surface tube irrigation system (Jack Keller, Keller-Bliesner Engineering LLC, personal communication, April 29, 2008). That might put SDI out of reach for all but small-scale growers of high-value crops.

If it could be made more affordable, SDI offers a number of other potential advantages over other types of irrigations systems, including the following:

Better nutrient management—When water is applied to the surface of the soil, it carries away nutrients like nitrogen. With SDI, water is applied at the roots, so less nitrate is leached from the soil. If used in conjunction with fertilizer (fertigation), the most active part of the root zone will receive nutrients more directly.

Better weed control—A dry soil surface means that weed seeds may have a more difficult time germinating, and the absence of moisture on the parts of the crop above the soil may reduce conditions for disease.

Ability to use waste water—Because water is applied below the surface, contamination of the crop with disease-causing microorganisms is greatly reduced. Thus the opportunity to use wastewater will result in even greater efficiency. However, this would not be appropriate for root crops (e.g., cassava, yam, radish, turnip, carrot, potatoes).

Longer system life—Because they are placed underground, drip lines are protected from damage due to cultivation and other farm operations. Furthermore, buried tubes will last longer than those above ground, due to the exposure to heat and ultraviolet sunlight. The robustness and longer life of SDI systems makes their comparatively higher costs economical in the long term, relative to above ground systems.

Water Storage

The storage of water in large aboveground tanks during the monsoon season and its use during the dry season for irrigation and human and livestock needs have been practiced in SA for millennia. Tanks have been a traditional common-property resource, especially in southern India (Anbumozhi et al., 2001). The efficiency of the ancient technology is low because of the large losses during conveyance and through evaporation and percolation.

In the last 4 decades, systems have evolved to store water underground in aquifers, and a recent study by the National Research Council found that, given the "generally successful track record of managed underground storage [MUS] in a variety of forms and environments, MUS should be seriously considered as a tool in a water manager's arsenal" (NRC, 2008). In MUS systems, surface water, groundwater, treated effluent, and occasionally storm water are stored in different types of underground aquifers—from unconsolidated alluvial deposits to limestone and fractured volcanic rocks. Water to be stored is directed into an aquifer through recharge basins or recharge wells and recovered for use with extraction wells or dual-purpose recharge-extraction wells. The recovered water is used for drinking, irrigation, industrial cooling, and environmental and other purposes.

The science and technology of MUS are still emerging. Scientists are learning through experience that the matrix, hydrogeological, and geochemical characteristics of some types of aquifers are better suited than others for storing water and that different recharge, storage, and recovery methods are needed for different aquifers. Research is needed to assess the suitability of recharge sites and the hydrogeological characteristics of candidate aquifers.

The potential interactions of the stored water with other surface-water and groundwater supplies must also be carefully investigated.

It is well documented that underground storage has "the capacity to attenuate many chemical constituents and pathogens via physical (e.g., filtration and sorption), chemical, and biological processes. In places where the groundwater quality is saline or otherwise poor, the implementation of MUS will likely improve overall groundwater quality and provide a benefit to the aquifer"; and "a monitoring program is needed to document the water quality behavior and establish the reliability of the MUS system. This will involve installation of monitoring points to track the behavior of the water and the constituents in the water as the source water is introduced, stored, and eventually extracted" (NRC, 2008).

In general, there appears to be a rich body of research that supports the use of MUS in arid parts of the United States, and this may be a subject for exploration in SSA and SA. Such research could yield substantial benefits to farmers, assuming that efficient systems for bringing stored water back to the surface and distributing it for use in agriculture can be devised.

Wastewater Reclamation

Because of its ability to improve water quality, MUS might be used in conjunction with treatment of urban storm-water runoff and municipal wastewater. Wastewater is already used in periurban agriculture but often without substantial treatment standards (Van Rooijen et al., 2005). Modern wastewater-treatment plants typically treat wastewater biologically and then pass it through a final sand filtration step before it is used for irrigation (NRC, 2004). Wastewater reclamation has benefited from the recent development of membrane bioreactors—bioreactors coupled to filtration units—that enable biomass to be concentrated without impeding the flow of water through the filter (Daubert et al., 2003). The treatment of wastewater might also be accomplished by nanofiltration devices that are rapidly emerging for small applications, such as household use. Although the committee was not able to undertake a thorough investigation of all these devices, several may have applications on the scale that could make wastewater a source of both irrigation and drinking water (see Box 4-1).

Desalination

One way to create additional water supply is to remove salt from seawater or inland brackish aquifers. Desalination technology is evolving and, in addition to removing salt, has been proposed as a method for treating wastewater. The committee was not able to conduct an in-depth exploration of desalination technologies, but one expert who addressed the committee

BOX 4-1
Nanomaterials for Water Purification

Several nanomaterial-based products that are both economical and effective in purifying water have been developed, including

- The NanoCeram filter that uses a positive charge to attract negatively charged viruses and bacteria (20 to 100 nm).
- A fused carbon nanotube mesh that can filter out waterborne pathogens, lead, uranium, and arsenic.
- Carbon nanotube filters for water filtration.
- Zinc oxide nanoparticles to remove arsenic from water with an "at-the-tap" purification device.
- Nanoparticle filters to remove pesticides (such as DDT, endosulfan, malathion, and chlorpyrifos) and other organic particles from water.

suggested that for cost and energy considerations, desalinated water should be produced for human consumption and municipal wastewater used for agriculture (Donald Slack, University of Arizona, presentation to the committee, October 16, 2007). However, another expert suggested that small-scale desalination was possible and economical for specialized applications, such as the production of high-value greenhouse crops, and that integrated systems could be engineered for this purpose (David Furukawa, presentation to the committee, October 16, 2007).

A review of the U.S. desalination and water purification roadmap provided a cogent summary of the state of the technology, its potential, and research directions (NRC, 2004). That review is a useful vantage point for considering what developments in desalination technologies might benefit small-scale farmers in SSA and SA.

Because profit margins on clean water production by desalination are small, commercial interest in the technology is weak. Most desalination projects are heavily subsidized with public funding, and research focuses on reducing costs by expanding economies of scale and optimizing operational efficiency. Nevertheless, there have been major advances in the performance and cost of membranes used in reverse osmosis, one of the two most common methods of removing salt from water; the other major method is thermal distillation, which is used throughout the Middle East because of the lower costs of fuel in the region.

The major cost of either type of operation is power (which accounts for 44 percent of the cost of reverse osmosis and 59 percent of the cost of thermal distillation). The other major expense is capital costs. Although the use of alternative sources of energy was discussed in the National Research Council report, it focused on reducing energy costs in reverse-osmosis plants by improving the water-pretreatment processes and the precision of the membranes in removing specific contaminants or salts and in thermal-distillation plants by cogenerating the heat needed for desalination with electrical power generation. In either of the two dominant techniques, the current cost of desalination is about $2 to $3 per 1,000 gallons of seawater and $1 to $1.50 per 1,000 gallons of brackish water (Hinkebein, 2004).

Two other thermal techniques—solar distillation and membrane distillation—have remained somewhat undeveloped (Buros, 2000). In solar distillation, salt water in a shallow basin is evaporated by the sun and condensed on a sloped glass roof. In membrane distillation, the vapor from heated salt water passes through a membrane (which allows vapor but not water to pass) and then condensed. Those methods require more space (and more energy per unit of clean water produced), but their simplicity and the need for only small temperature differentials to operate make them viable technologies where inexpensive thermal energy, such as that from solar collectors, is available (Cooley et al., 2006).

Two other aspects of desalination that are worthy of further exploration for SSA and SA are related to the disposal of the salty concentrate that remains after desalination. In some applications, the concentrate is disposed of at sea, where dilution theoretically minimizes adverse effects. In an inland situation, an alternative is to deposit the salty brine in a solar-energy pond, where the lower dense layers of salty water reach high temperatures. A heat exchanger can be used to extract the stored energy from the bottom layer of the pond (NRC, 2004). The National Research Council report (2004) also speculated on whether the leftover salt concentrate might have commercial value. Because membrane systems can be designed to be selective in their recovery of chemical compounds, the production of commercially valuable salt solids—such as gypsum, sodium chloride, and magnesium sulfate—may be possible.

Weather Modification: Cloud Seeding

Cloud seeding involves the introduction of agents into a cloud to increase the efficiency of its precipitation. Commonly used agents include silver iodide, dry ice (granulated solid carbon dioxide), and salt. The agents are introduced by ground flares or deployed from an airplane (Hunter, 2007) and act as nuclei around which water vapor coalesces into ice crystals that are released from clouds as snow or rain.

The practice of seeding clouds began in the 1940s and remains somewhat controversial, generally because of the difficulty of measuring the effect of seeding on the amount of precipitation. A 2003 National Research Council report concluded that the overall efficacy of intentional cloud-seeding efforts was still unproved, not on the scientific basis of the weather modification concepts, but on the "absence of adequate understanding of critical atmospheric processes" that reduce its predictability (NRC, 2003).

In spite of its uncertain results, cloud-seeding programs have been implemented in at least 24 countries, including India, Zimbabwe, Burkina Faso, South Africa, Honduras, Mexico, Cuba, Australia, Thailand, Egypt, Israel, Japan, the United Arab Emirates, China, and the United States (Salleh, 2007); the largest number of individual projects take place annually in China and the United States (Chalon, 2007). In recent years, weather-modification projects in the United States have been implemented in 11 western states with funding by state agencies and private (mostly hydroelectric power) agencies. In California, cloud seeding has been conducted to increase the snowpack in the Sierra Nevada Mountains since the 1950s (CDWR, 2005).

States and countries pursue the programs because of the need to augment local water resources. Most of the projects are not research-oriented; that is, they are implemented with little scientific guidance that might improve their chances of success. And the programs do not methodically document their circumstances or quantify their results. However a few cloud seeding experiments (see Box 4-2) have been repeatedly scrutinized by the scientific community, and some successes have been confirmed, even if many questions remain about what is taking place in the clouds (Silverman, 2003).

The individuality of clouds and the weather systems in which they operate confound the transferability of seeding techniques because scientists lack a reliable record of the conditions and outcomes of cloud-seeding trials and need better models of the physical and chemical interactions in clouds. A National Research Council report (NRC, 2003) described a framework of basic research needs on weather modification and recommended steps to validate cloud-seeding operations that include statistical evaluations of their effects, tracking of introduced seeding agents and their effects in cloud cells, and physical measurement of rainfall.

Cloud seeding is not a solution for breaking a drought or making it rain where no clouds exist. Its potential for SSA and SA might lie in increasing overall rainfall that could be captured and distributed to farmers and in avoiding some of the otherwise inevitable effects of climate change. For example, the Himalayan glaciers have been receding rapidly (WWF, 2005), and enhancing snowfall in these regions could increase the availability of water to the Indus River Basin that relies on the spring thaws. Typically, only about 30 percent of the atmospheric water vapor that enters southern

BOX 4-2
Cloud-Seeding Experiments

Silverman (2003) analyzed four datasets from controlled experiments in which clouds were randomly seeded or not seeded from airplanes with different kinds of nucleating materials. Two experiments were conducted in cold convective clouds (in South Africa from 1992 to 1997 and in Mexico from 1997 to 1998), and two were conducted in warm convective clouds (in Thailand from 1995 to 1998 and in India from 1973 to 1986). In all cases, statistically significant differences were observed between the experimental and control clouds on the basis of radar-based estimates of rain mass that was produced. However, the hypothesis that the seeding material would act to increase the efficiency of the rain-forming process by accelerating the coalescence of particles in a cloud to a size at which precipitation would occur was not supported by physical measurements of particle sizes in the clouds. In summary, although the experiments appeared to have worked, there was no independent confirmation of the cause-effect aspects of seeding.

Africa reaches the ground as precipitation (Mather et al., 1997). Increasing the efficiency of rainfall by 10 percent—a figure that the American Meteorological Society considers to be the conservative potential of the technology—could significantly affect water availability. Because clouds are large systems, precipitation gains from cloud seeding in one location are thought to be incremental and additive; that is, seeding does not create rain in one location at the expense of another along a cloud's path of travel. However, in reality, the models and measurements that can be more definitive on this point are only now evolving.

The cost-to-benefit ratio of cloud-seeding projects in the western United States has been estimated at $1-20/acre-feet of water produced. In the case of Wyoming, where an estimated 10 percent increase in snowpack in the project's targeted areas would provide 130,000 to 260,000 acre-feet of water in additional runoff each spring, conservative estimates value the extra water at $2.4 million to $4.9 million. Of course, the scarcity of water determines the monetary value of additional water supplies, but the amount of water that would be needed to support farmers on a large scale across a large landscape requires further evaluation (UCAR, 2006).

Weather-modification technology goes hand in hand with weather prediction, and efforts to improve one will assist in improving the other. Because of the major impact of weather and water availability on farmers, research on both should be pursued with the involvement of local institutions and with adequate training, funding, and equipment to increase their ability to participate.

WEATHER AND CLIMATE FORECASTING

For four reasons, SSA and SA would benefit from climate and weather forecasting: early warnings of severe weather could be provided to rural populations; farmers and planners could be informed of the likelihood and intensity of drought; forecasters could help farmers to anticipate the onset of the monsoon or rain in general; and long-term climate change that would affect the lives of the rural poor in these regions could be predicted. The effects of regional human activity on local weather might also be discerned. For example, it has been observed in Indonesia and the Amazon that particles of soot (from burning of forests) may have inhibited rainfall despite the presence of clouds (Rosenfeld and Woodley, 2003). Physical evidence of cloud changes induced by air pollution downwind of urban areas has been documented with satellite measurements (Rosenfeld, 2000).

Climate scientists and meteorologists worldwide use observational data provided by numerous remotely positioned satellites, which they access by subscription through Earth-based receiving stations or the Internet. The data, often represented as an image or a map, are assimilated into a climate model by using algorithms (rules for incorporating the data); as datasets are collected and integrated, the models are used to predict climate trends and weather events. Until recently, however, predictive weather and climate models have relied on global averages of climate data and have focused on upper atmospheric processes even though it is known that such landscape features as soil moisture, terrain, and type of vegetation affect regional and local climate and weather. That information was not consistently available for a given swath of land, and the algorithms to integrate it into current models did not exist. As a result, the predictive power of the models has been relatively weak with respect to regional outcomes (Pielke et al., 2007).

In the last decade, remote devices that can measure those characteristics at increasingly high resolution have been placed on satellites, and they offer a much better opportunity to understand how local landscapes, anthropogenic activity, and geophysical processes influence mesoscale convections of wind, clouds, and rainfall. The new datasets form the basis of an emerging technology that could provide important tools for farmers and others in SSA and SA. If algorithms for new models can be developed for those regions with specific applications for agriculture, for severe weather alerts, and prediction of such long-term weather events as the coming of the monsoon, farmers' decision-making capability could be greatly improved.

Many remote measurement tools are in development or have been deployed recently, but it was beyond the expertise of the present committee to understand the potential utility of each unique source of data fully. Four examples of such devices are described below.

Moderate-Resolution Imaging Spectroradiometer

Two moderate-resolution imaging spectrometer (MODIS) instruments have been placed on satellites—one launched in late 1999, the second in 2002. MODIS generates global maps of several land surface characteristics: surface reflectance, land surface temperature, and vegetation indexes, such as the density of vegetation. MODIS can distinguish urban areas from non-urban areas and distinguish among 11 categories of vegetation (deciduous forests, coniferous forest, crops, grassland, and so on) and between bare soil and water. It can be used to monitor water quality by sensing the turbidity and dissolved oxygen in surface water (rivers, lakes, and estuaries). Because the maps are generated daily, they provide data on changes in land cover and land uses that can be fed into models of climate and weather. MODIS provides data all day and every day, so it is considered complementary to LandSat, an older remote observation system that provides data at a higher resolution but only once every 16 days.

Gravity Recovery and Climate Experiment

Launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) consists of twin satellites positioned bout 220 km apart in space. They track changes in Earth's gravity field by sensing tiny changes in the distance between the satellites with a microwave ranging system and a global positioning system. The motion of water and air on time scales ranging from hours to decades contributes to variations in Earth's gravity field that affect the relative positions of the two satellites. Every 30 days, GRACE generates a model and a global map of changes in Earth's gravity field that correspond to mass changes caused in part by the movement of water. By combining information from GRACE with soil-moisture and other data, hydrologists can monitor groundwater storage in aquifers on a monthly basis.

GRACE was used to measure the rapid melting of the Greenland ice sheet essentially by detecting changes in its mass. It has a wide variety of applications for estimating changes in water quantity in snowpack, lakes, river basins, aquifers, and soils and for evaluating and modeling such processes as river runoff and evapotranspiration. The sensitivity of GRACE is such that it detects changes in Earth's mass in response to weather patterns and climate change in periods of at least a month (Adam, 2002).

The expansion of irrigation, especially in SSA, requires credible assessment of groundwater and surface-water resources. In that regard, remote sensing systems and geographic information systems can be extremely useful (Chowdary et al., 2003). The same technology can also be used to monitor the risks of non-point-source pollution of groundwater (Chowdary et al., 2005).

Tropical Rainfall Measuring Mission

The Tropical Rainfall Measuring Mission (TRMM) was launched in 1997 by the U.S. and Japanese space agencies. It consists of a satellite-based precipitation radar (the only one of its type in space) that can provide three-dimensional images of clouds; a microwave instrument that provides quantitative estimates of rainfall, water vapor, cloud water content, and sea surface temperature; a visible and infrared spectrum scanner; and a lightning detector. The data that TRMM has provided have been of great use to the scientific community in learning about tropical weather systems and the structure of hurricanes and typhoons. For a number of reasons, the data have not yet been incorporated into weather-prediction models. However, they do reveal interesting information, for example, that in monsoon regions urban areas have more precipitation (Lei et al., 2008). The program has numerous partner countries involved in validating data collected by satellite, although they do not include partners in Africa or SA. There is a proposal to launch a global precipitation measurement program, which would expand the number of satellites with TRMM-type equipment so that more sensitive, real-time data can be made available (NRC, 2006).

Advanced Microwave Scanning Radiometer for the Earth Observing System

The Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) is a 12-channel, 6-frequency radiometer system for passively detecting Earth-emitted microwave radiation. It was launched in 2002, and its main value is in measuring cloud water, water vapor, sea surface winds, sea surface temperature, ice, snow, and soil moisture. AMSR-E is considered a valuable tool in the study of the movement of water from the oceans to the atmosphere and back again as precipitation, and it provides critically important data on global climate change. In addition, it can be used to provide accurate information on moisture in soil even if it is densely covered with crops (Bindlish et al., 2006).

MODEL DEVELOPMENT FOR CLIMATE AND WEATHER PREDICTION

NOAH Land Surface Model

To be understood in the context of what is occurring on local and regional scales, information derived from remotely based satellite tools, such as the ones described above, must be integrated into models. That requires the development of novel algorithms. The NOAH Land Surface Model (LSM) was developed in 1999 by a partnership of the National Centers for Environmental Prediction, Oregon State University, the U.S. Air Force, and the former Hydrologic Research Lab of the National Weather Service; the first letter of each partner's name gave the project its acronym. The model attempts to describe the effects of land surface on climatic and atmospheric chemistry on micro-scale and meso-scale levels (Figure 4-4). The model continues to be enhanced (Gochis and Chen, 2003). The NOAH

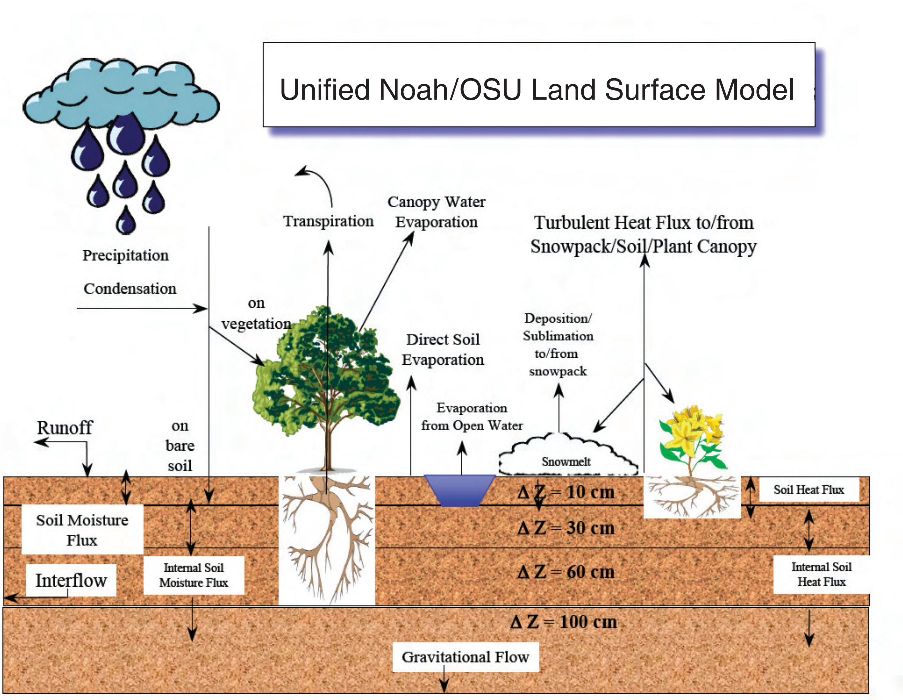

FIGURE 4-4 Schematic of NOAH Land Surface Model.
SOURCE: UCAR, 2008. 2008 © University Corporation for Atmospheric Research. Used with permission.

LSM measures 33 characteristics: 10 related to vegetation (such as minimal stomatal resistance, leaf area index, and canopy water evaporation) and 23 to soil properties (such as slope, porosity, and soil moisture). The model can be run for nine soil types and 13 types of vegetation cover (Hogue et al., 2005). NOAH LSM was initially developed in the context of a temperate region, and its utility in other environments is being tested, including environments in Burkina Faso, West Africa, where investigators concluded that adjustments to the model were needed to take seasonal dynamics into account (Bagayoko et al., 2006).

Land-Data Assimilation System

Weather prediction relies on remote observations of land surface conditions (for example, soil moisture and temperature) combined with models, such as NOAH LSM. However, both sources of information are subject to small errors that accumulate and reduce the accuracy of predictions. A land-data assimilation system is a method to correct the modeled land-surface fields in an ad hoc fashion by using real-time output from multiple observational data streams to improve the realism of weather-prediction models (Houser, 2006). One of the challenges is to ensure that atmospheric states and land states (which affect each other) are fully consistent with each other in the prediction system. Efforts are under way to create global land-data assimilation systems in addition to those developed regionally. Such systems currently do not exist for Africa or SA.

Predicting the onset of a rainy season and of the occurrence and frequency of 1- to 2-week drought periods during the growing season could be important to farmers. An early-warning system for severe weather would also save lives. And better regional predictions could improve the ability of financial institutions to take risks with investments to sustain and lead regional growth.

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5

Technologies for Soil Improvement

More than two-thirds of the agricultural land in sub-Saharan Africa (SSA) is considered to be severely degraded, and the situation is equally alarming in South Asia (SA) (FAO, 1994; GEF, 2003). If agricultural production in those regions must double in the next 2 decades, as implied by estimates of the future demand for food, substantial effort must be made to restore and maintain the productivity of their soils. If more food must be produced on the same amount of available land, agriculture must be intensified, and this will require that inputs to the soil be used as efficiently as possible (Henao and Baanante, 2006).

This chapter examines technologies to restore and maintain the physical structure of soils, improve the efficiency of water and nutrient use, and manipulate the rhizosphere—where plant roots interact with microbes—to enhance the soil and plant performance. It presents both some well-known methods for protecting and building soils that have not been widely adopted in SSA and SA but are essential for soil health and some novel, science-based concepts for improving soil that require research and additional exploration.

SOIL DEGRADATION IN SUB-SAHARAN AFRICA AND SOUTH ASIA

The severe problems of soil degradation and desertification in SSA and SA are attributed to the long-term use of extractive farming practices that fail to rebuild the soil with organic material and mineral nutrients that maintain soil productivity and prevent erosion. The negative nutrient balance in soils of SSA (Henao and Baanante, 2006), underpinned by poverty, affects 95 million hectares of arable land that have reached such a state of degradation that only huge investments in soil restoration can make them productive again (IFDC, 2006). In densely populated SA, soil is often irrigated with polluted or contaminated water because of poor resource management and competition for the resource. The overpumping of groundwater aquifers also has led to the deposit of salt on the land, which destroys soil productivity.

Socioeconomic, political, and cultural factors reinforce conditions that affect soil quality. For example, the main source of fuel for household energy in SA, other than fossil fuel, is wood, crop residues, and cattle manure (Venkataraman et al., 2005). The use of those traditional fuels has set in motion a cycle of natural resource degradation. Rather than being used as soil amendments, crop residues and manure are removed, and this has depleted the soil organic carbon (SOC) pool, created a negative nutrient budget, increased the susceptibility of soils to erosion, and reduced agronomic productivity. Runoff from soil leads to contamination and eutrophication of water resources, and the incomplete combustion of the biomass leads to emission of soot and noxious gases that have adverse effects on human health (Venkataraman et al., 2005). The degradation of the environment as a whole is a self-reinforcing system (Figure 5-1), and there is an urgent need to identify and foster technologies and management practices that can break the cycle of agrarian stagnation, enhance food security, and improve the environment.

RESTORING SOIL QUALITY WITH ESTABLISHED MANAGEMENT PRACTICES

Soil provides the physical, chemical (including water), and biological environment for sustaining plant growth. There are strong interdependences among soil characteristics, and maximizing the productivity of the soil requires attention to each of them. Because soils and the climatic and socioeconomic conditions in which they exist differ regionally, approaches to soil management are highly situational. There are many soil types in SSA and SA, from the highly erodible desert Aridisols and the easily compacted Alfisols to the less-permeable Vertisols (clayey soils with low infiltration rate and high susceptibility to erosion), and each has distinct needs and vulnerabilities. Some crops grow better than others in particular soil types, and the nutrient content of soils can vary widely.

Nevertheless, successful soil management systems have several common objectives: to increase carbon content, enhance water infiltration, ensure the availability of water at the plant-root zone, reduce erosion, create a positive nutrient budget, and encourage beneficial organisms.

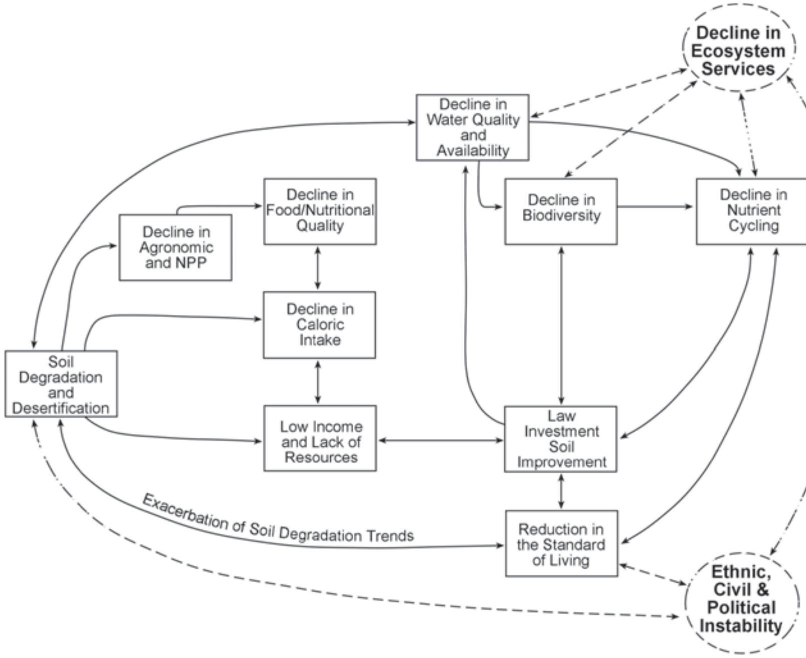

FIGURE 5-1 Soil-degradation-induced poverty, starvation, and political, ethnic, and social unrest are linked.
SOURCE: Lal, 2007a. Reprinted with permission.

Established techniques used in various combinations to accomplish those objectives are summarized in Box 5-1. All the techniques have proven agronomic benefits, but for various reasons they have yet to be widely adopted in SSA and SA. Research has shown that the technologies can increase crop productivity and improve soil environments within 2 to 5 years (Lal, 1987, 2006a,b, 2007b, 2008; Kapkiyai et al., 1999; Sanchez, 2002; Wani et al., 2003; Singh et al., 2005; Smaling and Dixon, 2006; Rockstrom et al., 2007).

The fundamental effects of the techniques in Box 5-1 are to improve soil structure, provide nutrients essential for plant growth, and maintain water availability in the soil.

Improving Soil Structure with Established Practices

A major benefit of the management approaches in Box 5-1 is that they can be used to restore and maintain optimal SOC for healthy soil structure and tilth. SOC provides energy for soil microbes and other fauna and flora;

BOX 5-1
Established Management Practices to Maintain Soil Productivity

To improve soil structure and biological health, reduce erosion, and increase efficiency of water and fertilizer use:

- Mulching with natural materials and plastic.
- Leaving crop residue.
- Application of manure and biosolids.
- Incorporation of cover crops in the rotation cycle.
- Agroforestry.
- Contouring of hedge rows.
- Terracing and engineering structures.
- Precision farming.
- Conservation tillage and nontilling.
- Controlled grazing.
- Improved pasture species.
- Controlled use of irrigation.
- Land-use planning and land-tenure reform.

To improve soil nutrient budget:

- Integrated nutrient management.
- Biological nitrogen fixation.
- Judicious use of chemical fertilizers.

enables the soil to hold water and nutrients; increases fertilizer-use efficiency by decreasing losses through erosion, volatilization, and leaching; and ultimately improves crop yield. The critical minimal SOC for the productivity of most soils of SSA and SA is 1.1 percent. Most agricultural soils of SSA and SA are severely depleted and have lost 75 to 85 percent of their original SOC pool. The concentration in degraded and desertified agricultural soils in SSA and SA is often as low as about 0.1 to 0.2 percent.

SOC is highly correlated with productivity. Field experiments in SA have shown that the yield of mustard grain increased by 360 kg/ha for each ton of increase in the SOC pool in the surface soil layer (the top 15 cm) (Shankar et al., 2002). In central India, adoption of management practices to increase SOC in Vertisols increased crop yield from 1.0 t/ha per year to 4.7 t/ha per year (Wani et al., 2003).

In Kenya, an 18-year study showed that maize and bean yields were increased from 1.4 t/ha per year to 6.0 t/ha per year when stover was returned to the soil as mulch, and fertilizer and manure were applied to increase the SOC pool from 23.6 t/ha to 28.7 t/ha in the surface layer (Kapkiyai et al., 1999). One estimate suggests that increasing the SOC pool in the agricultural soils of SSA and SA by 1 t/ha per year would increase total annual food grain production in SSA by $4.6 \pm 1.6 \times 10^6$ t and in SA by $18.6 \pm 7.1 \times 10^6$ t (Lal, 2006a,b).

As noted earlier, management practices that rebuild SOC have not been widely applied throughout SSA and SA. Weak government institutions and extension, inadequate infrastructure, and resource-poor agricultural systems are barriers to the adoption of such practices. However, growing interest in carbon sequestration projects (Box 5-2) might provide an opportunity to improve SOC dramatically while increasing farmers' income.

Improving the Soil Nutrient Budget with Established Practices

An important limiting factor in soils of SSA and SA is fertilization. Rice, wheat, and maize—the three major staple food crops—can require as much as about 100-200 kg of nitrogen-based fertilizer per hectare to produce optimal yields under ideal moisture and temperature conditions. SSA and SA farmers typically are unable to afford such high rates of nitrogen fertilizer, and crop yields therefore are chronically low.

Extractive farming practices are unsustainable, but adoption of management practices listed in Box 5-1 can help to create a positive nutrient balance in the soil. Integrated nutrient management techniques consist of a combination of organic amendments, such as the use of manure and compost, and the judicious use of inorganic fertilizers (Vanlauwe and Giller, 2006). Those practices have to be implemented alongside those that build soil structure and carbon content (Lal, 1987, 2006a,b, 2007b, 2008; Kapkiyai et al., 1999; Sanchez, 2002; Wani et al., 2003; Singh et al., 2005; Smaling and Dixon, 2006; Rockstrom et al., 2007).

As noted earlier, biofertilization accounts for about 65 percent of the nitrogen supply of crops worldwide, primarily via Rhizobiaceae-legume symbiosis (Lugtenberg et al., 2002). Although background concentrations of nitrogen fixation by free-living or endophytic bacteria are probably low (about 5 to 10 kg/ha), the bacteria produce bioavailable nitrogen at the root interface. The standard fertilization method of soil amendments is inefficient: only 40 to 60 percent of the nitrogen applied is taken up by plants, because it is lost through leaching or immobilized by soil microbes. Encouraging the growth of beneficial organisms in legume crop systems reduces the need for fertilizer.

BOX 5-2
Carbon Sequestration: A Possible Opportunity for Resource-Limited Farmers

Carbon sequestered in soils can be traded as a commodity in accord with the Clean Development Mechanism of the Kyoto Treaty, the BioCarbon Fund of the World Bank, the Chicago Climate Exchange, the European Climate Exchange, and national or domestic industry (Schlamadinger and Marland, 1998; Tucker, 2001; Diakoulaki et al., 2007). Although there are only a few projects to date in SSA and SA, carbon trading has the potential to bring a new income stream to resource-poor farmers (Kandlikar, 1996; Persson et al., 2006). Trading carbon credits implies payments to farmers of SSA and SA for environmental services through international industry and private and public sectors. With the adoption of the soil and crop management practices listed in Box 5-1, atmospheric carbon dioxide can be sequestered in agricultural soils.

The rate of increase in soil organic carbon (SOC) after conversion to restorative land use follows a sigmoid curve and attains a maximum 5 to 20 years after adoption. Sequestration of carbon in agricultural soils worldwide has the potential to sequester 0.4 to 1.2 billion tons of carbon per year, or about 5 to 15 percent of global fossil fuel emission of carbon (Lal, 2004). Control of desertification and restoration of degraded soils have the potential to sequester an additional 0.9 to 1.9 billion tons per year (Lal, 2001). SOC sequestration in improved agricultural and restored ecosystems in SSA and SA ranges from 100 to 1,000 kg of carbon per hectare per year (Lal, 2000). Higher rates of SOC sequestration are observed in humid climates and in fine-textured soils, and lower rates in dry climates and in coarse-textured soils.

Projects to sequester carbon in soils receive qualification to be used by world markets through independent validators. Involvement of diverse stakeholders in trading carbon credits has the potential to promote industry's interest in this strategy (Johnson and Heinen, 2004) and to encourage development of a relevant climate policy for the region (Fouquet, 2003).

Soil-Water Conservation with Established Practices

Soil and water are closely linked in agricultural systems. Conserving water in the root zone and enhancing the efficiency of its use require that soil structure and quality be improved (Rockstrom et al., 2007). At the same time, the conservation of soil requires that it be protected from erosion by water and wind. The management practices listed in Box 5-1 can address both goals.

In arid and semi-arid regions with low vegetation cover and crusted or compacted soils of low infiltration capacity, water runoff is high, especially in the monsoonal climate of SA, where rainfall is concentrated over short periods of 100 hours or 25 consecutive days (Agarwal, 2000; Biswas, 2001; Swaminathan, 2001). Runoff is a source of contamination and pollution of surface water and groundwater, and the leaching of chemicals from agricultural lands, especially in the intensively farmed areas of the Indo-Gangetic (IG) Basin, is a severe problem (Pachauri and Sridharan, 1999). Improving soil structure is the key to improving water infiltration into the soil. The maintenance and enhancement of soil organic matter, the use of biosolids or mulch, and conservation and no-till techniques are important strategies for improving soil structure. Mulching with biomass or plastic is also effective in reducing water losses by evaporation.

Agroforestry, which is practiced to some degree in SSA and SA, has been shown to improve soil quality. However, trees growing in farmers' fields may compete with crops, and there has been little success in adoption of such systems (Rhoades, 1997; Buresh and Tian, 1998). Recent research in the Sahel suggests that native shrubs are a previously unrecognized alternative that potentially can be used to enhance the fertility and quality of soils without such competition (Kizito et al., 2007). *Piliostigma reticulatum* and *Guiera senegalensis* play multiple roles in improving soil quality—such as providing carbon to the soil (Lufafa et al., 2008), increasing nutrient availability in soil beneath and near the canopy (Dossa, 2007), and moving subsoil water to the surface (Caldwell et al., 1998; Kizito et al., 2009)—and have been shown experimentally to increase yields in peanut and millet by more than 50 percent (Dossa, 2007). Developing woody species companion plants has great potential throughout semi-arid SSA and SA to restore degraded landscapes, buffer desert encroachment, and increase crop productivity. However, alternatives for fuel are needed because these shrubs are cut and burned each year, and this constitutes a loss of organic inputs that the impoverished soils need.

The efficient use of water will be critical in the future, not only because of its increasing scarcity (as described in Chapter 4) but because of its potential to bring salts into the soil that inhibit water uptake by crops and damage the physical structure of the soil. In parts of northwestern India, the problem of soil salinity was once associated mainly with a high groundwater table (waterlogging) that brought salt into the root zone through capillary action. More recently, overexploitation of groundwater has led to a decline in water tables, so farmers are forced to use poor-quality saline groundwater for irrigation that has led to high-sodium conditions that destroy the soil (Datta and De Jong, 2002).

An important technology, which is gaining momentum in the IG Basin of SA and elsewhere, is the conversion of flooded rice paddies to aerobic rice. The latter, with specific varieties that can be grown as upland culture similar to wheat or corn, can save the scarce water resources and greatly improve water-use efficiency. Effective weed control measures are important for successful adoption of aerobic rice, but adoption of this technology would be directly relevant to the entire IG Basin and the 12.5 million hectares of area now under rice-wheat culture.

Soil conservation and desertification control, which have high priority in SSA and SA, also can be effectively controlled by practices outlined in Box 5-1, including no-till or low-till farming with retention of crop residue mulch and incorporation of cover crops in the rotation cycle. To transition into no-till farming, appropriate seeding equipment and herbicides need to be available and affordable. The effectiveness of no-till farming can be enhanced by integrating it with agroforestry, establishing contour hedge rows of perennial grasses or shrubs, establishing engineering techniques, and using complex crop rotations. Those measures improve ecosystem services of soil resources and increase crop yields.

Vertisols can be effectively managed through adoption of the conservation-effective technology described above. The use of soil conditioners, such as mulch and biosolids, will result in improved soil structure and productivity. Zeolites and related materials, described in the next section, also have specific potential for improving Vertisols.

NOVEL TECHNOLOGIES TO IMPROVE SOIL PRODUCTIVITY

The practices described in the preceding sections are considered established because their use has been studied extensively and their contributions to increased crop yields have been documented through research. However, understanding which combinations of practices work best in different environmental and social circumstances requires additional study and planning. Because that has not been done for most of SSA and SA, it presents an important opportunity and an unmet need for agricultural development.

The increasing demand for food and changing land and water conditions have prompted scientists to search for new tools to build soil structure, maximize the efficient use of water, and provide essential nitrogen and phosphorus to crops. Advances in plant, microbial, and computational biology; materials science; electronics; and optical sensing may provide new tools to improve soil productivity. Several technologies that are emerging from those fields of science are described below.

Remote Sensing of Plant Physiology for Nutrient Management and Soil Quality

More effective use of remote sensing technologies could enable farmers to better manage inputs to increase crop yields, decrease input costs, and reduce the potential for adverse environmental effects. If farmers could have access to remotely measured plant health and soil conditions—such as water content, acidity, aeration, and the availability of nutrients—they could take appropriate steps to address soil quality before adverse effects occur. The low yields of cereal crops in SSA (about 1,000 kg/ha) could potentially be quadrupled by using sub-surface drip irrigation (mentioned in Chapter 4) and technology to manage fertilizer and nutrients.

Remote sensing technology for nutrient management was initially based on the Normalized Difference Vegetative Index, which predicts plant cover (Stone et al., 1996). It was later used to document extensive variability between plants at distances 30 cm or less in production fields (Raun et al., 1998; 2001). The present technology is based on optical sensors with high spatial resolution that have the ability to predict yield potential midway through the growing season. It permits calculations of fertilizer rates based on projected nitrogen removal, and it permits adjustment of fertilizer rates as a result of conversion of organic to inorganic nitrogen (Johnson and Raun, 2003). Considering the extremely low rates of nitrogen application in SSA, improved nitrogen fertilizer practices, such as fertigation with drip irrigation, can enhance nutrient-use efficiency and substantially increase crop yields. Spectral data on plants and soils could be measured remotely and the information sent to farmers on cellular phones or other communication devices. Alternatively, a simple low-cost handheld "optical pocket sensor" and institutional support to deliver the data and education about management practices to farmers in SSA and SA could be developed. As discussed in Chapter 2, the use of hyperspectral imaging can coupled with the development of sentinel species able to emit specific stress signals that are detectable remotely or locally would assist farmers' management practices.

Zeolites and Synthesized Nanomaterials

Zeolites, members of a family of crystalline aluminum silicates that consist of a unique tetrahedral frame within which sit large ions or other molecules, have multiple applications in soil and water conservation (Tokano and Bish, 2005). Natural deposits of zeolites occur throughout the world, but they can also be synthesized and tailored for specific uses.

The utility of zeolites is derived from their unique flexible internal structures that permit the exchange of ions and reversible dehydration (Watanabe et al., 2004). Because they absorb and slowly release water, zeolites can be used as a soil amendment to improve water retention in sandy and low-clay soils and to improve porosity of impermeable soils. They could be used to conserve water in the root zone in conjunction with traditional techniques, such as mulch farming and application of manure (Bhattacharyya et al., 2006; Pal et al., 2006; Oren and Kaya, 2006).

When pretreated with nutrients, zeolites can be used as an agent for the slow release of nitrogen and phosphorus. They can also be used to enhance the availability of micronutrients, such as zinc (Oren and Kaya, 2006). Alternatively, zeolites can be used in soil remediation to absorb metal cations and reduce local concentrations of toxic substances that inhibit plant growth and nitrogen-fixing soil microbes (Pisarovic et al., 2003). The potential diversity and multiple uses of zeolites make them ripe for further research and development. Changing the structure of the molecular framework, the internal cations, and guest molecules can change the characteristics of the zeolite and its effectiveness in a particular application. The dimensionality and size of zeolite pores also define many of its properties.

Advances in nanotechnology suggest that it is possible to engineer zeolites further or develop similar materials with precisely determined properties. One opportunity is to increase the efficiency of fertilizer by developing slow-release delivery molecules that decrease losses to water and air and increase uptake by plants.

A second potential application of nanotechnology is as a soil surface conditioner that enhances soil structural stability, reduces erosion, and dissipates heat. In many of the countries in SSA and SA, heat stress on crops intersects with other abiotic and biotic stresses to reduce yield (Senthil-Kumar et al., 2007). High-soil temperatures exacerbate the stress of drought and point to a possible point of intervention (Mittler, 2006). Use of innovative technology for conserving water in the soil is a promising option to address heat and drought (Kijne, 2001).

In addition, when dry Vertisols are rapidly exposed to water, they release a large amount of heat at the soil surface, which causes slaking of soil aggregates that reduces the ability of water to percolate downward and results in water runoff. Although no current method addresses this problem, it is conceivable that materials could be developed to interrupt the process by improving the biophysical stability of soil aggregates and dissipating the heat emitted during wetting.

A third application of nanomaterials is to improve the quality of irrigation water. Zeolites have been used in some parts of the world to remove some contaminants from water, but nanoparticle filters of ceramics, carbon, and zinc oxides that effectively remove contaminants—including viruses, bacteria, lead, arsenic, uranium, and pesticides—are now being produced. Inexpensive applications are needed to remove those contaminants and others, such as sodium and salts, from irrigation water. Further development of this technology has the potential to reduce a major health burden and improve soils in rural communities in SSA and SA.

The application of nanomaterials and zeolites, particularly the synthetic types, on an entire farm is prohibitive for resource-poor farmers of SSA and SA, so finding ways to bring the cost down would be essential. However, at their current price, they would be appropriate for specific niches, such as in screenhouses and greenhouses for production of vegetables or horticultural crops to supply large urban centers.

New Cultivars, Plant Breeding, and Biotechnology

The productivity associated with soil, water, and nutrients depends in part on the requirements of the crops they support. The tools of modern plant breeding and biotechnology, described in greater detail in Chapter 3, offer the hope that crops can be developed to better tolerate specific soil-related constraints. Genes that provide some degree of tolerance of cold, drought, salinity, aluminum and manganese toxicity, anaerobiosis, and low nutrient conditions are being widely investigated (Fageria and Balizar, 2005; Chinnusamy et al., 2006; Eicher et al., 2006; Umezawa et al., 2006; Sunkar et al., 2007).

Because drought is a prevailing concern, improving the water-use efficiency of crops (biomass produced per unit of water transpired) is of particular interest. Breeding for early flowering and developing crops that can be planted at a higher density to minimize soil-water evaporation are two strategies to cope with water deficits. Sowing such crops as sorghum and millet in clumps can increase water-use efficiency and improve yields (Bandaru et al., 2006). Developing new varieties of aerobic rice to shift the rice-wheat-based cropping systems of the IG Basin away from flooded rice paddies would save massive amounts of groundwater and improve soil, although new ways to control weeds would be needed (Peng et al., 2006).

Two additional opportunities at the interface of soil and plants are discussed below.

Development of Better Roots

Current research suggests that it is possible to optimize root structure for various purposes, including increased carbon sequestration, improved grain yields, and better water and nutrient uptake. High-resolution root expression mapping (Birnbaum et al., 2003, 2005; Brady et al., 2007) and root architecture imaging and analysis have potential to enhance or select for desirable root traits, such as rapid and early shallow root emergence, diffuse and extensive root architecture and root hairs, and long tap roots (Philip Benfey, Duke University, presentation to committee, October 15, 2007). It may be possible to develop improved cultivars with a favorable root:shoot ratio and improved harvest index, which favors both grain and biomass production.

Development of Transgenic Nitrogen Fixation in Non-legumes

As noted earlier, biofertilization accounts for about 65 percent of the nitrogen supply of crops worldwide, primarily through Rhizobiaceae-legume symbiosis, in which *Rhizobium* bacteria fix atmospheric nitrogen and deliver it to plants via nodules on roots (Lugtenberg et al., 2002).

Extending that relationship to non-legume crops would be a major step forward in plant science and would be transformative for farmers in SSA and SA.

There are two potential approaches to engineering nitrogen fixation in non-legume plants. The first involves altering the plants to enable infection by rhizobia, which results in nitrogen-fixing nodules (Jones et al., 2007). Accomplishing that would require a nearly complete understanding of the *Rhizobium*-legume symbiosis—a complex process of signaling between the plant and bacterium partners at every stage of interaction from attraction and attachment to invasion and colonization. Dozens of bacterial genes would be required to develop non-legume *Rhizobium* nodulating crops, and this would entail mimicking millions of years of evolution (Eric Triplett, University of Florida, presentation to committee, October 15, 2007).

An alternative approach is to transform plants with nitrogen-fixation (nif) genes; this does not require a symbiotic relationship with a microorganism. Establishing N_2-fixation in cereals and other non-legumes would require a whole complex biochemistry to support active nitrogenase, including oxygen protection. Three nitrogenases are well known, and some bacteria have all three. It may be possible to express the bacterial KpnifH gene in plant chloroplasts (Cheng et al., 2005). Alternatively, it could be transferred to the mitochondria (Frazzon et al., 2007). Overall, this procedure could be difficult in that at least 10 genes would have to be inserted into plants to transform nif genes into organelles (mitochondria or chloroplasts), but it might be possible if approached in an organized way (Eric Triplett, University of Florida, presentation to committee, October 15, 2007). Possible approaches could be direct transformation of organelles and the nuclear transformation of genes that possess the appropriate upstream target sequence to ensure organelle localization of the resulting protein (Remacle et al., 2006; Liu et al., 2007).

There may be pathways to fixing nitrogen other than those most familiar to the scientific community. Ortwin Meyer at the Universität Bayreuth found that *Streptomyces thermoautotrophicus* isolated from a burning charcoal pile could fix nitrogen (Gadkari et al., 1992). The organism grows aerobically at 65°C with N_2 as a sole nitrogen source and CO or CO_2 + H_2 as a sole carbon source, and it contains no genes with homology to traditional nif genes (Ribbe et al., 1997). There has been no follow-up of this work for 10 years, but the results suggest that simpler nitrogen-fixing systems that exist in nature could be used by plants (Eric Triplett, University of Florida, presentation to committee, October 15, 2007).

Potential concerns about transgenic plants and microbes include control over insertion sites for introduced DNA sequences as they affect the plant genome and mutagenesis, linkage of favorable genes to genes that could confer resistance to an antibiotic or a herbicide, insertion of undesired bacterial plasmid sequences, and gene flow from transgenic plants to nontransgenic crops or wild plants (Rosellini and Veronesi, 2007). However, with adequate foresight embedded in research plans to consider outcomes for control mechanisms of transgenes, modifications of the genome should be minimal and completely known, so unexpected effects could be avoided (Rosellini and Veronesi, 2007).

MANIPULATING MICROORGANISMS IN THE RHIZOSPHERE

The rhizosphere is a diverse, highly competitive, and complex ecological environment for microorganisms. It encompasses intracellular root tissue, root surfaces, and the surrounding soil that is influenced by the root, including the physical structure of aggregates and pore space and within the intestines of soil animals. On plants or soil surfaces, microbes exist in thin water films and biofilms, occupying a small (1 to 5 percent) portion of the total soil space where environmental conditions are sufficient to support microbial life. The rhizosphere is biologically and chemically different from bulk soil and very more important in determining the effects of plant pathogens, plant growth-promoting microbes, and biogeochemical processes that together strongly affect the yield and quality of crops.

We now know that soil microbes exhibit highly regulated cell-to-cell communication by using signaling compounds to monitor their surroundings and alter their activities, and plants are also involved in these signaling mechanisms. Knowledge of quorum sensing compounds that induce a wide array of physiological responses in soil bacteria has dramatically advanced (Lithgow et al., 2000; Fray, 2002). In addition, much is now known about the importance of root exudates as sources of nutrients and carbon that promote and sustain organisms. Roots exude ions, free oxygen and water, extracellular enzymes, mucilage, and a wide assortment of primary and secondary metabolites with various functions, most of them unknown (Bertin et al., 2003; Uren, 2007). The exudates are low-molecular weight compounds such as amino acids, sugars, organic acids, phenolics, and other secondary metabolites, and they include less diverse high-molecular weight polysaccharides and proteins. Plants expend considerable energy and release a substantial amount of carbon material through exudation, which can include more than 30 percent of the energy captured by photosynthesis (Morgan and Whipps, 2001).

Root exudates and leachates affect microbial communities in two main ways: they provide rich and relatively readily available sources of energy and nutrients to microbes, and growing evidence suggests that chemical signals between plant roots and microbes influence community structure and functions. Those effects create a functionally complex community with a high level of competition for colonization by bacteria and fungi that may be beneficial, neutral, or pathogenic to plants.

In the last 10 years, research has increasingly indicated the feasibility of manipulating soil microorganisms to reduce the need for off-farm inputs and to stimulate plant growth. This section describes novel strategies for plant protection, disease suppression, plant growth stimulation, and enhanced plant nutrition that have exciting potential for agriculture. To develop those strategies as technologies, it is imperative to have a better basic understanding of microbial ecology in major crop systems of SSA and SA.

Phytostimulators

A diverse array of bacteria and some fungi that can produce substances that promote plant growth and increase crop yields have been identified (Chen et al., 1994; Amara and Dahdoh, 1997; Biswas et al., 2000a,b; Hilali et al., 2001; Asghar et al., 2002; Khalid et al., 2004; Larkin, 2008). Many of the substances include phytohormones such as auxin, cytokinins, indole-3-acetic acid, and gibberellin, which are known to play various roles in root and leaf development and plant response to environmental stimuli, such as light and gravity (Hagen, 1990; Steenhoudt and Vanderleyden, 2000; Garcia de Salamone et al., 2001). Some organisms stimulate plant growth in other ways, for example, by enzymatically removing ethylene, a natural byproduct of plant metabolism that retards root growth, from the soil; *Pseudomona*s spp. accomplishes this with 1-aminocyclopropane-1-carboxylate (ACC) deaminase that hydrolyzes the ethylene precursor ACC (Penrose and Glick, 2001).

Why rhizobacteria have evolved to produce phytohormones is not known. It may be that they stimulate greater production of root exudates and increase root development that provides enhanced nutritional benefits and space for microbial colonization, giving microbes with phytostimulating properties an evolutionary advantage. Although the mechanisms of the relationship of rhizobacteria to plants are not yet well understood, the use of rhizosphere microbes that stimulate plant growth presents a promising opportunity to increase crop yields (Broughton et al., 2003). Inoculation of different crop types with various organisms has demonstrated measurable yield or growth increases (Box 5-3).

Commercially available biological inoculation technologies have been developed and are available in industrialized countries, but the scientific underpinning of most of them is limited. Local environmental or agronomic conditions apparently influence the effectiveness of the organisms in increasing crop yields, and this variability needs to be investigated more thoroughly (Larkin, 2008). For example, a strain of *Bradyrhizobium japonicum* that was inoculated on soybeans was found to grow best (and to increase soybean protein content) under cooler soil conditions (Zhang et al., 2002). Although yield increases can be demonstrated, the magnitude varies widely, in part because these microorganisms operate in complex microbial com-

BOX 5-3
Examples of Organisms Inoculated onto Crop Roots That Increased Yield or Growth

- *Azospirillum* on various crops.
- *Rhizobium leguminosarum* on rice and wheat (only in presence of nitrogen fertilizer) (Biwas et al., 2000a).
- *Pseudomonas* on potato (Kloepper et al., 1980).
- *Bacillus* spp., producing various gibberellins, on alder (Gutierrez Munero et al., 2001).
- *Pseudomonas fluorescens* strain on radish (Leeman et al., 1995).
- *Bacillus licheniformis* on *Pinus pinea* L. seedlings (Probanza, 2002).

munities and can themselves have multiple effects on plants; for example *Azospirillum* produces phytohormones but can also fix nitrogen (Okon and Labandera-Gonzalez, 1994).

The prospect of using soil microorganisms to boost crop growth is exciting, but substantial research is required to fully develop phytostimulating microbial systems. Research at all levels, from ecology to proteomics and metabolomics, will be needed to increase the predictability of outcomes.

Disease-Suppressive Soils

Over the last 15 years, there have been surprising discoveries of soil microbial communities that are able to protect plants and suppress plant pathogens. Intensive studies of disease-suppressive soils have led to the development of new methods of analysis and insights into the nature of soilborne disease suppression (Hoitink and Boehm, 1999; Weller et al., 2002; Bolwerk et al., 2005; Benitez et al., 2007; Borneman and Becker, 2007; Gross et al., 2007). Such advances indicate that it is possible to manage soil microbial communities to suppress soilborne diseases and improve crop productivity (Mazzola, 2004).

Generally speaking, there are three ways to manage crop-associated microbial communities actively. The first is to develop disease-suppressive soils through manipulation of carbon inputs. This involves adjusting the types and timing of organic inputs, for example, by using cover crops, animal manures, and composts. Such approaches have been shown to provide site-specific reductions in disease and pest incidence (Abassi et al., 2002; Widmer et al., 2002; Stone et al., 2003; Rotenberg et al., 2005; Cespedes-

Leon et al., 2006; Darby et al., 2006; Larkin, 2008). Some soils in Africa can be induced to cause high seed mortality in the pernicious weed *Striga* by adding organic matter and mineral nitrogen (Ghèhounou et al., 1996; Ransom et al., 2000). The advantage is that primarily locally available resources can be used to maximize soil health in a sustainable way. The disadvantage is that outcomes vary with soil type, and a better understanding of the combinations of soil and locally available amendments that work well together is needed.

The second way involves crop sequencing (Cook, 2006). This has proven effective for the control of "take all" disease in wheat, which is caused by the soilborne fungus *Gaeumannomyces graminis* var. *tritici*. In this case, disease control is mediated by the buildup in the rhizosphere where certain genotypes of *Pseudomonas fluorescens* have the ability to produce the antibiotic 2-4-diacylphloroglucinol that is inhibitory to the pathogen. This shift in the microbial make-up of the soil, and more specifically the wheat rhizosphere, accounts for the well-documented take-all decline whereby the soil changes from microbiologically conducive to take-all to suppressive following one or more outbreaks of disease and with consecutive crops of wheat.

The third approach uses inoculation of disease-suppressive microbes into the soil or the more common method of inoculation with seeds or other planting material. All soils harbor detectable populations of disease-suppressive organisms, but the diversity, relative abundance, and activities of the organisms can vary substantially from site to site. Molecular tools now allow us to identify microbes that are suppressive in situ and to recover them in a directed fashion (Borneman and Becker, 2007). Such an approach has already proved useful in collecting indigenous fungi that acted as effective inoculants to suppress soilborne diseases caused by nematodes (Olatinwo et al., 2006).

Control of *Fusarium* wilt of watermelon with nonpathogenic strains of *F. oxysporum* is explained by induced systemic resistance to the pathogenic strains (Alabouvette et al., 2007). Effective "immunization" of this sort will more broadly require considerable research; in one model, the interaction between maize and *Trichoderma harzianum* strain T22 induces systemic resistance, increases growth responses and yields, and increases nutrient uptake and fertilizer-use efficiency (Harman and Shoresh, 2007).

Analyses of the genetics and genomics of disease-suppressive microbes have led to new methods to isolate the microbes in a directed fashion from any location (Bangera and Thomashow, 1999; McSpadden Gardener et al., 2001; Koumoutsi et al., 2004; Joshi et al., 2006; Paulsen et al., 2005) and to the development of effective and inexpensive inoculants (McSpadden Gardener et al., 2005).

A non-aflatoxigenic strain (AF36) of *Aspergillus flavus* has been identified, and its application to cotton plants early in the growing season effectively displaced strains that produce aflatoxin and consequently led to a large reduction of aflatoxin in bolls (Cotty, 1994). A commercial competitive exclusion product called Afla-guard® has been used successfully to lower aflatoxin concentrations in peanut (Dorner and Lamb, 2006) and will be tested on pistachio in 2008. Non-aflatoxigenic strains have not yet been commercialized for maize, but a recent study applied toxin-producing and non-toxin-producing types of *Aspergillus* to soil in Nigeria, and the non-toxin-producing type spread to maize growing in the field and reduced aflatoxin concentrations by up to 99.8 percent (Bandyopadhyay et al., 2005). This work needs scaling up to test the efficacy of the strains in a larger scale across Nigeria and to develop an Africa-wide aflatoxin biocontrol program.

Considerable progress has been made in identifying specific organisms and managing organic inputs to suppress diseases or to protect plants from infection in developed countries. Given the regionality of crop systems and the disease pressures, such new tools would be valuable for developing inoculants for commercial use in SSA and SA. Little such work has been done on their soils, and research on them is an opportunity to contribute to environmentally sustainable systems that reduce the need for pesticides.

Biological Nitrogen Fixation

The single most important factor in soils in SSA and SA is adequate fertilization. Most farmers cannot afford or do not have access to commercial fertilizers. Despite its dominance in the atmosphere, nitrogen is universally the most limiting crop nutrient because plants cannot transform atmospheric nitrogen into biologically active molecules.

Diazotrophs are bacteria that are able to capture atmospheric nitrogen and transform it into molecules that are usable by plants. Some species live freely in the soil; others are endophytes, living in plant roots and obtaining energy from plants (An et al., 2001). The most well-studied relationship is that of the bacterial species *Rhizobium* with legumes. Although further basic research on this symbiotic relationship may result in a means of providing more nitrogen for agricultural systems, the increases are likely to be incremental. However, the use of legumes in agriculture as sources of nitrogen fertilizer could be expanded with regional applied research.

There has long been interest in developing systems of biological nitrogen fixation for non-legume crops, such as rice, wheat, sorghum, and millet. A wide array of root endophytic bacteria that can fix nitrogen have been identified (Box 5-4). Inoculating maize, sorghum, and wheat with *Azospirillum* has been shown to increase yields by as much as 30 percent,

BOX 5-4
Genera of Root Endophytic Bacteria That Can Fix Nitrogen

Burkholderia, *Gluconacetobacter*, *Herbaspirillum*, *Azoarcus*. *Acetobacter*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Beijerinckia*, *Derxia*, *Enterobacter*, *Herbaspirillum*, *Klebsiella*, *Pseudomonas*, *Stenotrophomonas*, and *Zoogloea*.

SOURCES: Barraquio et al., 2000; James et al., 2000; Lodewyckx et al., 2002.

but more research is needed to ascertain whether the yield increases are due to nitrogen fixation or to other mechanisms, such as the production of phytohormones (Dobbelaere et al., 2001). If successful, the technology could dramatically increase grain productivity in SSA and SA while reducing the need for synthetic fertilizer.

Typically, the largest plant response to diazotrophic bacteria has been in degraded soils and water-stressed regions when low or intermediate concentrations of fertilizer were applied (Dobbelacre et al., 2001). That is encouraging for SSA and SA farmers because those are the kinds of soils and conditions they regularly encounter. The most notable example for practical use of biological nitrogen fixation is sugarcane, in which 60 to 70 percent of the nitrogen comes from endophytic bacteria (Boddey et al., 1995). Studies on rice have shown that up to about 30 to 40 percent of the nitrogen uptake can be attributed to three diazotrophic species (Hurek et al., 2002). It should be pointed out that field level measurement of N_2 fixation is difficult to definitively quantify. However, greenhouse studies that utilize the ^{15}N dilution method to provide a full accounting of the N inputs have shown the potential of free-living N-fixing microorganisms to provide nitrogen to plants (Iniguez et al., 2004). That study demonstrated that up to 44 percent of the nitrogen taken up by wheat came from the fixed nitrogen of a bacteria *Klebsiella pneumoniae* 342. Iniguez and colleagues (2004) showed that (1) total nitrogen uptake was significantly greater than uninoculated or inoculated nifH *K. pneumoniae* mutant (genetically identical except unable to fix nitrogen) controls; (2) nitrogenase activity of *K. pneumoniae* 342 was occurring in wheat roots and not in the presence of the mutant strain; (3) fixed nitrogen was found in chlorophyll; and (4) Koch's postulates were fulfilled (inoculum strain 342 was recovered from the host plant).

To develop the technology, much more needs to be known about which physiological plant responses to endophytic diazotrophs will enhance nitrogen fixation. The role of phytohormones, some of which encourage the development of root nodules where diazotrophic bacteria colonize, is not yet understood (Vessey, 2003). The energy and nutritional signaling requirements needed to stimulate nitrogen-fixing bacteria must also be elucidated. It may be that considerably more carbon (as an energy source) is needed than is currently produced in modern non-legume crop rhizospheres. For example, legumes can fix agronomically significant levels of nitrogen but do so by using over 30 percent of the photosynthesate produced by the host plant.

More work is also needed on the role of plant defenses in regulating endophytic colonization. Most of the work done to date has been in *Arabidopsis* but not in crop plants (Iniguez et al., 2005). Research is needed on the mechanisms of endophytic colonization relative to root characteristics and soil conditions that would enable beneficial bacteria to thrive and elude plant defenses. It is worth noting that modern crop breeding programs have typically developed crops under high nitrogen levels that emphasize above-ground yield without considering the rhizosphere. It may well be that those programs selected against rhizospheres that promote nitrogen-fixing microorganisms and against colonization of beneficial endophytic bacteria. Thus, plant scientists and microbiologists need to work in concert to develop truly effective rhizospheres of non-legume crop systems that can encourage nitrogen-fixing bacteria to optimize yields.

Microbial Enhancement of Phosphorus Uptake by Crops

In addition to nitrogen, phosphorus is an important nutrient for SSA and SA farmers. Many soils in the region have inherently low phosphorus concentrations that are reduced by crop harvesting and soil erosion (Tiessen, 2005). Unlike nitrogen deficiency that can potentially be corrected by biological fixation, phosphorus deficiencies must be corrected both by adding phosphorus sources to soils and by increasing the efficiency of phosphorus uptake by plants.

It should be noted that fertilizer is inefficient in delivering bioavailable phosphorus to plants, because it becomes rapidly "fixed" in plant-unavailable soil fractions (Sanyal and De Datta, 1991). The strong chemical reactivity of phosphorus results in very low plant recovery, typically 10 to 20 percent of the phosphorus applied to soils (McLaughlin et al., 1988; Holford, 1997). Moreover, the global annual consumption of phosphorus-based fertilizers exceeds 30 million tonnes, and it is expected that the world's known reserves of high-quality rock phosphate will be consumed within the next 80 years (Isherwood, 2000; IFIA, 2001).

Some bacteria (*Pseudomonas* spp. and *Bacillus* spp.) and fungi (most notably mycorrhizae but also *Aspergillus* and *Penicillium*) have been shown to enhance the availability of phosphorus to plants naturally through biochemical mechanisms such as solubilizing inorganic phosphorus by chelation or acidification (by production of organic acids, carbonic acid, or H+), mineralizing organic phosphorus by producing extracellular phosphatases or phytases, and increasing root growth or root-hair development by producing phytohormones (Jakobsen et al., 2005).

Many studies have improved phosphorus nutrition and yield in a wide variety of crops by inoculating phosphorus-enhancing microorganism (Whitelaw, 2000; Leggettt et al., 2001; Jakobsen et al., 2005). Besides the expected response to phosphorus-deficient soils, studies have shown improvement with phosphorus-enhancing microorganisms in the presence of rock phosphate (Barea et al., 2002). The latter is important for SSA and SA farms, where indigenous sources of rock phosphate could be used directly without manufacturing commercial phosphorus fertilizer. In addition, in high-phosphorus-fixing soils, rock phosphate can have longer residual effects that last several years on acid soils (Sahrawat et al., 2001).

Endomycorrhizae form arbuscular structures in close association with host cells of almost all annual crops. Ectomycorrhizae form associations with many woody plants, and their interactions with timber species are well studied. A plant provides carbohydrates to a fungus; in turn, the fungus develops an extensive hyphal network that can transport phosphorus and other nutrients to the plant (Smith and Read, 1997). That greatly increases the volume of soil that the plant can explore; in addition, mycorrhizae can mobilize phosphorus by excreting phosphatases and organic acids (Whitelaw, 2000). It should also be noted that co-inoculation of plants with mycorrhizal fungi and phosphate-solubilizing or -mineralizing microorganisms (so-called helper microorganisms—many of the same ones mentioned above) can further increase the plant response to phosphorus and therefore the effectiveness of mycorrhizal fungi (see review by Jakobsen et al., 2005). It is relevant to this nutrient exchange that the mycorrhizal plants tend to resist drought and infection by soilborne pathogens.

Direct exploitation of microbial processes to increase phosphorus uptake by crops has had little success so far, but if more information about the relationship between crops and these organisms is uncovered, the basis of a future technology to dramatically increase fertilizer efficiency may be recognized (Jakobson et al., 2005). Ultimately, the development of effective, low-cost, and simple inoculation strategies could help farmers to overcome phosphorus shortages in their soils. Agriculture might be transformed if we can combine knowledge of the microbial ecology of phosphorus-enhancing microorganisms with plant breeding or insertion of transgenes to develop roots with architectures, exudates, and signaling that optimize root and microbial responses to increase phosphorus uptake by crops.

Microbe-Enhanced Drought Tolerance

Bacterial species that can enhance the ability of plants to withstand water stress by increasing seedling root elongation—which promotes stand establishment and various other crop physiological responses, such as reductions in cell elasticity and osmotic potential and a rise in root cell water fractions—have been isolated (Alvarez et al., 1996; Creus et al., 1998). Co-inoculation of autochthonous arbuscular mycorrhizae and *Bacillus thuringiensis* has been shown to increase plant resistance to water stress because it reduces the amount of water required to produce shoot biomass (Marulanda et al., 2007). The findings suggest that the root microbial community could be manipulated to improve the drought tolerance of plants, but research in this field is in its infancy.

Various experiments with sorghum inoculated with *Azospirillum*—which resulted in a larger root system, increased leaf water potential, lowered canopy temperatures, and increased stomatal conductance and transpiration—also suggest the potential of the approach (Sarig et al., 1988; Fallik et al., 1994). Inoculated sorghum also had 15 percent greater total water extraction from soil than the noninoculated controls and obtained water from deeper soil layers than the controls. Similarly, Hamaoui et al. (2001) showed that inoculation of sorghum with *Azospirillum brasilense* significantly reduced the adverse effects of saline irrigation water because of stimulation of root development, delayed leaf senescence, and improved water uptake in saline soils (Sarig et al., 1990).

Microbial-induced drought resistance is a potentially important technology for SSA and SA farmers because large parts of the target region are semi-arid and crops regularly experience drought stress. However, research on the interactions of microbes with plants and the relationship of the interactions to drought resistance is in its infancy, and there is virtually no such research in SSA and SA.

Research Considerations in Manipulating Microorganisms in the Rhizosphere

Although a general understanding of root exudates and their overall importance relative to plant nutrition, pathogen responses, and beneficial microbial interactions has been established, the role and magnitude of chemical signaling of root to root, root to microbe or invertebrate, and microbe or invertebrate to root are just beginning to be understood (Uren, 2007). At this stage, what is done about these interactions is provocative and offers exciting potential for their future use in agricultural technologies.

Box 5-5 shows some of the fundamental information and resources

BOX 5-5
Major Research and Technology Needs for Manipulating Microbes in the Rhizosphere

- Microbial genome sequencing and functional genomics of plant-associated microbes that are important in the agriculture of sub-Saharan Africa and South Asia.
- Discovery of the genes that control microbial-plant signaling, biofilm formation, interspecies interactions, production of plant-growth-promoting substances, nutrient uptake enhancement, plant protection, and the structures of multi-species microbial communities.
- Basic multidisciplinary research on microbial ecology of microbial-plant interactions that optimize growth of crops.

needed to bring the manipulation of the rhizosphere to reality. Given the diversity and complexity of microbial communities and, until recently, the lack of tools to study them, the task requires a major interdisciplinary initiative. In that regard, it is worth pointing out that there is currently a distinct lack of interaction between microbiologists and plant scientists, and this has held back the field of rhizosphere science. The emphasis of plant sciences has been on breeding and developing plants for optimal yield and resistance to disease, pests, and environmental stresses. There has been little research on developing plants to promote interactions with beneficial microbes or to optimize the crop rhizosphere. To benefit farmers in SSA and SA, research should focus on local crops and local soil communities. Teams of soil and rhizosphere microbial ecologists, geneticists, molecular biologists, plant physiologists, plant breeders, agronomists, and anthropologists need to be assembled in an integrative project to conduct multidisciplinary research on the major crops of the regions.

As research proceeds, it will be important to put it into a regional and farm-level crop system context. To emphasize that, we present one example related to manipulation of biocontrol microbes. Larkin (2008) compared various biostimulants and known microbial control agents of potato diseases. All had measurable effects on soil microbial properties in the field, but none reduced disease in continuous potato plots; rather, effective controls occurred only in particular crop rotations. The results indicate that some rotations are better able to support the added beneficial organisms and amendments that enable more effective biocontrol of disease. Establishment and persistence of microbial inoculants, soil amendments, and engineered rhizospheres probably depend on many soil and climate factors.

That emphasizes the need for early testing of promising biological technologies at the farm or crop system level.

In addition to biological interactions and adaptation to local conditions, research for SSA and SA needs to take into account regional cultural and socioeconomic considerations. Over the last 50 years, the developing world has been littered with agricultural technologies that might have been agronomically superior under controlled research conditions but were unacceptable for subsistence farmers because of the local culture, lack of technical support, or management scales and markets of rural economies.

To attain practical outcomes for microbial technology, it seems that the emphasis should be placed on approaches that depend on manipulating native populations. For example, there is a body of research on the feasibility of using organic amendments to create soil conditions and microbial responses to naturally suppress soilborne diseases. Similarly, this is an appropriate technology consideration that makes breeding or insertion of transgenic genes attractive. Such an approach is desirable because attributes such as optimized roots for efficient water and nutrient uptake or stimulation of beneficial microbial gene expression would require only the introduction of new cultivars into existing systems with minimal technical support and reduce the need for external input.

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6

Technologies for Improving Animal Health and Production

ROLES OF ANIMALS IN SOCIETY

The importance of livestock in the economies of developing countries can be measured in terms of human health, as a contribution to gross domestic product, as a pathway out of poverty, and as a buffer against unforeseen disasters often faced by small-holder farmers. In addition to the direct financial benefits they provide, animals play many roles for small-holder farmers: they provide food, manure (as a soil amendment or fuel), traction, a savings mechanism, and social status (Randolph et al., 2007). When household members on crop-livestock farms in western Kenya were asked why their incomes had risen above the rural Kenyan poverty line (US$0.53/day), the top three reasons given were off-farm employment of a family member, production of cash crops, and livestock acquisition (Kristjanson et al., 2004). More than half the farmers who remained poor cited funeral expenses that typically involved the slaughter of livestock. Animals are perceived by farmers to be a useful hedge against drought, pests, and health problems. However, many farmers appear unwilling to sell animals even in stressful times, so economists debate whether they truly serve as a financial buffer (Dercon, 1998; Fafchamps et al., 1998).

Animal protein plays an important role in human nutrition in sub-Saharan Africa (SSA) and South Asia (SA). Small amounts of meat or milk added to typical diets of Kenyan primary-school children increased their performance in school, improved results on cognitive-ability tests and activity levels, and reduced the incidence of stunted growth (Neumann et al., 2003).

This chapter discusses the farming systems in which animals are produced in SSA and SA and describes technologies for improving the health nutrition of food animals, the genetic foundation of food animal herds, and the protection of animals against disease.

ANIMAL PRODUCTION SYSTEMS

Animals are raised in several production systems in SSA and SA, each of which is constrained in different ways. Interventions to improve livestock (and the welfare of farmers) in each system must take into account the nature of its relationship to sources of animal feed or forage, the availability of food-processing facilities, and access to the intermediary or direct consumer markets for meat and dairy products. System modeling may be one way to envision the effects of interventions, not only on improving animal productivity but also on increasing income, reducing poverty, and preventing environmental damage associated with livestock production (Box 6-1) (Charles Nicholson, Cornell University, presentation to committee, October 15, 2007).

Of the 687 million poor who own livestock, 20 percent produce them in extensive systems (see Box 6-2), 57 percent live on mixed crop-livestock farms, and 23 percent are landless, peri-urban producers (Devendra et al., 2005). In Asia, more than 95 percent of the ruminants and many swine and poultry are raised on small crop-livestock farms. Those operations typically are land-constrained—often less than a hectare—so feed availability is likely to pose a problem. Well-managed crop-livestock farms can take advantage of the value added by livestock by using manure to prevent soil-nutrient depletion. As the demand for meat increases, mixed crop-livestock farms are intensifying and increasing the risks of environmental problems associated with agriculture.

The landless livestock systems, mostly in peri-urban areas, typically include swine, poultry, and ruminants. Because very little land is involved, less than 10 percent of the feed resources are produced where the animals are housed (Seré and Steinfeld, 1996). The peri-urban farmers, especially those raising poultry and swine, rely more on concentrates for feeds and are likely to be adversely affected when grain prices increase, for example, in response to international demand for biofuels. The use of byproducts from processing human food could potentially provide valuable feed resources for these farmers.

There is a need for improved food processing capabilities (see Box 6-3) that would help small farmers to have better access to markets (Delgado, 2005). The accumulation of nutrients (animal waste) often leads to contamination of water supplies and health issues related to animal density and proximity to people; the use of animal waste for biogas production would

BOX 6-1
Environmental Effects of Livestock Production

A 400-page review of livestock production in the developing and developed worlds describes its associated environmental effects, including land degradation, contributions to greenhouse gas production (carbon dioxide, CO_2; methane, CH_4; and nitrogen dioxide, NO_2), depletion and contamination of water supplies, spread of zoonotic diseases through poor animal and manure management, and reduction in biodiversity (Steinfeld et al., 2006). The extent to which livestock contribute to environmental problems depends on the production system, but a comprehensive evaluation of livestock production systems is needed, including marketing, land tenure arrangements, and germane policies to minimize adverse effects. Scenario testing of alternative strategies will require robust models to evaluate the effects of changes in management, marketing, and policy.

For example, it is estimated that livestock contribute about 9 percent to total anthropogenic CO_2 production and 35 to 40 percent of CH_4 emission, including those from enteric fermentation, manure management, and livestock-associated fertilizer application, tillage, feed processing, and transportation (Steinfeld et al., 2006). Effective manure management and use of biogas may reduce emissions by as much as 75 percent in warm climates. However, manure gas emissions are affected by temperature, moisture, animal diet, physiological status of the animal, and storage methods, so current predictions of emissions all have huge coefficients of variation. Both data and appropriate models are needed to predict which parts of the system are amenable to useful manipulation to decrease greenhouse gas emissions.

be an area worth further exploration. In many cases, the term *peri-urban* is essentially used to describe agriculture in the slums, where poor sanitation, disease, and non-potable water already pose serious problems. Peri-urban swine and poultry systems are already a major source of food for city dwellers, but because of the hefty initial capital requirements and environmental considerations they are unlikely to become pathways out of poverty.

IMPROVING ANIMAL NUTRITION

Many of the animals raised by small farmers in SSA and SA suffer from poor nutrition. As a result, they grow slowly, produce small amounts of milk or meat, have low reproductive rates, and are vulnerable to disease, even from birth. This section discusses some current and emerging opportunities to decrease mortality in young livestock and improve the nutrition of farm animals.

BOX 6-2
Animal Production in Extensive Rangeland Systems

In many semi-arid and arid areas in Africa where rainfall is insufficient for reliable cereal harvests, animals contribute more than 80 percent of the agricultural GDP (Winrock International, 1992). The extensive livestock systems in the dry lands produce about 10 percent of the global meat supply, but the areas where these systems dominate make up about one-fourth of the world's land mass, and low rainfall makes crop production impossible or very risky. Livestock production is the primary food- and income-generating activity for the people in those areas. When market values were assigned to home-consumed goods in a study of the Gabra of northern Kenya, 76 percent of the total was from home-consumed milk and meat, and 21 percent was from goods purchased with revenue from livestock sales, so only 3 percent of household consumption was from non-livestock sources (McPeak, 2003).

More people in the world depend on sheep and goats for their survival than any other species; these small ruminants therefore play an important role in the sustainability of humans. Many parts of SSA either do not have the grain-based diets for commercial production of monogastrics such as chickens and pigs or may have religious practices that are not conducive to the development of a swine industry. Also, the lack of disease surveillance, particularly in poor rural areas, makes it difficult to raise swine and poultry in the countries most affected by disease. Consequently, increasing the knowledge of the genetics, physiology, breeding, nutrition, and diseases of small ruminants and the social structures of pastoralism is of paramount importance. It can be argued that the populations of pastoralists and herders are small and that development resources would be better spent elsewhere. That choice would be devastating to the herding populations of Niger, Burkina Faso, Mali, Chad, and Ethiopia, the five

Reducing Preweaning Mortality

A nutritional intervention for decreasing mortality in young livestock would include the use of colostrum for neonates. Colostrum contains high levels of energy and nutritionally important proteins, and neonates depend on the early infusion of nutrients to maintain body temperature because their energy stores are low at birth. More information on neonatal passive immunity is provided later in this chapter.

Improving Grass Forage

Many forage-fed animals in the tropics grow slowly and produce small amounts of milk because their diets are inadequate in protein, energy, and micronutrients. The types of forage available to the animals are mainly the countries ranked at the bottom of the UN human development report in 2005. Likewise, drier areas of central and southern Asia, where livestock dominate, suffer from extreme poverty.

Dryland livestock production is heavily affected by low and variable rainfall and is thus vulnerable to the effects of climate change. In harsh environments, survival of animals and their owners depends on access to somewhat less marginal areas for part of the year. Changes in land tenure and increases in protected areas have decreased the mobility needed to avert overgrazing and to obtain access to feed reserves during dry seasons. Suboptimal distribution of animals results in localized degradation surrounded by range that remains productive. Post-drought restocking programs often provide families that have lost all their animals with one or two replacements despite data from northern Kenya and southern Ethiopia that show that at least five cattle are needed for self-sufficiency (McPeak, 2003).

Nutritional inadequacy is a severe seasonal constraint in dry areas, but pasture improvement of extensive land systems is extremely difficult. Farmers lack the equipment and improved forage varieties needed for pasture establishment, and free-ranging animals often consume newly planted pastures. Although there is potential to improve livestock productivity in dry areas, many of the most feasible solutions involve integrated applications of current knowledge rather than new technologies. Biophysical and socio-economic models that include policy considerations that influence rangeland productivity could be used to predict effects of fluctuations in herd sizes, rainfall, and land tenure. Early warning systems and drought predictions could benefit herders in extensive systems provided they were mobile enough to access reserve pastures or were willing to sell stock. Efforts of that sort are under way, but more comprehensive data and better modeling techniques are both needed.

C_4 grasses (so named for the metabolic pathway used to fix carbon dioxide). The C_4 grasses that predominate in the tropics are less digestible than temperate C_3 grasses and have low energy and protein content. As the data in Figure 6-1 show, only 45 percent of the 80 tropical feed samples tested met the maintenance requirements for both protein and energy and 30 percent of the samples were inadequate in both (Van Soest, 1994).

Until recently, there was little work on characterization of forage traits that need improvement, and temperate forage still receives far more attention than that grown in the tropics (Spangenberg, 2005; Smith et al., 2007). In general, tropical forage plants have received little attention from plant breeders with a few notable exceptions: alfalfa, which is grown in some tropical highlands; *Brachiaria* spp.; *Pennisetum purpureum* (elephant or Napier grass); and *Panicum maximum* (Guinea, colonial, or Tanganyika grass (Jank et al., 2005).

BOX 6-3
Food Processing and Production

Post-harvest mishandling of animal products results in substantial product losses and health hazards due to foodborne disease, but lack of refrigeration, inadequacy of fly control, and contaminated water supplies make preservation of highly perishable products difficult. Because risk of contracting foodborne disease is higher by as much as 3,000 percent in malnourished populations (Morris and Potter, 1997), appropriate control is particularly important in food-insecure areas. There are opportunities for local improvements in preserving meat, milk, and fish. In developing countries, people rely on drying, salting, and fermentation for food preservation because of capital constraints and lack of electricity, whereas people in developed countries depend more on refrigeration, canning, freezing, dehydration, and fermentation. Traditional fermentation is used widely around the world (Steinkraus, 2002), but there are promising improvements in the use of bacterial inocula that have nutritional benefits or that stimulate production of bacteriocins to reduce microbial contamination. Amino acid profiles and contents of vitamins and protein may be improved through fermentation. Much is known about these technologies, but adaptive research is needed to ensure their effectiveness in low-resource environments. Investment in interdisciplinary adaptive research in African or Asian universities would both provide better methods to preserve animal-source foods and address the pressing need for more people with expertise in food safety. Such research should include the Hazard Analysis and Critical Control Point approach, which focuses on areas where significant improvements can be made.

The collections of germplasm of tropical forage are poorly funded, and loss of current accessions is threatened. The collections include diverse accessions that may be important sources of disease resistance, increase in digestibility, or increase in biomass production. For example, the most recent outbreak of a smut (*Ustilago kamerunensis*) is affecting Napier grass. In much of eastern and southern Africa, farmers rely heavily on Napier grass because it produces copious amounts of reasonably high-quality forage. The smut has the potential to affect the small-holder dairy industry seriously and has already reduced forage yields in much of the Kenyan highlands (Farrell et al., 2002; Mwendia et al., 2007). Research to understand smut biology and to develop resistant strains of Napier grass is important for the rapidly growing dairy industry in the Kenyan highlands.

As noted in Chapter 3, a better understanding of plant chemistry and lignin synthesis could help plant breeding programs to improve the nutritional value of forage because the lignin cross-linkages affect whether

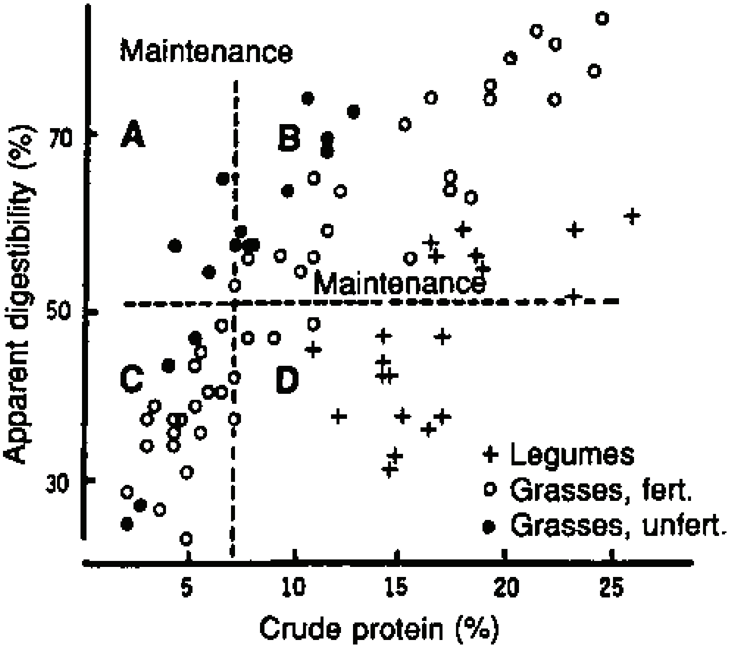

FIGURE 6-1 Digestibility and crude protein content of tropical grasses (fertilized and unfertilized) and legumes and their adequacy in meeting maintenance requirements of ruminants.

NOTE: 52 percent dry matter digestibility and 8 percent crude protein.

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plants are easily digested (Spangenberg, 2005). There may be advantages in attaching work on this problem to the burgeoning international interest in biofuels, such as switchgrass. There is a common interest in understanding how lignin cross-linkages can be broken down, whether in the context of biofuels or with respect to the processes occurring in forage digestion by ruminants (Box 6-4).

Improving Legume Forage

In temperate areas, legumes, especially alfalfa and clover, are high-protein, highly digestible forage that permit cows to sustain milk production as high as 20 kg/day on forage alone. In the tropics, however, many

BOX 6-4
Rumen Function, Fiber Digestion, and Metagenomics

Ruminants will probably be important in livestock strategies to assist the poor (Delgado, 2005), therefore their ability to convert locally available feedstuffs to animal products should be improved. Increasing the efficiency of the ruminal microorganisms that play important roles in fiber digestion and nitrogen metabolism will improve animal productivity. When Hungate (1966) published *The Rumen and Its Microbes*, about 23 bacterial species were thought to play prominent roles in ruminal metabolism; by 1996, the number exceeded 200 (Krause and Russell, 1996). When several discrete ribosomal DNA libraries were analyzed, 341 operational taxonomic units of organisms were identified (Edwards et al., 2004); this indicated that culture-based estimates of ruminal organisms greatly underestimated ruminal diversity. Simple identification of individual species is far less important than understanding the functions of microbial populations and relating them to sequence-based information to draw ecological inferences (Handelsman, 2004).

The recent study of gypsy moth gut microflora that included quorum sensing, the coordination of biological functions among bacteria, and identification of cell signaling mechanisms (Guan et al., 2007) is an example of the type of research needed to improve ruminal fiber digestion and nitrogen metabolism and to reduce methane production. Because the techniques needed for the study of the rumen are similar to those required for the study of other microbial systems—including soils, food fermentation (such as that of yogurt and cheese), and biofuel production—emphasis on various methods for studying microbial ecology would have broad benefits.

Not only is ruminal microbial diversity much greater than early estimates suggested, but the enzyme systems involved in lignocellulosic degradation are much more complex (Huang and Forsberg, 1990; White et al., 1990; Bayer et al., 1998). Each bacterium has many types of enzymes (for example, endoglucanases, exoglucanases, cellobiohydrolases, and xylanases) and many enzymes with overlapping activities. Our knowledge of the enzymes remains incomplete, and novel hydrolases are being discovered (Ferrer et al., 2005). In some cellulolytic anaerobic bacteria (such as *Clostridium thermocellum*, *Ruminococcus albus*, and *Ruminococcus flavefaciens*), the diverse enzymes are organized by scaffolding proteins into cellulosomes in which dockerins permit substrate binding and efficient cellulose degradation (Bayer et al., 2004). Much has been learned in the last 20 years about the functions and organization of cellulosomes and their many enzymes, but this remains a fertile field of inquiry. Recent advances in genomics and proteomics should assist in the research, but the inability to transform and genetically manipulate ruminal microorganisms constrains progress.

promising legume species contain high concentrations of anti-nutritional factors (such as proanthocyanidins, hydrolyzable tannins, alkaloids, and terpenoids) that confer disease resistance on the plants and deter herbivory.

Condensed tannins have both beneficial and deleterious effects on domestic animals (Mueller-Harvey, 2006). The adverse effects of consuming high-tannin forage include lower feed intake, lower protein and dry matter digestibility, inhibition of microbial and mammalian enzymes, reduced live weight gain and milk yield, and systemic effects that are due to absorption of phenolics and are sometimes offset by lower urinary nitrogen loss, greater parasite resistance, and improved efficiency of nutrient use (Mueller-Harvey, 2006). The apparently contradictory research results are due largely to the heterogeneity of tannin structures and to variation in the quantities ingested.

Achieving the goal of developing disease-resistant legumes that provide animals with needed nutrients requires research on tannin chemistry linked to legume breeding programs. Progress has been made in understanding some aspects of tannin synthesis, but the polymerization process that affects tannin chemistry and anti-nutritive effects remains poorly understood (Xie and Dixon, 2005).

EXISTING AND EVOLVING TECHNOLOGIES FOR IMPROVING ANIMAL GERMPLASM

Since the beginning of domestication of animals, substantial progress has been made in improving their characteristics as food and fiber producers by selectively mating individual animals that had advantageous traits (phenotypes). The importance of phenotypic information is sometimes lost in this age of genomics, and it is astonishing to recognize that animal breeders could triple average milk yield of dairy cattle in 50 years without knowing a single gene involved or having any genome sequence information to guide them. They simply needed to know the milk production traits of members of the dairy cattle family and select the right mates to breed.

Although it is possible to practice breeding of that type on a farm or village scale, small-herd owners in SSA and SA are likely to have difficulty in systematically improving the genetic potential of their livestock by using only locally available germplasm. Nor can small-holders apply modern quantitative breeding practices on the basis of the knowledge of genotypic associations with specific traits; information systems to collect phenotypic and genotypic data from populations of the desired species or breeds systematically have not been put into place.

The use of quantitative phenotypic methods to improve breeding requires collecting data on a large number of animals in a family that exhibit

BOX 6-5
Genetic Improvement of Fish for Aquaculture

Fish provide substantial amounts of protein and other frequently deficient nutrients in Asia and parts of Africa. In SSA and SA and globally, aquaculture is growing in economic and nutritional importance. The World Fish Center (2005) recently identified strategies for aquaculture development with representatives of Bangladesh, China, India, Indonesia, Malaysia, Philippines, Sri Lanka, Thailand, and Viet Nam. The use of molecular markers associated with genetic improvement of fish, including disease resistance, has long been recognized as feasible (Austin, 1998), and one can identify a wide array of disease susceptibility in fish populations (Kettunan et al., 2007; Quillet et al., 2007). The development of inbred lines and the use of markers for selection are meeting with success (Gilbey et al., 2006; Zhang et al., 2006).

wide variation in the traits of interest. That kind of effort typically takes place in breeding centers, where resource populations of animals can be developed over a decade or two and individual phenotypes can be collected and recorded to make it possible to identify genetically superior animals (Meuwissen and Goddard, 2000, 2001). Infrastructure is needed to distribute the germplasm to farmers through artificial insemination and embryo transfer techniques.

In industrialized countries, that approach has been used over the last 50 years to develop animals with superior genetics, and it is the model used in developing countries, often successfully (Box 6-5). However, the scientific community is now in a position to bypass many of the heavily resource-dependent approaches used in the industrialized world. Emerging technologies offer potentially practical approaches for more rapidly discovering superior livestock genetics and delivering them to subsistence farmers in SSA and SA.

LEAPFROGGING SELECTIVE BREEDING WITH MOLECULAR SAMPLING: DNA-DERIVED PEDIGREES

There are about 170 million buffalo (Bovidae) in the world, 96 percent of which are in Asia, including 95 million in India alone (Borghese, 2005). The American bison is also included in that estimate. The current status of buffalo production and research has recently been described in detail (Borghese, 2005). The buffalo is a primary source of milk protein and is used for draught and as a supplementary source of meat in parts of Asia. Ten major breeds exist in India, some having been selected and maintained for each of the three functions, which are essential to the farm economy. National programs to improve milk and meat production have been initiated and are being termed the "white" and "red" revolutions, respectively, in keeping with the name of the Green Revolution.

Genetic improvement for production traits and disease resistance in buffalo does not benefit from the availability of the powerful genomic tools recently generated for domestic cattle in the United States, for two main reasons: the areas of the world where buffalo are economically important lack the financial resources for genomic research, and the application of genomic research to identify genetically meritorious individual animals can be applied only within families of animals. There is no such information on *Bubalus bubalis*, the Asian water buffalo, or on any farm animals (such as goats and hair sheep) raised by subsistence farmers in SSA and SA, so the use of well-established quantitative genetic tools is precluded.

However, it may be possible to construct an equivalent dataset from the bottom up with the aid of molecular genetic tools. To implement that approach, a reference genome of the breed of interest would need to be generated with DNA sequencing, and DNA samples and phenotypic data would have to be collected from several thousand animals in geographic regions that have common environmental stresses. Single nucleotide polymorphisms (SNPs) would be generated from the DNA samples by sequencing regions of the genome that have proved to be informative in related species. The database of tag SNPs generated from the sequencing data would be aligned with the reference sequence to build family pedigrees. With pedigrees in hand, traditional quantitative tools could be applied to identify animals of superior genetic merit. The approach requires several lines of research. An inexpensive field kit for preserving DNA in tissue samples (ear snips, buccal swabs, or the equivalent) that does not require refrigeration would have to be developed, as would an effective questionnaire for gathering trait phenotypes. Whole genome sequencing (6X coverage) of *Bubalis Bubalis*, the African buffalo (*Syncerus caffer*), *Bos indicus* cattle, sheep, and at least a few representative milk- and meat-producing breeds of goats and sheep should be included in the sequencing project. Finally, substantial investment in developing informatics algorithms for what is essentially reverse engineering of pedigrees from SNP data would be needed.

With today's sequencing capability, it might take 2 years to generate a reference genome sequence for a species. It might take a year each to develop a DNA tissue-sample preservation kit and a phenotype questionnaire, 3 to 5 years to collect DNA samples and phenotypic data, and a year to build pedigrees and test the hypothesis that animals of high genetic merit can be identified with this approach. All the steps except the last can be conducted in parallel, the overall timeframe of the project to reach proof of concept would be 6 to 10 years.

If the project were successful, its impact would be large. DNA-enabled approaches to building a pedigree would leapfrog existing approaches by eliminating the decades of breeding needed to create resource populations, the usual starting point of contemporary genetic-genomic analyses. The substantial costs of housing and feeding such a population would be eliminated. Most important, it would provide a tool to identify genetically superior animals without having to develop the enormous infrastructure currently used in the developed world.

GENETIC ENGINEERING

For the first 8 to 10 millennia since animal domestication began, selective breeding has been the method by which desirable phenotypes were enriched in a population. The dramatic diversity generated in dog breeds and improvement in the efficiency of producing dairy cattle are just two examples of the power of selective breeding (Weller, 1994; Pennisi, 2007). However, the approach has limitations, of which the largest is the inability to introduce a trait if genetic information on the trait does not exist in the species of interest. For example, endowing swine with the ability to synthesize lysine *de novo*, which would eliminate the need to supplement feed with what is now an essential amino acid, is impossible because the biochemical pathway does not exist in any breed of swine. The pathway does exist in bacteria and yeast, but that is of no use to the animal breeder. Furthermore, selective breeding lacks precision. There are many examples of selecting for one important economic trait at the expense of another, such as sacrificing the reproductive performance of dairy cattle for increased milk production (Wicks and Leaver, 2004). But, as previously described, the most serious constraint in applying modern tools of genetic selection is the time needed to build resource populations and harvest the phenotypic information needed to populate the genetic algorithms for each breed of interest.

In 1981, a new method for altering the genetic makeup of mammalian offspring led to the ability to place genes from one species (transgenes) into the genome of another (Gordon and Ruddle, 1981). Transgenes can encode completely novel natural or synthetic information, modulate the level of gene expression, or switch transcription on or off conditionally or permanently (Niemann and Kues, 2007). In the last 2 decades, genetically engineered cattle, chickens, goats, pigs, rabbits, and sheep have been produced (Hammer et al., 1985; Salter et al., 1987; Bondioli et al., 1991; Ebert et al., 1991; Krimpenfort et al., 1991). Transgenic livestock applications have been diverse and range from projects focused on animal well-being (Wall et al., 2005) to drug manufacturing (Edmunds et al., 1998). Transgenic animal technology has now advanced to the point where specific genetic information can be introduced precisely into any desired location of the genome (Richt et al., 2007). In theory, the technology provides a vast array of new ways to address challenges in animal agriculture.

Engineering Animals for Disease Resistance

Transgenic technology can be used in many ways to reduce susceptibility to disease in animals. It can be directed at a specific pathogen or a wide variety of pathogens, depending on the protein encoded by the transgene. There are dozens of examples of successful application of genetic engineering to protect mice, and many are expected to be predictive of outcomes of transgenic livestock experiments. However, to date there is only one example of genetic engineering that has protected a livestock species from disease (Wall et al., 2005).

In general, a transgenic strategy for disease resistance involves identifying an anti-pathogenic protein to be expressed in the animal and determining in which tissue and at what developmental stage expression should occur. The transgenic protein should cause no harm to the animal itself or to the consumer that eats it. If possible, the transgene product should avoid interfering with endogenous homeostatic feedback loops. The recombinant protein produced should be benign to the environment. Finally, a plan should be devised to prevent the target pathogen from developing resistance to the transgene product. Box 6-6 describes a project of this nature that would be considered promising but unprecedented and is of moderately high risk.

RNA Interference

RNA interference (RNAi), which is also discussed in Chapter 3, is an evolutionarily conserved mechanism of plants and animals that processes microRNA (miRNA) and destroys double-stranded RNA, targeting, in a sequence-specific manner, both messenger RNA and retroviral genomes (Hannon, 2002; McCaffrey et al., 2002). Theoretically, it should be possible to target any virus with this mechanism. Retroviruses, with their RNA genomes, are an obvious potential target (see Box 6-7), but DNA viruses could be targeted if their provirus encodes a unique mRNA that could serve as a target.

The RNAi approach to targeting HIV-1 infection has been demonstrated in cell-culture studies (Anderson and Akkina, 2005). And RNAi approaches have been devised to inhibit viral evolution of resistance (Anderson et al., 2007). The idea of using RNAi as a viral therapeutic is not new but has

BOX 6-6
Engineering Chitinase as an Insecticide

It may be possible to use transgenic technology to protect animals simultaneously against a variety of vector-borne parasitic diseases, such as trypanosomiasis (carried by tsetse flies), tick-borne East Coast fever, and Rift Valley fever (carried by mosquitoes). The strategy is based on attacking the carrier insect by disrupting chitin, an abundant *N*-acetyl-β-D-glucosamine polysaccharide that serves as a protective structural component of its exoskeleton. The transgene product, chitinase, which hydrolyzes the β-1,4 linkages in chitin, would be expressed from the transgenic animal's hair follicles. This approach, which uses chitinase as an insecticide, has been demonstrated in transgenic plants (Ding et al., 1998; McCafferty et al., 2006; Vellicce et al., 2006; Funkhouser and Aronson, 2007). Furthermore, hair follicle-specific promoters, such as keratin, have been shown to express transgene products in a tissue-specific manner in genetically engineered animals and in a gene therapy context (Powell et al., 1983; Ward and Brown, 1998; Paus and Cotsarelis, 1999).

A proof-of-concept transgenic mouse experiment would need to be conducted to determine whether the strategy is safe and effective. Transgene design optimization to improve efficacy might be required. To create a herd of transgenic animals, knowledge of the reproductive physiology of the breed of interest must be known. When a herd is produced, an experiment should be conducted to test the hypothesis that expression of the transgene is protective; if it works, it will be necessary to begin a second phase of the project designed to discover at least two more anti-insect vector peptides (perhaps antibodies to insect gut organisms or proteins) that can be used in conjunction with chitinase to reduce the likelihood that insects would become resistant to the strategy.

Overall, proof of concept in a livestock species would take at least 15 years for water buffalo and somewhat less for small ruminants because of the difference in generation intervals. Discovery and testing of second-phase anti-insect vector peptides may require another 10 to 15 years. Insect vector-borne diseases have been the focus of research efforts for nearly 100 years. Classically, each disease is studied in isolation primarily because each disease has a fairly unusual set of circumstances. If livestock could be protected against these insect vector-borne diseases, animal lives would be saved, and vast regions of western Africa that are now restricted by such diseases could be opened to livestock production.

not been fully explored, possibly because of a number of potential hurdles (Silva et al., 2002) and because the focus has been on using the technology in basic research (Hannon and Rossi, 2004; Silva et al., 2005). But it is clear that targeting gene expression can be achieved with this approach in mammals (Kunath et al., 2003; Dann et al., 2006), and RNAi has recently been shown to work against influenza virus in mice (Zhou et al., 2007). As

BOX 6-7
RNAi Technology to Resist Bluetongue Virus

Bluetongue is a non-contagious, insect vector-borne viral disease of domestic and wild ruminants. In India and parts of Africa, bluetongue virus (an RNA orbivirus) is endemic; cattle and wild ruminants serve as reservoirs for the virus. Sheep are the ruminants most susceptible to the virus, which attacks the animal's vascular system, sometimes causing the tongue to appear blue, and results in death within 2 to 5 weeks of infection (OIE, 1998).

Transgenic animals resistant to the bluetongue virus would be produced by introducing a transgene that encodes several 19- to 25-base-pair inverted nucleotide repeats and creates short double-stranded RNA hairpins (shRNA) under the control of constitutive promoters—such as cytomegalovirus, ubiquitin C, or U6 promoters—in a lentivirus vector. Cell-culture studies followed by transgenic mice studies would be used to assess and optimize construct design before moving into a livestock species. All the components needed to conduct such a study seem to be available.

The therapeutic use of RNAi in livestock would be novel. Bluetongue is suggested as a target because it is not a communicable disease, so challenge studies are easier to undertake. In addition, the complete sequence of the bluetongue virus is known (NCBI, 2008).

The overall proof of concept for using RNAi in a small ruminant would take about 10 years, including the design of an optimized transgene construct, cell-culture and mouse experiments, gamete harvesting, and production of transgenic livestock. Once an adequate number of transgenic and control animals are available, infection studies to test the hypothesis will be needed, and additional time will be necessary to demonstrate that resistance does not develop. Introgressing the transgenes into a wider population through conventional breeding will take additional time.

If successful, this project would serve as a new paradigm for prophylactic treatment of viral disease for which vaccines or other approaches are ineffectual or too expensive. Furthermore, the understanding of the reproductive physiology of the indigenous breed tested and knowledge about the shRNA transgene design will make future targeting projects less expensive.

with any small interfering RNA project, it would be necessary to monitor potential off-target effects (Schramke et al., 2005).

Fundamental Research Needed for Genetic Engineering

Before genetically engineered animals can be produced, it is necessary to have a precise understanding of the reproductive physiology of the breeds of interest and protocols for processing their gametes and embryos.

Optimized procedures will have to be developed for estrus synchronization, superovulation, ovum pickup, gamete preservation, in vitro fertilization, embryo culture, embryo manipulation, and somatic cell nuclear transfer for each of the local species of interest. It is not enough to have a general understanding of the species of interest, because subtle breed differences can often result in suboptimal yields.

Most of the economically important animals of SSA and SA are related to species that have been the subjects of intensive scientific investigations in the agricultural setting of Europe and North America. Furthermore, initial studies have been conducted on indigenous species. Therefore, to develop the baseline technology needed to introduce new genetic information directly into the animals of interest, researchers can take advantage of experimental designs and nominal parameters established in European breeds of dairy and beef cattle, dairy and meat goats, and sheep.

Advancing the technologies to the level of proficiency necessary to conduct genetic-engineering experiments has other direct and immediate advantages. Efficient procedures for collecting, manipulating, and preserving gametes and embryos can serve as the basis for distributing the best genetics of the day when the physical infrastructure and preservation methods are in place and genetically superior germplasm has been identified.

A significant effort has already been made to apply strategies developed for *Bos taurus* (common domestic cattle of Europe) to the water buffalo. It is clear from the current scientific literature that the general characteristics of domestic cattle's reproductive physiology are similar to those of the water buffalo, but specific differences require additional breed-focused research to optimize control of reproduction and in vitro viability of gametes and embryos (Saikhun et al., 2004; Boonkusol et al., 2007; Drost, 2007). Similarly, the procedures developed for European and Egyptian breeds of goats should serve as good starting points for the various commercially useful breeds of goats in SSA and SA (Armstrong and Evans, 1983; Cameron et al., 1988; Baril et al., 1989; Nowshari et al., 1995).

Scientists in SSA, SA, and China are contributing to the scientific literature that defines protocols for assisted reproduction technologies in goats (Espinosa-Márquez et al., 2004; Hasin et al., 2004; lez-Bulnes et al., 2004; Goel and Agrawal, 2005).

GERM CELL DISTRIBUTION

No matter how the genetics of indigenous farm animals are improved, there needs to be a means of distributing the improved genetics to farmers. Whether by quantitative genetics (selective breeding) or transgenic technology, the germplasm of the lineage progenitors will be produced at a high-technology center that resembles a modern-day artificial insemination (AI) stud farm. A distribution system must be in place to allow farmers access to the superior genetic material; the lack of a distribution system seriously constrains the improvement of the genetic potential of subsistence farmers' livestock.

Since the 1950s, genetic improvement of the livestock herds in industrialized nations has been achieved primarily by distributing gametes (spermatozoa) from outstanding sires and more recently by distributing embryos from meritorious females (Hasler, 1992; Foote, 1998; Thibier, 2005). As currently practiced, AI and embryo transfer (ET) require a ready supply of inexpensive liquid nitrogen. Liquid nitrogen must be available during the initial gamete- or embryo-freezing process and thereafter as a storage medium. On-farm storage dewars require replenishment (commonly every 4 to 6 weeks) that depends on use and environmental temperature. Furthermore, the use of preserved spermatozoa or embryos requires a specific knowledge of female reproductive physiology and highly skilled and practiced people to transfer the gametes or embryos into the recipient females. Even in developed countries, AI and ET are practiced mainly in intensively managed livestock operations, such as medium to large dairy, swine, and poultry farms. Less intensively managed enterprises, such as beef-cow and -calf operations or small farms, do not use these reproductive strategies, primarily because of the cost of estrous cycle management, the lack of availability of skilled AI technicians, and the low return on investment.

Attempts have been made to eliminate the dependence on liquid nitrogen for preservation of gametes. At first, freeze-dried spermatozoa were not very successful (Norman et al., 1958; Foote et al., 1962; Wakayama and Yanagimachi, 1998). Recent refinements in freeze-drying protocols have resulted in live-born mice from spermatozoa stored for over a year at 4°C (Bhowmick et al., 2002; Ward et al., 2003; McGinnis et al., 2005). Such freeze-dried spermatozoa are not viable in the traditional sense, but viable offspring can be produced by injection of their nuclei into an oocyte (intracytoplasmic sperm injection, ICSI). Storage at –20°C or –80°C improves the success rate of ICSI over storage at 4°C (Li et al., 2007). Most recent attempts to adapt this technology to a non-rodent species have been unsuccessful (Meyers, 2006; Nakai et al., 2007). Modern cryobiology may eventually develop room-temperature storage methods that will preserve the genome of gametes. But it is also likely that any such technique will require some highly sophisticated method, such as ICSI, to introduce the stored genetics into a living organism. Such an approach would be impractical for production of breeding stock.

SPERMATOGONIAL STEM CELL TRANSPLANTATION

The use of an emerging technology called spermatogonial stem cell (SSC) transplantation may be able to overcome the infrastructure and technical skill deficiencies that will inhibit subsistence farmers from taking advantage of meritorious germplasm when it is available. SSC transplantation (also known as male germ-cell transplantation or germline stem cell transplantation) involves transplanting self-renewing male germ-cell stem cells from one male to another. The recipient male becomes the mechanism for spreading the genetics through a herd.

In the early 1990s, it was demonstrated that the stem cells that give rise to spermatozoa in a male mouse could colonize the testes of another mouse, and the recipient mouse could sire offspring with the donor-derived spermatozoa (Brinster and Avarbock, 1994; Brinster and Zimmermann, 1994). The SSCs can also be frozen and stored at –196°C and, on thawing, be used to colonize a recipient's testes after transplantation (Avarbock et al., 1996). The technique also works in rats (Ryu et al., 2007), and it has been shown that it can be used to restore fertility in two mouse models of infertility (Ogawa et al., 2000).

Most relevant here are reports that demonstrate the potential of applying the technology to livestock. SSCs isolated from immature pig testes have been transplanted (Honaramooz et al., 2002), and the transplanted spermatogonia remained in the seminiferous tubules of the recipients for at least a month; somewhat surprisingly, not only did SSCs colonize the seminiferous tubules and generate spermatozoa capable of siring offspring, but this was possible in recipients unrelated to the host. Several studies also demonstrated the feasibility of the approach in goats (Honaramooz et al., 2003; Honaramooz et al., 2007). One attempt has been made to demonstrate its efficacy in cattle: testicular cells were isolated from *Bos taurus* bull calves and transferred, after fluorescent staining, into *Bos indicus* prepubertal recipient calves (Herrid et al., 2006); *Bos taurus* fluorescently labeled cells were found in the testes of recipients up to 6 months after transfer.

It is envisioned that once this technology has been refined and adapted to local breeds, SSCs harvested from males with superior genetic merit will be distributed to males of average genetic merit but good libido. The recipient males, harboring the "good genetics," could then be distributed to farmers. Alternatively, because the transplantation procedure can be performed in the field, the SSCs from genetically superior males could be frozen, transported to farms (or villages), and transplanted into farmers' (villages') own breeding males by someone skilled in the surgical procedure.

The main constraint limiting the technology is the acquisition of enough SSCs. It is possible on rare occasions to harvest enough SSCs from a donor to distribute to four recipients (Ina Dobrinski, University of Pennsylvania, presentation to the committee, October 15, 2007). Protocols are needed for multiplying SSCs in culture so that dozens, if not hundreds, of males can be serviced by a single genetically superior donor. In addition to a propagation system, there is a need for more efficient SSC-enrichment methods. Finally, methods to improve the ability of the newly acquired

SSCs to dominate the testes of the recipient will need to be devised. The current literature on this new procedure is not vast, but there are enough examples to suggest that SSC transplantation should be applicable in a wide array of species. It will be necessary to confirm that SSC transplantation can be implemented in the breeds and species of interest in SSA and SA and, if so, that it can be optimized for each species.

IMPROVING ANIMAL HEALTH

Improving the health of animals can have a substantial impact on the livelihood of farmers, especially subsistence farmers that rely on animals for labor, food, and additional income. Some of the ways to improve animal health discussed below include fortification of neonatal passive immunity, development of animal vaccines for diseases affecting SSA and SA, and use of animal disease surveillance. Not explored by the committee are the development of novel drugs and drug delivery strategies for animal disease infections in SSA and SA, two areas in which innovations have been lacking.

Neonatal Passive Immunity

In Kenya, calf mortality after weaning ranges from 6 to 70 percent, depending on health and nutritional management (Homewood et al., 2006; Lanyasunya et al., 2006). Almost all the primary causes of high preweaning mortality—including failure to ensure that the young receive colostrum within 6 hours of birth, respiratory diseases, diarrhea, and inadequacy of maternal milk production—can be substantially reduced with currently available, low-cost management interventions. These include giving young animals the same salt- and sugar-based rehydration solutions made with clean water as are given to children who have diarrhea. The application of existing knowledge to raising calves, lambs, and kids could reduce mortality to below 9 percent, a commonly accepted target, and improve animal productivity and profitability.

Technologies are used to enhance colostrum quality by vaccinating pregnant dams. Also, the preparation and preservation (freeze-drying) of serum antibody extracts are used as artificial colostrums substitutes. There are some truly nutritional interventions to prevent preweaning mortality, such as enhancing the nutrition of the lactating dam and providing nutritional supplements to the diets of lactating animals.

The issue of access to veterinary services by the poor in SSA and SA is critical. The delivery of appropriate medicines and information on livestock health has been compromised by privatization of veterinary services in many countries. Now only those able to pay have access to veterinary services, so livestock productivity is low and the risk of outbreaks of zoonotic and other diseases is high. Very simple interventions in providing education, medicines, and vaccines could have a major impact in protecting the health and productivity of animal populations in SSA and SA. Reversing the situation would make meeting the projected increased demand for meat products more feasible without large increases in the number of breeding females.

Animal Vaccine Development

Disease is a major constraint on livestock productivity in developing countries. Chapter 2 describes the long list of disease problems in SSA and SA. Estimates of losses due to disease in the regions are not well quantified, although one estimate of the annual economic loss due to animal diseases in SSA is around US$40 billion, or 25 percent of the total value of livestock production. There is a substantial worldwide effort to develop animal vaccines, and several major U.S., European, and Asian pharmaceutical companies are highly invested in food animal vaccine production. In fact, when the committee asked several experts what could have a major effect on improving the life of poor farmers, they noted that effective vaccines already exist to prevent globally endemic disease, such as brucellosis, leptospirosis, and bovine virus diarrhea (Hans Draayer and Raja Krishnan, Pfizer Animal Health, presentation to committee, September 24, 2007). However, some factors that affect the use of current vaccines in SSA and SA include strain variations, costs of vaccines, and the need to have an effective cold-chain for transportation, marketing, distribution, and delivery to the animals in the field. Technologies to develop thermostable vaccines, such as the development of a thermostable attenuated vaccine for Newcastle disease in chickens in Australia and Malaysia, can compensate for the lack of a cold-chain.

A focus on infections for which vaccines exist and on others that cause respiratory and intestinal diseases in young, preweaned animals could reduce mortality and improve productivity. The other two categories of opportunity identified by experts the committee consulted were zoonotic diseases, particularly those associated with foodborne illness, and endemic infections peculiar to SSA and SA (Guy Palmer, Washington State University, and Roy Curtiss, Arizona State University, presentation to committee, September 24, 2007).

SSA and SA are home to the most severe vector-borne diseases, including trypanosomiasis, babesiosis, and theileriosis (the last two of which are parasitic diseases spread by ticks). Diseases, such as trypanosomiasis, have been the subject of vaccine investigations for many years and have thwarted vaccine effectiveness because of the great variability of surface proteins of the parasite, which the organism is able to “switch” under the pressure of the host immune system. The greatest challenge for these vaccines is the discovery of antigens that will result in a protective immune response in the host. Such a discovery will be assisted by the complete genome sequences that have been completed for all six major vector-borne pathogens in the last 2 years, including *Anaplasma marginale*, *Babesia bovis*, *Ehrlichia ruminantium*, *Theileria parva*, *T. annulata*, and *Trypanosoma bruci*. For example, it is known that immunity to East Coast fever, caused by the tick-borne parasite *T. parva*, can be created by inoculating a host with sporozoites of the parasite in conjunction with long-acting oxytetracycline. However, until the *T. parva* genome was available, the antigens involved in the immune response were unknown. Using gene prediction methods, investigators were able to identify candidate genes in the genome that were associated with a secretion signal on the basis of the idea that secreted proteins would be the first to become associated with the host major histocompatibility complex apparatus. Screening of the protein products of those genes narrowed the search to the ones involved in establishing immunity and paved the way to future vaccine development (Graham et al., 2006).

Zoonotic diseases were suggested as targets for disease control because of their implications for limiting the spread of diseases to humans and back to animals. Effective vaccines exist for some of the diseases, including brucellosis, salmonellosis, and listeriosis; but problems related to supply, cost, and delivery mechanisms slow their widespread use.

Bacteria as Antigen Vectors

Because they are so infectious, serotypes of some of the disease-causing organisms have been used, in attenuated forms, as packages to deliver antigens for several pathogens in “attenuated recombinant bacterial host-vector vaccine systems.” Experimental work with *Salmonella typhi* suggests that it could be developed into a vaccine to protect against hepatitis B virus, human enterotoxigenic *Escherichia coli*, *Mycobacterium tuberculosis*, *Clostridrium*, *Yersinia pestis*, and other pathogens (Curtiss, 2002).

The use of genetic engineering methods has dramatically improved vaccine production compared with conventional methods of developing live attenuated and inactivated pathogens. The basic strategy for developing bacteria-based vaccines is to transfect a bacterial vector, such as *Salmonella* or *Shigella*, with plasmids that express the antigen of interest and inject the transformed bacteria into the host. This system allows the delivery of multiple antigens, and the resulting expressed antigens would elicit antibody production to protect against several diseases. Attenuated strains of *Salmonella typhimurium* have been used for delivery and expression of vaccine antigens in the mouse (Ashby et al., 2005). In all cases, specific antibody against the antigen is detected in host blood. Information on comparisons with conventional vaccines is not complete, but this approach offers potential help in preventing parasitic diseases for which it has been extremely challenging to develop effective vaccines.

For example, attenuated *Salmonella typhimurium* transformed with the *Plasmodium berghei* CS (circumsporozoite protein) gene induced protective cell-mediated immunity to sporozoites in the host. The transformants, used orally to immunize mice, colonize the liver, express CS proteins, and induce antigen-specific cell-mediated immunity, protecting mice against sporozoite challenge in the absence of antisporozoite antibodies. It has been established that immunization with CS proteins by injection does not offer protection against sporozoites. However, *Salmonella* as the carrier of the CS gene and later the expression of CS protein stimulated T-cell-mediated immunity. It is worth investigating the possible use of a vaccine for controlling other parasitic diseases caused by trypanosomes and *Leishmania*. Another case study demonstrated that live attenuated *Shigella flexneri* strains act as vectors for the induction of local and systemic antibody responses against poliovirus epitopes (Levine, 2006). Poliovirus proteins (IpaC-C3 hybrid proteins) were expressed by recombinant plasmids in *S. flexneri*. Research in this definitive area will yield new vaccines against diseases previously deemed difficult. More development is needed before these vaccines are reliable in immune protection of the host.

Plant-Based Expression System for Vaccine Development

Genetic engineering also has made it possible to use plants as factories for pharmaceutical protein production. Unlike bacterial cells, plants are capable of some post-translational modification and other assembly steps that are needed for biological activity in complex multi-component proteins, such as antibodies. The plants that have been successfully transformed include tobacco, potato, tomato, corn, soybean, alfalfa, rice, and wheat. The proteins made in plants have been used to produce antibodies, vaccines, hormones, enzymes, interleukins, interferons, and human serum albumins (Moschini, 2006).

Plant-made biologicals are created by inserting into plant cells a segment of DNA that encodes the protein of choice. The plants or plant cells are essentially molecular factories that can be used to produce the desired proteins and are grown only for pharmaceutical applications. In addition to vaccines meant for humans, plant-based vaccines are being developed for use in animal health. In fact, edible plant-based vaccines might be best suited for animal applications: an edible product can be conveniently added to animal feed, and even partial protection could be acceptable and economical in that setting. A plant-based vaccine to protect poultry from Newcastle disease virus was developed by Dow and approved by the U.S. Department of Agriculture in 2006. That was a notable milestone in that it was the first plant-based vaccine to win regulatory approval. However, the vaccine is not expressed in whole plants but is produced by means of genetically modified plant cells cultured in steel fermenters; this production method resolves many issues related to containment (Moschini, 2006).

One approach to vaccine development uses an RNA virus as a vector, mediated by *Agrobacterium tumefaciens* to deliver genes that are expressed throughout the recipient plant. The transformation and expression system is efficient and is referred to as a launch vector. The system is not based on the natural mode of virus infection, so there is no size constraint on the gene construct within the vector. Its advantage is that the whole plant biomass can be infused without concern about the vector's cell-to-cell movement. The time from inoculation to harvest is 2 to 4 days. A large amount of antigen—up to hundreds of kilograms—can be produced in a greenhouse, without the need to grow large batches of crops. Vaccines made this way can be highly suitable for a region where local delivery is important (Yusibov et al., 2002).

In addition to tissues, vaccines could be produced and stored as seeds, which would provide a stable form in which the protein will not degrade over time. The choice of the crop would determine how the vaccine is administered: some plants can be consumed raw, but others must be processed. Processing introduces the potential of heat or pressure treatments to destroy the protein. Cereal crops are attractive for expressing subunit vaccines because they can produce proteins in their seeds that are stable for long storage periods. For animal vaccines, the plant selection could be based on what is eaten as a major part of the diet.

The production of vaccines from plants has the following advantages over traditional systems that involve the administration of dead or attenuated viruses: plant-based vaccines offer greater biological security because plants do not become contaminated with human or animal pathogens; plant-based vaccines can be administered orally in the form of a single-dose capsule, so the use of needles and syringes is avoided; the vaccines do not have to be kept refrigerated; the production system is economical and can easily be put into large-scale production with conventional agricultural techniques; and the system offers the possibility of producing multi-component vaccines (Agrobiotechnology Institute, *http://www.agrobiotecnologia.es/en/index.htm*). A disadvantage is the potential variation in the concentration of vaccine produced in different plants, which might make it difficult to feed an efficacious dose.

DNA Vaccines

DNA vaccination stimulates the immune response by introducing into the host naked DNA that codes for antigens of a pathogen. The protein synthesis machinery of the host cell expresses the antigen and stimulates a specific response by the host's immune system. In theory, DNA vaccines can be manufactured far more easily and less expensively than vaccines composed of inactivated pathogens, protein subunits, or recombinant proteins. Other potential advantages include stability, resistance to extreme temperatures, efficacy as an oral vaccine, and the ability to introduce multiple antigens (Mwangi et al., 2007). However, substantial development is needed before DNA vaccines become an alternative to conventional methods. Most of the experimental DNA vaccines have not shown as great protective immunity as conventional vaccines, but new technologies, such as the coating of colloidal gold with DNA, that are in development could improve effectiveness. If future research can deliver a DNA vaccine that offers protective immunization, this approach would add flexibility to the custom designing of vaccines for regional needs. For instance, it is easier to change the sequence of an antigenic protein or to add heterologous epitopes. The protective immunity of the expressed protein can be easily evaluated after the DNA is injected into a model animal, such as the mouse. This simple, elegant method could quickly allow researchers to learn about the effectiveness of candidate antigens. The final goal of effective DNA vaccines is considered to be far in the future because of the many unresolved problems, but the potential high payoff will continue to draw investment.

Animal Disease Surveillance

It is pointless to develop and deliver drugs and vaccines without knowing which syndromes are present in a region, because protecting an animal against one pathogen only to have it succumb to another will not reduce the burden of disease on a small-holder farmer. Developing a database of such information will require field research, trained technicians, and diagnostics. The relatively new World Animal Health Information Database managed by the World Organization for Animal Health (OIE) is a significant database that tracks disease prevalence in all regions of the world. In cooperation with the Food and Agriculture Organization of the United Nations (FAO), the OIE is investigating disease rumors that surface on ProMED or other non-scientific sources of information; these early warning systems serve as good alert systems for emerging disease outbreaks.

The use of satellite-based remote sensing technologies could be useful as early warning systems for the emergence of serious infectious diseases, particularly those that are transmitted by arthropods. The FAO's Emergency Prevention System (EMPRES) for Transboundary Animal and Plant Pests and Diseases program currently uses remote sensing technologies to determine the Normalized Difference Vegetation Index (NDVI), and the use of such data has led to the successful advanced prediction of Rift Valley fever outbreaks (FAO, 2008). Similar technologies have been used for the advanced notification of blooms of desert locus and of outbreaks of Venezuelan Equine Encephalomyelitis (FAO, 2008).

Inexpensive diagnostic tests, like that developed for rinderpest (Yilma, 1989; Ismall et al., 1994), are needed for disease detection and vaccination campaigns. Other similar rapid pen-side tests for the recognition of infectious diseases have been developed and are in use, such as the field diagnosis of human and avian influenza outbreaks. Increasing in greater numbers are the development, validation, and deployment of rapid RT-PCR technologies for accurate diagnosis of a variety of diseases affecting SSA and SA. These tests require only a nasal swab as a sample and are not sensitive to the effect of higher temperatures in the transportation to diagnostic laboratories.

Furthermore, emerging technologies, such as biosensors (Box 6-8), are promising because of their sensitivity, speed, portability, and ease of use and could be developed for a variety of surveillance efforts and especially useful in resource-constrained countries in SSA and SA. Moreover, if farmers have

BOX 6-8
Biosensors for Rapid Diagnosis

A biosensor is an electronic device that contains a biological receptor close to a transducer that converts the interaction between the receptor and the target of analysis (such as a pathogen) into a measurable electric signal whose strength is related to the concentration of the target. There are a number of experimental configurations and platforms. In one type of biosensor, very thin nanowires are bound to a biomolecule, such as a short piece of DNA (an oligonucleotide), whose conformation changes when a target binds to it; the change in conformation produces a change in charge that is detected by and transmitted by the nanowire. Biosensor technology has progressed quickly in recent years because of the homeland security interest in rapid detection of small amounts of biological agents that could be used for terrorism. Several technologies feed into the development of biosensors, including genomics, nano- and micro-fabrication and instrumentation, chemical and polymer science, and signal processing and data transmission. New generations of biosensors have automated signal transmission to record and send information from remote locations. The key advantages of biosensors are sensitivity, speed (4 to 6 minutes vs. 2 hours for the polymerase chain reaction), portability, and ease of use. Specificity, cost, and manufacture will need additional research.

SOURCE: Evangelyn Alocilja, Michigan State University, presentation to committee, August 17, 2007.

tools to detect the presence of disease, they are more likely to seek out a drug or vaccine. Farmers' confidence in medical treatment and vaccination depends on their seeing a benefit, which they will not if a problem is not solved by a drug or vaccine that targets a single pathogen (Guy Palmer, Washington State University, presentation to committee, September 24, 2007).

Transgenic Arthropods

The genetic engineering of arthropods to alter vector competency and disease transmission could conceivably reduce vector-borne diseases in animals, plants, and humans. By genetically manipulating vectors, such as mosquitoes, and eventually changing their life-cycle dynamics in the field, the ability of local populations of arthropod vectors to transmit diseases could be significantly altered (Scott et al., 2008).

NEEDS FOR DRUG AND VACCINE DEVELOPMENT FOR SUB-SAHARAN AFRICA AND SOUTH ASIA

Knowledge of Pathogen and Host Variability

In addition to the very presence of a pathogen, pathogen serotype is important in drug and vaccine development. For example, although it is not difficult to find conventional vaccines for many major animal diseases, it is not clear that vaccines based on pathogen serotypes in the industrialized world would necessarily provide protection to animals in SSA and SA, because a given causative agent might have different immunogenic characteristics in different regions. Moreover, most vaccines have not been tested on the indigenous animals to be protected, and knowledge of the diversity of the major histocompatibilty complex in a region must be accounted for.

Genomic tools can be used to identify differences in geographic strains of a pathogen by comparing highly useful epitopes (that offer immune protection for the host) according to the homology of a pathogen in two distinct regions of the world. Sequencing can help to identify potential antigens of the pathogen of interest that could be evaluated as vaccines. If a pathogen has a standard reference sequence, partial sequencing can help to identify differences in epitopes of a similar strain in a developing country. Faults in a vaccine could be identified and result in the design of a better vaccine for a region. Genomics research on important animal pathogens should be supported because it will lead to better vaccine designs (Dertzbaugh, 1998).

Adjuvants

A vaccine stimulates a host's production of antibodies specific to antigens of the pathogen. For various reasons, however, vaccines do not always produce an immune reaction strong enough to protect the host. That is especially true of parasitic diseases that require a vaccine to elicit strong T-cell-mediated immunity in addition to stimulating protective antibodies. Adjuvants are compounds added to vaccines that cause the immune system to respond more vigorously, and they include organic and inorganic salts, virosomes, and experimental compounds. Most adjuvants have been developed by pharmaceutical companies and held as proprietary property (Guy Palmer, Washington State University, presentation to committee, September 24, 2007). There is a need to develop and make available adjuvants to improve current vaccines.

Distinguishing Vaccination from Infection

Livestock and meat from regions where infectious diseases persist are prohibited from exportation to other countries regardless of whether the animals have been vaccinated. Until recently, it was not possible to distinguish between vaccinated and diseased animals in that both will have produced antibodies to a pathogen. That has served as a major barrier to entry markets for farmers in SSA and SA where several diseases persist.

The ability to distinguish between animals exposed to a whole virus and vaccinated animals consistently and reliably would be important in the development of vaccines. Such a diagnostic system for differentiating infected from vaccinated individuals (DIVA) already exists and has been applied successfully for pseudorabies and avian influenza (Pasick, 2004). In addition, several DIVA vaccines and their companion diagnostic tests are on the market and can be applied for foot-in-mouth disease and classical swine fever (Pasick, 2004). Attenuated vaccines have been widely used in SSA and SA for the control of diseases such as peste des petits ruminants, sheep and goat pox, and hemorrhagic septicemia. The use of preimmunization, or the deliberate infection of animals with viable pathogenic organisms followed by a treatment with chemotherapeutic agents, for several homoparastic diseases such as *Anaplasma marginale, Babesia bovis, Ehrlichia ruminantium*, and *Theileria annulata* in SSA and SA are not safe technologies because they do not propagate the infectious organisms to naïve populations. In this respect, live attenuated vaccines provide better immunity than subunit or killed vaccines. The development of stable strains and insertion of marker genes into these strains to differentiate them from wild-type strains would facilitate vaccine deployment for diseases most relevant to SSA and SA.

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7

Emerging Technologies to Meet Local Energy Needs

THE ROLE OF ENERGY IN CATALYZING GROWTH AND POVERTY REDUCTION

Small-scale farmers in sub-Saharan Africa (SSA) and South Asia (SA) operate with minimal energy input. Could the availability of greater energy resources transform the lives of farmers? It is not difficult to envision how the energy could be used to increase agricultural productivity. With additional energy, farmers could power pumps for water supplies and irrigation and thus decrease the risks associated with rain-fed systems, increase crop and pasture productivity, and possibly switch to higher-value crops. Mechanization, including the use of small mechanized hand tools, would be possible; it might reduce the burden of cultivation that falls so heavily on women. Manure would no longer be needed for cooking and could be left on the field for fertilization. The presence of alternatives to the use of biomass for fuel would save the time and effort needed to collect firewood, reduce local environmental degradation, and be less polluting. Refrigeration would be possible and could enable better storage of meat, milk, and other products. With energy to power lights, farmers could extend their workday and accomplish more, increasing productivity so that their children would no longer be needed as field workers and would be free to attend school and pursue other activities. Radio, television, and computers would become common mechanisms of obtaining and exchanging information.

This chapter examines a number of energy technologies that might be developed to lessen or remove the current reliance on expensive petroleum-based sources of portable energy, such as kerosene and diesel. Energy technologies are in a state of rapid innovation and growth, and while the committee was in agreement that future energy sources will need to move towards non-petroleum based ones, it was beyond the ability of this study to fully contemplate which of these technologies has the greatest potential to help rural farmers. Applications that are scalable, produce affordable energy, are consistent with the climatic conditions of SSA and SA, and are produced locally might be considered the most appropriate.

INSUFFICIENCY OF ELECTRIC-POWER GRIDS

About 2 billion people (some 30 percent of the world's population) lack access to electricity (UNDP, 2004), and about 85 percent of them are the rural poor of SSA and SA (IEA, 2002). Of those 85 percent, half live in SA; India alone is home to one-third (Ailawadi and Bhattacharyya, 2006). In Bangladesh and Pakistan, the proportions of households without access to electricity are 60 percent and 40 percent, respectively (Sarkar et al., 2003). About 600 million people in SSA are without electricity. Oil-rich Nigeria tops the list of African countries with the greatest numbers of electricity-deprived citizens, followed by Ethiopia, Tanzania, Kenya, and Mozambique.

The physical infrastructure to provide electricity to the rural poor is lacking, and demand for electricity in urban areas where grids do exist is outpacing the ability to generate power. In early 2008, even South Africa, the only country in Africa with large coal reserves, was experiencing daily blackouts that led to the declaration of a national emergency (Bearack and Dugger, 2008). Electric grids in eastern, western, and central Africa are powered primarily by hydropower and oil- or diesel-fired thermal power. Even with ample rainfall, hydroelectric generating capacity is often inadequate; with low water levels in lakes and an increasing silting problem in storage structures, more expensive diesel generation is needed for peak-demand management, and blackouts are common.

Most countries in SSA and SA have plans to expand power-generation capacity, and a widely recognized high priority is the development of long-range technical planning for these regions to replace the day-to-day crisis management that is the current mode of many energy ministers. Many studies of long-term energy futures for Africa and SA envisage an increasingly important role for renewable energy, much of which is site-specific and thus will require local research (Goldemberg et al., 2004; Uddin et al., 2006). Whether new technologies are implemented on or off the grid, trained people who can create them will be needed. In addition, expanded energy services at a local level will probably require a variety of alternative ownership and market structures. These approaches will require an emphasis on flexibility to identify least-cost options for particular geographical, technological, demographic, and economic situations. Thus, some have advocated for policies geared not toward promotion of specific technologies but toward supporting diverse energy technologies and service-delivery models (Modi et al., 2006).

STATUS OF LARGE-SCALE RENEWABLE ENERGY PROJECTS

Among the types of renewable energy options that exist or are being explored for national and regional grid systems in SSA and SA are geothermal power, hydropower, wind power, and wave and tidal power. The first three are reasonably established technologies; the fourth is under experimentation. The capital cost of developing all those large-scale resources and building distribution systems for them is high. Because the density of demand in rural areas is low, a lack of grid connections to isolated rural communities is likely to continue for decades. Small-scale farmers outside peri-urban areas are therefore unlikely to benefit from the technologies for some time, but they are briefly mentioned here because they will be important in the long term to support an industrial base that should be built to complement economic development.

Hydropower

Hydropower is a mature technology that provides some energy in both SSA and SA. There is strong interest in expanding the number of hydropower plants in those regions, although the adverse impact of hydropower projects on the environment and their displacement of local populations are continuing concerns, as are the potential effects of silting and droughts on magnitudes of electricity generation. Nevertheless, Chinese companies plan to build a 2-gigawatt (2-GW) plant in the Mambila Plateau in Nigeria in exchange for oil rights. The World Bank recently provided loans for a 250-megawatt (MW) plant on the Nile at Lake Victoria in Uganda and made a US$297 million grant to repair silting at two existing hydropower plants (Inga I and II) on the Congo (World Bank, 2007a,b). The governments and utility companies of South Africa, Botswana, Angola, Namibia, and the Democratic Republic of Congo have formed an alliance to build the world's largest hydropower installation on the Congo River. The Grand Inga, as it is known, could generate 39 GW of continuous energy and would cost US$30-80 billion. A final decision about the plan is not expected to take place until 2015, when preliminary studies are complete. If transmission lines are successfully built, the plant could supply electricity to nearly all of Africa and possibly as far away as Europe (IWP&DC, 2007).

Hydropower already accounts for almost 25 percent of India's electricity use, and there are plans to add 16.5 GW of hydropower generating capacity by 2012. Because of the demand for electricity, Indian power companies have pursued projects in remote areas of Bhutan and Nepal to produce electricity and export it to India.

Wind Power

Modern wind-turbine generators are capable of producing more than 1 MW of electricity, and large wind installations have become common in many developed countries. India has the fourth-largest installed wind-energy capacity in the world, with 6.2 GW and growing (BP, 2007). The Indian government has a goal of adding 12 GW by 2012, and there are several turbine-component manufacturers in India, including General Electric. In contrast, SSA has virtually no installed wind power. There are demonstration projects in South Africa, and the coastal areas of South Africa are thought to have the greatest potential for expansion of wind energy in Africa outside the countries in the north (for example, Tunisia and Egypt, which have installed wind-power facilities). Although wind is in most locations an intermittent resource and wind resources are thought to be relatively poor in SSA, little information to support this assumption has been collected.

Geothermal Power

Geothermal power plants use steam or hot water from geothermal reservoirs to turn turbines. Geothermal energy is the only clean source that can provide firm, predictable power on 24 hours per day, and it is in much greater amounts for a given installation than other renewable sources (Brown and Garnish, 2004). The East Africa Rift Valley is the site of two geothermal electricity projects, and by some estimates the region might be able to provide up to 7 GW, which would double the entire grid capacity of eastern Africa and serve as a buffer to high oil and diesel prices (BP, 2007).

Wave and Tidal Power

Wave and tidal power is an emerging technology that has lagged in development because of the high relative cost of installation. The World Energy Council has estimated the worldwide wave-power resource to be 2 terawatts (2 TW, or 2,000 GW) (Thorpe, 1999). Among the proposed designs for capturing wave power are oscillating water columns that use the up and down motion of waves to generate electricity, moored floating devices that capture the tension between a fixed point and the movement of the bobbing flotation device, and hinged contour devices that channel waves into an elevated reservoir, whose outflow is used to generate electricity. Tidal power is collected by using the cyclic daily movement of currents in and out of shoreline basins to turn turbines (EC, 2008). There are virtually no significant commercial wave or tidal operations worldwide except the 240-MW facility in LaRance, France, built in 1966.

The utility of a location for wave power generation depends somewhat on the size of waves. With the exception of southern Africa and the horn of Africa, estimates of wave power density are on the average low (about 15 kW/m of crest length) on African coasts, compared with European coasts (about 50 kW/m) and the Atlantic seaboard (about 35 kW/m). The same is true of much of Asia, but China, India, Korea, and Indonesia are developing offshore energy converters that will exploit breakwaters provided for harbors and local gullies and shorelines formed by steep cliffs that have energetic wave climates (Duckers, 2004).

LOCAL ELECTRICITY GENERATION

An alternative to national or regional electric grids is the development of small-scale, localized grid networks or stand-alone electricity-generating facilities. These may also be powered by relatively expensive fossil fuels, but there is much interest in using renewable resources, and small-scale hydropower, wind power, solar (photovoltaic) power, and biogas are being used in rural electrification projects in the developing world (Anderson et al., 1999).

Small-Scale Hydropower

Microscale hydropower installations (300 kW or less) are generally not connected to power grids. These units are “run-of-the-river” installations; that is, they do not use dams or reservoirs to create the energy potential but rather use the natural flow and elevation drop in the river to turn a turbine. Because small-scale hydropower typically does not interfere with river flow, they offer an environmentally benign way to replace diesel generators and to provide energy to rural populations up to a mile from the generator. Microscale hydropower does not provide storage capacity and is vulnerable to supply variations. In the industrialized world, there are many manufacturers of microscale hydropower generators, which come in different designs for different water-flow conditions. The technology is very scalable, although the larger the system, the more skilled maintenance is required. The cost of microscale generators is about US$200-500 per kilowatt of capacity. Local industry could be developed to produce small-scale systems, such as the tiny Peltric turbo generator (basically a series of cups attached to a hub), which is able to produce 1 kW of power and has been used in many countries (Ramage, 2004).

There seems to be little information on the overall potential for sites, but some applications that are in place are potential models, such as a 60-kW system installed in a rural hospital in western Uganda at a cost of US$15,000. In Malawi, a 600-kW system installed in the 1920s is still in operation (Zachary, 2007).

Small-Scale Wind Power

Small-scale wind generators for supplying electricity for battery-charging, stand-alone applications, and connection to small grids are evolving. The U.S. Department of Energy (DOE) recently announced that it had met its goal of reducing the cost of residence-size wind turbines (less than 10-kW capacity) to US$0.10 per kilowatt-hour and the cost of small village-size turbines (less than 100-kW capacity) to under US$0.11 per kilowatt-hour (DOE, 2008).

Small wind generators in the 1-kW range might be built locally with a variety of available materials, such as laminated wood, steel, and plastics. But the efficiency and reliability of the device depend on the design of the foils and on the engineering of the electronics. Among DOE partners, the most cost-competitive microscale design so far is a 1.8-kW design that costs US$5,500 (not including installation) and that the manufacturers estimate could provide 100,000 kW-h over a 20-year life span (DOE, 2008). An accurate map of the prevailing wind speeds in SSA and SA on the scale needed to determine the viability of small wind generators is, to the committee's knowledge, unavailable, but obtaining such information would have to be a preliminary step in estimating the utility of these devices. If the technology were practical and the market were large enough, there would be value in developing the technology for use in rural areas and establishing local manufacturing capacity.

Solar Power

Concentrated Solar (Thermal) Energy

Solar cookers collect heat from sunlight and provide energy for boiling and cooking, reducing the use of firewood and the pollution associated with burning of wood. They typically consist of a small number of reflectors (or a parabolic mirror) focused on an oven box. Parabolic solar cookers with a diameter of 1 m are large enough for a family; in India, solar cookers supply boiling water for a kitchen serving more than 1,000 people. A number of projects scattered throughout SSA and SA distribute solar cookers produced in China. Solar cookers function only during the day (and are therefore used as a supplement), and, like other improved cookers, they are not always accepted by recipients. However, these projects have considerable potential for expansion (SCI, 2007).

Solar heat can produce electricity if parabolic troughs are used to focus solar radiation on the heating chamber of a Stirling engine (Box 7-1 and Figure 7-1) or a heat exchanger coupled to a steam engine. This technology might have particular relevance for arid and semi-arid regions in Africa (Everett, 2004). However, it is in large-scale applications—such as the 64-MW, 300-acre power plant opened in 2007 near Las Vegas, Nevada—that the efficiency of sunlight-to-electricity conversion can reach 40 percent as the heat generated by the mirrors reaches 750°F. The Nevada plant cost US$250 million to build and is expected to provide power for a half-million people at an approximate cost of US$0.09-0.13 per kilowatt-hour. The

BOX 7-1
Stirling Engine

In contrast with the industrialized world, SSA and SA have a need to reliably produce power in the range of 500 to 5,000 W for small rural communities at low cost. Diesel generators are typically used to power small grids for rural communities, but diesel is an increasingly expensive source of energy, and diesel generators break down often.

A more robust source of energy is provided by the Stirling engine, which uses a technology that is more than 100 years old. Stirling engines work on the principle of a thermodynamic cycle in which a gas or liquid in a cylinder is heated so that it expands (driving a piston to perform work), then undergoes cooling and isothermal compression before the cycle is repeated. The engines, of which there are multiple designs and scale, can be more energy-efficient, quieter, and more reliable and require less maintenance than an internal-combustion engine, although they are initially more expensive (Andrews and Jelley, 2007). It is particularly important that they can generate electricity from heat-producing energy sources, such as solar thermal energy or combusted agricultural waste and domestic refuse. Stirling engines can be directly coupled with mechanical power to pump water and perform other mechanical applications.

NASA has recently called attention to a modernized version of the Stirling engine manufactured by Lockheed Martin and Sunpower that achieves more than 35 percent efficiency (Shaltens and Wong, 2007). The modern Stirling engine can be powered by solar energy with concentrators, radio isotopes, or combustion of wastes, coal, or agricultural disposals. The design of this engine is intended for space applications but could be adapted for terrestrial use.

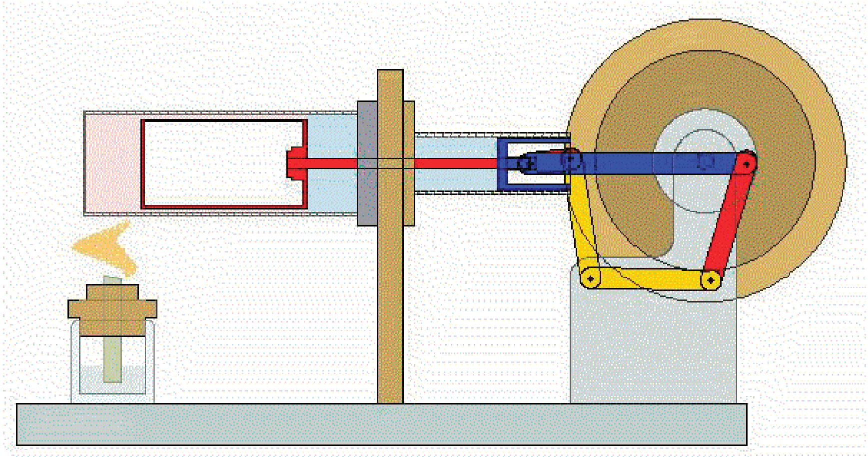

FIGURE 7-1 Schematic of a Stirling engine.
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goal for larger projects is to bring the cost down to US$0.07 per kilowatt-hour (Broehl, 2006). Building a plant of that size requires substantial land and presumes the existence of an electric grid. Recently, plans to develop smaller-scale applications of the technology were announced (LaMonica, 2008). Although little information on smaller systems was available, the cost per kilowatt-hour would certainly increase. Nevertheless, given the abundance of solar energy in SSA and SA and the relative simplicity and low maintenance of such a system, the technology warrants further exploration. Solar concentrators can also be used with photovoltaic electric cells, as described in the next section.

Photovoltaic Energy

Conventional solar photovoltaic (PV) technology uses silicon-based semiconductors to convert photons directly into electricity at an efficiency of up to 22 percent. The efficiency of PV technology is limited in part by the "density" of solar energy reaching Earth. The sun radiates energy at about 1 kW/m2 of Earth's surface; every square mile receives about 2.6 GW. One way to overcome that limitation is to concentrate the solar energy with mirrors, Fresnel lenses, and other devices that are typically placed above the solar cells. The benefit is increased conversion efficiency; as a result, less silicon (which is expensive and of limited availability) needs to be used to generate the same amount of electricity, and the cells cost much less. The drawback is that cooling mechanisms are needed to prevent the concentrators from overheating the cells. Concentrator systems are being tested around the world.

PV technology is ideally suited for meeting low demands for electricity. The current cost is relatively high, however—about US$8 per watt. Thus, one estimate is that a 10-kW system (which would be considered a large residential or small industrial system by U.S. standards) installed in 2007 would cost about US$80,000 (Borenstein, 2008).

Solar-cell technologies are diversifying rapidly, and waves of innovations are focused on reducing cost and increasing conversion efficiencies. A second-generation technology (thin-film cells) reduces the amount of mass in a cell by using new light-absorbing materials (inorganic materials, dyes, and organic polymers). A third generation is based on nanocrystals (such as quantum dots) that generate and capture, at different levels of excitement, electrons that would ordinarily be lost in silicon systems; experimental cells of this type are approaching 40 percent conversion efficiency and would push the costs of PV cells down dramatically (Nozik, 2005).

However, reductions in other system components are just as important. The International Energy Agency (2006) summarized the potential of solar PV technology as huge, but at current rates the research and learning efforts needed to bring costs down to competitive levels could approximate US$100 billion—much higher than the cost for any other renewable resource technology.

Energy Storage

Emerging innovations in energy storage are highly relevant for the poor farmer in SSA and SA. First, they could reduce the costs and improve the efficiency of the current form of energy storage in use by the rural poor in these regions—batteries. In Uganda, where more than 80 percent of the population lives on US$1 a day, more than US$100 million is being spent each year on small, disposable dry-cell batteries for radios and lighting. Car batteries are used for other applications and are brought into town for recharging with a diesel generator. Second, energy storage has a role in maximizing the benefits of off-grid solar, hydro, and wind power, which are inherently intermittent. If excess power generated when operating conditions are favorable could be stored, energy would be available when operating conditions reduce generating capacity.

One practical way to store energy is in the form of pumped water. Japan uses this method in conjunction with nuclear-power stations. It pumps water from a low reservoir to an upper reservoir when electricity demand is at its lowest; during peak demand, the water is discharged back to the lower reservoir and drives a turbine to generate electricity (Ramage, 2004; Andrews and Jelley, 2007).

For a number of reasons, this is a good time to look for energy-storage solutions for small-scale farmers. Consumer-products manufacturers are in a race to miniaturize components, and hybrid-vehicle manufacturers are seeking to build lighter and less expensive batteries. As interest in renewable energy sources has grown, so have ways to increase their efficiency with energy storage.

Batteries store electricity in the form of chemical energy. A battery consists of two electrodes made of materials that have different chemical potentials with an electrolyte between them. When the electrodes are connected to a device, electrons flow through the device toward the more positive electrode, and ions move in both directions through the electrolyte. Lithium-ion batteries, first introduced in 1991, are rechargeable because ions of the same type, Li^+, move from each electrode through the electrolyte and are simultaneously extracted from and inserted into each electrode (Armand and Tarascon, 2008).

The energy-storage capacity of lithium-ion batteries is about five times higher than that of older lead-acid batteries and three times higher than that of conventional nickel-cadmium batteries. More than 2.4 billion batteries a year are produced for laptop computers and related devices. The shortcomings of current lithium-ion batteries include safety issues (fires due to runaway reactions), relatively low power output, and the fact that they ultimately lose their ability to be recharged (Scrosati, 2007). In addition, some of the battery components are mineral (cobalt or magnesium) ores that exist in scarce quantities and must be mined (Armand and Tarascon, 2008). They are also more expensive than conventional batteries, so people in rural parts of Africa are less likely to purchase them despite being reusable (Anand Gopal, University of California at Berkeley, presentation to committee, July 6, 2007).

Capacitors are conventionally used to provide a burst of electricity during the startup of a piece of electric equipment. Supercapacitors (also called electric double-layer capacitors or ultracapacitors) are more efficient and consist of two activated-carbon electrodes, an electrolyte, and a porous separator that permits the flow of ions but not electrons between the electrodes. When a current is passed across the electrodes, ions from the electrolyte are absorbed into the pores of both oppositely charged electrodes and are stored there. The storage of energy is electrostatic and not chemical, as in batteries; as a result, supercapacitors can both store and deliver energy rapidly. Their widely scalable storage capabilities make it possible to use them in conjunction with other devices, such as batteries and fuel cells (NRC, 2007). The benefits of supercapacitors are that they have a virtually unlimited life (they can be charged and discharged millions of times); they recharge in seconds, not hours; and they cannot be overcharged. Their limitations are that they discharge all their energy relatively quickly, can provide only rather low voltage, and until recently could not store electric energy very densely. For small applications and as a backup for short bursts of energy, a small supercapacitor could suffice; but for an electric car that otherwise runs on 400 kg of lead-acid batteries, a supercapacitor would have to weigh 8 tons (Okamura, 2004).

Batteries and capacitors are changing rapidly, and the two technologies are converging. Much of the change is being propelled by the manufacture of nanomaterials. In particular, the ability to make multiwall carbon nanotubes (MWCNs) promises to help supercapacitors to overcome their storage-density limits. Storage density is directly related to the amount of surface area of the electrodes and their pores where ions are absorbed. The electrodes of current supercapacitors are made of activated carbon, an amorphous material with nonuniform pores. In contrast, MWCNs are tightly packed, evenly spaced, vertically aligned strands (tubes). Packed together as viewed with an electron microscope, they collectively look like a paintbrush. Each 5-nm-wide strand of the brush is an electrode, so in the same space as activated carbon the MWCNs provide much more electrode surface area and, as a result, much greater storage capacity (Signorelli et al., 2004).

A recent breakthrough achieved in a seemingly simple fashion combined MWCNs with partially dissolved cellulose to make a highly flexible nanocomposite "paper" that functions as a superthin (less than 100 μm) supercapacitor with highly improved storage capacity and voltage. If a thin layer of lithium is deposited on one side of the nanocomposite paper, the device can act as a rechargeable battery. The two configurations can be used together as hybrids that have the desirable features of both batteries and supercapacitors (Pushparaj, 2007). The greatest hurdle that this technology faces is the cost of producing the MWCNs, although if production were scaled up costs would drop substantially (Scrosati, 2007).

There are many emerging approaches to batteries, for example, using biochemical processes to generate electricity and even using air as a chemical reactant in a lithium-oxygen or zinc-air device. The question for all of them is whether they can be developed into applications that meet the needs of small-scale farmers and rural communities. If they are to do that, the potential spectrum of the applications needs to be defined first—from rechargeable hand tools and small-farm equipment or vehicles to energy storage for the village-scale wind turbine. Coupling an understanding of the requirements for those applications with a plan for producing storage devices with the right specifications could move off-the-shelf applications to farmers much faster than the market normally would. Given the importance of stand-alone sources of energy and energy storage to rural farmers, helping to make these technologies more feasible and affordable warrants further research and commercialization.

Hydrogen and Fuel Cells

Hydrogen can be converted to electricity by using fuel cells. Fuel cells generate electricity or store energy in the form of hydrogen or other metals such as zinc or aluminum, and they provide carbon-free electricity with very low emissions, efficiencies of around 50 percent, and flexibility in that power output can be changed very quickly. They are currently expensive for routine use in developing countries, but this could change inasmuch as research is very active (Boyle and Everett, 2004). Hydrogen and metallic fuel cells have been widely advocated as an "energy carrier" for the future, but any practical scheme for large-scale use of hydrogen or other metals would require many steps, including storage and distribution facilities that require capital investments (Boyle and Everett, 2004).

Hydrogen is made now mostly from methane or natural gas, and the processes generate carbon dioxide (CO_2). Metals such as zinc and aluminum require significant electrical power to refine them from ore or the resulting oxide from battery use. In addition, in current market conditions, the 50 kWh of electricity consumed in the manufacture of 1 kg of hydrogen is roughly as valuable as the hydrogen produced, assuming US$0.08 per kilowatt-hour. However, many technologies that use renewable energy are being developed for hydrogen or metal generation; they are often suitable for local production, and Africa seems well suited to exploit several of them. The gasification of biomass produces large quantities of hydrogen and leaves behind a residue of high-grade carbon that can be used for chemical purposes and carbon that is likely to end up as CO_2 that can be reabsorbed if the biomass is sustainably grown (Larkin et al., 2004). Metallic "cycles" do not have the problem of CO_2 generation.

The desert regions of Africa seem optimal for the thermal dissociation of water into hydrogen and oxygen with solar collectors (Steinfield, 2005). Hydrogen can also be produced by direct electrolysis of water; this process could be used to produce hydrogen virtually anywhere from renewable energy: solar power in the deserts, wind power, hydropower, or geothermal energy (Everett and Boyle, 2004). Water can also be split by artificial chemical photosynthesis with photoelectrochemical cells; laboratory tests have confirmed the efficiency of this procedure, but there are problems, including corrosion of the semiconductors. Finally, the biological-energy production team of the J. Craig Venter Institute is focusing its efforts on biological production of hydrogen by recombinant cyanobacteria (Xu et al., 2005).

Biofuels

The production of liquid fuels from biomass is controversial worldwide for a number of reasons. One is that growing the feedstock competes with food production. For example, some economic analyses have suggested that if cassava were used as a major source of biofuel, food cassava prices could double or triple (Rosengrant et al., 2006). A second is that, depending on how it is produced, the energy from biofuels can vary widely. In SSA and SA, the starch encompassed in seed is more highly valued for food and animal feed. If agricultural productivity in those regions could be increased to world averages, land might be available for biofuel production.

Cellulosic Ethanol

Conversion of the vegetative tissues of plants into sugars or hydrocarbons can produce much more energy than conversion of seeds. The cell walls of plants and trees constitute the greatest amount of biomaterial on the planet. Plant cell walls consist of cellulose and hemicellulose fibrils intertwined with complex lignin molecules. During plant development, the chemical composition of cell walls varies from tissue to tissue within a species. The differences involve the length of cellulose and hemicellulose chains, the size and amount of lignin complexes, and thus the amount of constituent monomers. The amounts of inorganic molecules also differ, and this affects downstream processing of the plant material.

There are two general approaches to generating fuels from biomass:

1. The enzymatic conversion of the cellulose and hemicellulose in the biomass to sugars, followed by the fermentation of sugars to ethanol, butanol, or other alcohols.
2. A thermochemical step that involves pyrolysis of the biomass to make, for example, syngas (carbon monoxide and hydrogen) and conversion of these molecules to hydrocarbons of various sorts via Fischer-Tropsch synthesis.

Substantial investment and research are devoted to exploring different versions of those technologies to find the most efficient and cost-effective. Cellulosic fuel technologies will likely be cost-efficient by 2015.

Many areas of SSA and SA would be suitable for high biomass production, but the issue of whether land is to be devoted to energy or food production remains. Biomass from existing crop residues is available in all countries, but it is used for many purposes, including the important maintenance of soil fertility, which should not be sacrificed for fuel production (Doornbusch and Steenblick, 2007; Lal, 2007). The use of land that is marginal—that is, of poor quality for food production—has been proposed for growing biofuels. Warm-season, C_4 grasses—such as kallar grass, guinea grass, and elephant grass—might be candidates for energy production in SSA and SA. Sweet sorghum hybrids are particularly attractive sources of biofuels because they produce grain and sugar-rich stalks, and they produce more biomass, are more widely adapted, grow faster, and require less water than corn or sugar cane. As described in Box 7-2, there are many possible ways to make sweet sorghum, tropical trees, and grasses even better adapted for high biomass growth in various environments. Selected species need to be genetically selected for high biomass production and favorable energy-production ratios, and they should be the focus of modern breeding programs (discussed in Chapter 3).

A biofuel industry in SSA and SA can be considered appropriate only after food productivity increases so that it will not destabilize food production. Many of the crops proposed for biofuels would perpetuate subsistence

BOX 7-2
Breeding for Biofuels and Forage

Biomass for energy needs to be grown at high density to reduce transport costs, especially if it is not processed on the farm. Thus, biomass yield, incorporating high photosynthesis and optimal plant architecture, is a key trait for a breeding program. To sustain high yields, many improvements in crop-protection traits—such as drought and salt tolerance, disease resistances, and heat resistance—are also very important. Because the biomass needs to be processed in some way, the real yield is metric tons of fuel or energy per acre. Therefore, the plant breeder needs to improve traits that affect the chemical composition of energy crops to be commensurate with downstream processing technologies.

If the biomass is to be digested in an enzymatic process, it is desirable to breed for cell wall lignocellulose structures that are easily degraded by digestive enzymes. Today, a major cause of difficulty and cost is the pretreatment step applied to biomass before enzymes can efficiently degrade the cellulose and hemicellulose to sugars. It is possible to breed plants with reduced lignin and with different cell wall chemical structures that are easily degraded by enzyme cocktails or microorganisms. That has been achieved by forage crop breeders who assay plants for digestibility by enzyme systems characteristic of animal digestive systems.

There is a synergy between alternative uses of biomass on the farm. However, producing plants whose cell walls are easier to degrade often creates deficiencies that can result in reduced yields and increased susceptibility to pests and diseases. Thus, a balance has to be struck between yield and efficient cell wall degradation. The interest in cell wall biology in the United States that is being driven by the biofuels industry is likely to bring a new understanding of the lignocellulose complexes of plants and trees and aid in defining crop breeding objectives for processing to sugars for both biofuels and animal-feed purposes.

farming. Thus, biofuel production should be considered only if the biofuel crops produce sufficient revenue for rural communities, either from sale of the biomass or from additional employment in the biomass-to-energy sector. There can be many forms of such an industry. In some cases, the feedstocks could be regionally centralized if the transport costs were not too high and if centrally located biorefineries were built to process the biomass. In other cases, the biomass would be converted locally to supply local needs.

Halophytes

Halophytes appear to constitute a promising and relatively unexplored option for growing biofuel feedstocks that do not compete with scarce food-producing resources. Halophytes are salt-loving plants that grow in or with brackish water that most crops cannot tolerate. Halophytes with multiple uses include pickle weed and nypa forage (*Salicornia* spp.), salt grass (*Distichlis* spp.), saltbush (*Atriplex* spp.), and some algae (*Spirulina* spp.). The oilseed halophyte *Salicornia bigelovii* produces 2 tons of seed per hectare and fractions of oil and meal that are similar to soybeans (Glenn et al., 1999). Studies with *Atriplex* spp. and *Marianna* spp. in Pakistan showed high tolerance for salt, sodic, and waterlogged soils (Asad, 2002). Other halophytes with a high biomass-producing capacity include *Batis* spp., *Suaeda* spp., and *Sesuvium* spp. (Lal, 2001). Although those plants would seem to have applications in SSA and SA, most of the research on halophytes is taking place in Australia, which has a long-standing interest in halophytes for forage and for their potential to remediate saline soils (Barrett-Leonard, 2002).

Oilseeds

Jatropha curcas is probably the most highly promoted oilseed crop for biodiesel production in the developing world (Fairless, 2007). Immature fruits are harvested by hand in the dry season (winter) when the leaves have fallen; then they are dried in the shade, and the seeds are removed by hand. Common names for the nut—such as black vomit nut, purge nut, and physic nut—and for its oil, such as hell oil and oil infernale, refer to the plant's toxicity. The seeds contain alkaloids and curcin, a toxalbumin with similar sequences and similar oral toxicities to ricin (IPCS, 1990, 1994). The oil contains irritant and cancer potentiators or synergists: curcusones are diterpenoids of the tiglian (phorbol) type. The best removal procedures eliminate about half the phorbol esters (Haas and Mittelbach, 2000), and this is toxicologically unacceptable.

Castor bean (*Ricinus communis*) pollen contains numerous allergens, including some that are very common (such as latex allergens) and others that are found in poisonous seeds (Singh et al., 1997; Parui et al., 1999; Palosuo et al., 2002). Ricin, a toxalbumin, is the most toxic protein in the seeds (IPCS, 1990). When present at a low concentration, the ricin in the residue from manufacture of 50 L of biodiesel (a typical small-vehicle fueling) is sufficient to kill about two average-size people, and 30 people could be killed at the highest ricin concentrations. No antidote, vaccine, or other therapy is available for ricin poisoning, although attempts have been made to develop a vaccine against it (Griffiths et al., 2007).

After the seeds of *Jatropha* and castor bean are crushed for oil, the high-protein residue typically is spread on fields—a practice of questionable environmental safety and health. Removing the toxic compounds from these oilseeds might allow the residue to be safely used for animal feed. This is similar to the uses of soybean meal, which is both a high-quality animal feed and human food. Even with the recent demand of the oil for biodiesel, the value of the meal as a portion of the total value of soybean is greater than that of its edible and combustible oil.

Some *Jatropha* germplasm accessions have been found to be less poisonous than others (Makkar et al., 1998) but still too toxic for use as fodder. Castor bean varieties that are low in ricin and the related agglutinin have been bred, but they are still too toxic to be usable as feed (Auld et al., 2003). *Jatropha* can be transformed with transgenes and regenerated (Li et al., 2006). There are a number of possible strategies for interfering with *Jatropha* phorbol ester production, such as by antisense or RNAi suppression of genes in the phorbol ester biosynthesis pathway (Gressel, 2008). The gene for curcin, the toxin in *Jatropha*, has been cloned and the protein purified (Lin et al., 2003). The ricin gene from castor bean also has been sequenced (Tregear and Roberts 1992), and castor bean has been transformed and regenerated (McKeon and Chen 2003; Sujatha and Sailaja, 2005; Malathi et al., 2006). Curcin and ricin production could be suppressed by partial gene deletion with chimeraplasty surgery, a technology that uses RNA constructs to modify a gene without leaving a trace of recombinant material (Zhu et al., 2000).

By creating transgenic varieties of *Jatropha curcas* and *Ricinus communis* that are non-toxic to humans and animals, these transgenic varieties would be safe for humans and the environment and could be valuable for biofuels and animal feed. The removal of those toxins might make the plants more vulnerable to attack by insects and pathogens, but in one experiment this was counteracted by the addition of the *Bt* gene in the transformation cassette to control the castor semilooper (Malathi et al., 2006).

Other genes unrelated to the toxins would be helpful in domesticating the species. For example, *Jatropha* could be bred or modified for mechanical harvesting, just as breeding of castor bean has led to machine-harvestable varieties. Genes would have to be found that control shattering so that ripe seeds do not fall before harvest (Gressel, 2008).

Photosynthetic Microbes: Algae and Cyanobacteria

In the 1980s and 1990s, DOE's Aquatic Species Program explored the potential use of algae to make liquid fuels and decided that it was impractical because the growth of algae in open ponds was ruined by contamination from local microorganisms and the alternative, a closed bioreactor system, was too expensive to build and operate. Although the test sites met their goals of algae production, temperature fluctuations at night at the desert test site in New Mexico adversely affected the project. Nevertheless, when the project ended in 1996, the participants concluded that there was great potential for algae and that the main hurdle was the cost of production relative to the price of petroleum—US$70 per barrel versus what was then US$25 per barrel of fossil petroleum (Sheehan et al., 1998). There has recently been a modest revival of interest in the microbial production of biofuels in the United States, but it is in sunny, warm locations where the best natural conditions for growing photosynthetic microbes exist.

Algae and cyanobacteria, their prokaryotic forerunners, have several properties that make them promising for biodiesel production. First and foremost, algae species (*Botryococcus*, *Dunaliella*, *Scenedesmus*, and *Prymnesium*) can produce and accumulate more than 60 percent of their biomass as lipid (Becker, 1994). Some of the cyanobacteria, such as *Synechocystis* sp. 6803, have multilayered cell membranes that contain lipids. They can also be fed high concentrations of CO_2 from industrial flue gases without inhibition. The production of oil by photosynthetic microbes substantially outperforms other oil crops (Table 7-1).

Another feature of the organisms is that they have relatively simple growth requirements: water, sunlight, CO_2, and nutrients, such as nitrogen and phosphorus. Many of the organisms can tolerate saline or brackish

TABLE 7-1 Comparison of Lipid Production by Oil Crops and Microbes

Organism	Lipid Production (L/ha per year)
Microbes	72,000-130,000
Oil palm	4,000
Jatropha	2,700
Sunflower	570-1,030
Soybean	380-650

SOURCE: Courtesy of W. Vermaas (adapted from Huber et al. 2006 and incorporating data from W. Vermaas presentation to the committee in October 2007). Reprinted with permission. © 2007 by Willem Vermaas.

water, and most of the water used to grow them can be recycled. Finally, a byproduct of oil production is a residue that is potentially useful as animal feed.

Although algae produce oils at higher rates than cyanobacteria, oil production in algae appears to be inversely proportional to growth, so the algae double at a rate of only 0.6 times per day. Lipid production is triggered by environmental stress, so biofuel production is a survival mechanism. As a result, continuous oil production under stressed conditions eventually results in overall slower growth. Cyanobacteria are more easily manipulated with molecular biology, and the same evolutionary forces play a role in the growth of large amounts of the organism over time. Research on these microorganisms is assisted by the fact that the full genome sequences of several algae and cyanobacteria are available (NCBI, 2008).

It is possible to grow algae and cyanobacteria in open ponds, but ultimately, because of microbial contamination and the large parcels of land needed to increase the surface area exposed to solar radiation, relatively simple bioreactors can be devised. Plants evolved to take full advantage of sunlight can be grown erect, capturing not only direct sunlight but sunlight that is filtered or reflected by other plants before it reaches the ground. This upright design concept has been incorporated into sunlight-driven algal bioreactors to maximize the yield of biomass per acre of land. Closed bioreactors provide additional benefits, including physical containment and exclusion of microorganisms, convenient delivery of concentrated CO_2 to accelerate algal growth, facilitated harvest of biofuels from the organisms, the ability to reuse and recirculate water in the production system, and scalable modularity to support both large-scale and small-scale systems. To provide a controlled source of CO_2 for the plants, a bioreactor would be ideally constructed as an adjunct to a power plant, brewery, or other CO_2-emitting facility. However, some argue that because of the higher capital costs, the ideal design is to use simple closed bioreactors to feed open or covered ponds.

Federal and state sources funded substantial programs of algae cultivation in Hawaii during the 1990s. Bioreactors were developed to produce commercial quantities of astaxanthin for fish feed and medicinal applications. The enclosed bioreactors were also used in conjunction with open-air ponds aided by solar radiation.

The technical needs for developing photosynthetic microbes further for biofuels include the selection (or molecular design) of oil-producing organisms that are highly efficient in using light, can operate at temperatures where they will be used, and are readily amenable to biofuels extraction and processing; the ability to provide a high concentration of CO_2 in the liquids in which the organisms are growing; the availability of a secondary market for the residue; and an efficient bioreactor design.

Although the product is liquid that is de-esterified to produce diesel, it obviously can be combusted for electricity generation. The availability of molecular tools for increasing the efficiency of organisms, the flexibility of the technology with regard to scale, and the suitability of climates in SSA and SA make a convincing case to further pursue this unique opportunity.

Other Technologies

The committee was unable to examine all of the technological possibilities for energy production, including for example, manure bio-gas generators now used in rural farms in many parts of the world. Other types of technology not examined by the committee were innovations related to farm machinery. The replacement of rudimentary tools, such as the hoe, for mechanized tools that facilitate on-farm operations (ploughing, planting, weeding, drying, processing, storage) and reduce the drudgery of farming is likely to be a fertile area for innovation. However, mechanized technologies depend on an energy source, so these applications should be co-developed in combination with rechargeable batteries or capacitors. These and other energy technologies deserve further attention.

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8

Priorities for Emerging Technologies

The previous five chapters describe a wide variety of emerging technologies with the potential to improve the life of farmers in sub-Saharan Africa (SSA) and South Asia (SA) by increasing agricultural productivity and creating new opportunities for income. In this chapter, the committee recommends nine of those technologies for immediate development into applications for SSA and SA. Nine other technologies, in earlier stages of development, are recommended as priorities for intensive exploration. The chapter describes the committee's rationale and process for evaluating and prioritizing these technologies.

EVALUATING TECHNOLOGIES IN A BROAD CONTEXT

All of the technologies described in this report could potentially play a role in improving agricultural productivity. However, in addition to identifying technologies, the committee was asked to build a framework for prioritizing them, with the goal of recommending those most likely to have a transformative impact on farmers in SSA and SA. The committee's overall analysis was shaped by several themes that arose frequently during the course of the study. These themes or principles, described below, led the committee to examine priorities in a broader context. This approach was complemented by a set of criteria developed by the committee to evaluate the qualities of individual technologies.

- **Technologies must be implemented in a system-wide approach.**

Agricultural production is a complex system, the components of which are interdependent. In the ideal farm system, disease-resistant livestock are fed nutritious, easily digested forage and receive good veterinary care, producing healthy offspring and good quality meat and milk. High-quality, high-yielding seed are planted in fertile soil, and the crop is grown free of viruses, pests, and weeds. Nutrients are applied at appropriate times during the crop's growth cycle. Crops receive adequate sun and clean water, grow in an optimal temperature zone, and are harvested at the peak of maturity. Nutrients in the soil are replenished on a regular basis.

In reality, production systems in SSA and SA are far from this ideal. These agricultural systems are deficient in many components, collectively creating a barrier to improving production. Technological innovations can provide fixes for specific problems or components of the system, but they are not comprehensive solutions by themselves. In these regions, introducing even the most highly-effective technology may fail to provide even marginal increases in overall farm productivity. It is difficult to improve livestock reproduction or increase meat or milk production if the animals are chronically infected with pathogens and are fed low-quality, poorly digestible forages. The value of elite, locally-adapted germplasm is substantially diminished when it is planted in poor quality soil that is infested with weeds that harbor insect-borne viruses that infect the crop and limit its yield.

Developing solutions to the problem of poor agricultural productivity requires a multi-faceted approach to address deficiencies throughout the farming system. No one technology or constraint can be generally identified a priori as being more important than others.

- **The development and success of innovations require local expertise and participation.**

Individual farming systems require the development of their own set of technological priorities, and many of these requirements will need to be determined locally. Farmers will adopt a technology when they are convinced of its benefits; moreover, they need training to use technology effectively. As the individuals most intimately knowledgeable of their farm systems, they hold valuable insights for scientists trying to solve specific agricultural problems. An exchange between farmers and scientists is essential. Agricultural systems in industrialized nations have significant public and private extension services; the farmers in SSA and SA need the same support.

In addition, although not all aspects of technological innovations need to be developed locally, at some point, a technology will need to be evaluated to determine whether it fulfills local needs. Soils are diverse; their unique conditions need local evaluation and remediation plans. Animal vaccines will need to be tested against regional variants of pathogens in local breeds of cattle. Crop breeding requires the evaluation of phenotypes under local environmental conditions. The effective management of water requires local and regional coordination with the advice of local engineers and hydrologists. Weather prediction algorithms need rainfall data collected widely at the ground level. There is really no way to get around the fact that the successful development and implementation of technology requires the availability of local expertise.

- **Agricultural innovations for SSA and SA do not need to be based on "low" technology.**

Because farming systems and conditions in SSA and SA are different from those of many industrialized countries, there may be opportunities to adopt innovations that have been used less extensively in industrialized agriculture. For example, biocontrol programs or efforts to manipulate the soil biota, which have had mixed success in the United States, might perform better in regions where there has been less pesticide use. Subsurface irrigation, while expensive on a large scale, might be effective in growing high-value crops, like vegetables, on small plots.

Although farmers in SSA and SA are generally resource-poor, the need for innovations that are affordable should not be considered "low-tech" or "appropriate" technologies. Cost and cost-effectiveness are different concepts. For example, while farmer-saved seed will continue to be important for the very poor, it is counterproductive to suggest that it is the *only* good policy, given the performance of high-quality seed that has a high germination rate, is pathogen-free, and is clean of weed seed. Farmers who opt to plant seed saved from a previous harvest also forgo the benefits of heterosis—the vigorous performance of hybrid seeds that include higher yields and greater resistance to pests and diseases. The challenge to science is to either reduce the cost of hybrid seed or to find a way to maintain heterosis from generation to generation.

It is generally assumed that advanced technologies will be developed and used in industrialized countries before they are introduced to SSA and SA, but this means that technologies addressing specific needs in SSA and SA will never materialize if they do not fill a niche or need in the industrialized world. As a result, important opportunities may be missed, such as applications that could compensate for or provide alternatives to poor infrastructure that would otherwise take years to create. The development of off-the-grid energy sources is one example. Another is novel biofuels more suited to SSA and SA than to other regions. The use of biocontrol and biopesticides might be much more successful in SSA, where synthetic pesticide use is lower than in industrialized countries. Incentives and support for the development of specific applications could deliver benefits faster than waiting for market forces to propel technological development and letting benefits eventually trickle down to developing countries.

- **Climate change has implications for technological applications in SSA and SA.**

Farmers in SSA and SA already face severe environmental constraints, but by all predictions, their livelihoods will be imperiled by the future consequences of global climate change, especially water scarcity. Comprehensive planning to alleviate the economic and ecological impacts of drought will be needed. In Africa, where only 5 percent of agricultural land is irrigated compared to more than 60 percent in Asia, small-scale farmers suffer from the vagaries of weather that are inevitable in rain-fed agriculture. In Asia, water use is inefficient, water quality is increasingly poor, and the receding of Himalayan glaciers is an ominous sign for the future. For these reason, technologies that improve the availability and efficiency of water use, whether provided by irrigation, drought tolerant crops, or other mechanisms will be needed.

There are many unknowns about the future effect of global climate change on temperature, carbon dioxide levels, and the annual rain cycle in SSA and SA. In part, this is because existing weather conditions, models and forecasting tools for those regions are under-developed. If climate change creates more erratic weather conditions, it will be even more important in the future to provide farmers with forecasts of the onset of the rainy season, the prospect of severe weather events, and the likelihood of droughts.

CRITERIA FOR TECHNOLOGY EVALUATION

Within the context provided by these overarching themes, the committee used a set of questions or criteria to examine the relative merits of different technologies (Box 8-1). In general, higher value was placed on technologies that could be clearly aimed at a problem specific to agriculture in SSA and SA and that could provide the overall greatest benefit to farmers. This meant giving priority to technologies that could help the largest number of farmers and/or could most completely overcome the most severe problems. The next most important criterion was the speed at which a field-testable application could be developed, followed by the ability to easily disseminate the technology or to use it in applications of different scales. Other factors considered important, although given lesser weight, were the uniqueness of the “fix” provided by the application, the likelihood that development of the technology would lead to other breakthroughs, and whether the contemplated technological application was being developed

BOX 8-1
Criteria for Evaluating Technologies

- Is the technology relevant and applicable to agricultural constraints in sub-Saharan Africa and South Asia?
  - —Does it address a problem that is specific to these regions?
  - —Would it have a direct effect on agricultural productivity in these regions?
- What is the magnitude of the expected benefit?
  - —Will many farmers and the rural poor benefit from the technology?
  - —Will it address a widespread or severe problem?
  - —How complete a solution would it provide?
  - —Would it empower the farmer?
  - —Is it likely to have a direct effect on farmer income?
- How long would it take for the technology to become available?
- Could the technology be easily disseminated and adapted? Is it scalable?
- Does the technology address an issue that cannot be approached in any other way?
- Is the technology a gateway to other innovations in agriculture? Will it leverage the development of other technologies to help farmers in sub-Saharan Africa and South Asia?
- Is the technology already under consideration, or is the problem already being addressed?

elsewhere and was directed at a problem already receiving significant attention by many groups.

Although these criteria were useful for evaluating different technologies, using them to prioritize technologies had limitations, especially because the magnitude of the benefits anticipated from a particular technology could not be judged independently—the impacts of a single intervention are very dependent on the overall environmental conditions of farm systems. In some cases, because the technology or application was only in a conceptual stage, complete answers to the questions posed were not readily evident. In general, the criteria favored technologies that are more fully developed and proven rather than those in earlier stages of exploration. The committee considered these limitations as it reflected on the selection of priorities in the broader context of the themes described earlier.

CONCLUSIONS AND RECOMMENDATIONS

Of the more than 60 technologies described in the report, the committee selected 18, grouped into two tiers, as having the greatest potential impact on agricultural production in SSA and SA. The technologies are listed in Table 8-1 along with the chapters in which they appear in the report.

The committee concluded that applications based on existing technologies that enable better management of soil and water resources, harness the genetic diversity of crops and animals, and control biotic constraints on production will have the greatest impact on agriculture in SSA and SA in the least amount of time. The committee recommends that "Tier I" tools and technologies, which are connected to fundamental elements of agricultural production, be given the highest priority for development into specific applications. From the perspective of SSA and SA, these technologies are emerging, because applications specific to the needs of farmers in these regions have not been developed or widely used. Such applications can be built on existing technologies that have, in most cases, proven to be effective, but building those applications will be unique and challenging endeavors with a high payoff for farmers in these regions.

The committee also found that remarkable technological capabilities are emerging from advances in biology, chemistry, materials, remote sensing, and energy science that have important implications for agriculture. Although these advances will be universally important, farmers in SSA and SA may stand to gain the most from novel capabilities and agricultural applications that could meet their specific needs. The committee recommends that "Tier II" applications be given priority for further exploration to better elucidate their potential for implementation in SSA and SA. These applications are in various stages of development; some are not conceptually new but are being revitalized by scientific advances. Some of these will require

TABLE 8-1 Priority Tools and Technologies to Improve Agriculture in Sub-Saharan Africa and South Asia

Tier I High Priority for Application Development	Tier II High Priority for Additional Exploration
Soil management techniques—Chapter 5	Soil-related nanomaterials—Chapter 5
Integrated water management—Chapter 4	Manipulation of the rhizosphere—Chapter 5
Climate and weather prediction—Chapter 4	Site-specific gene integration—Chapter 3
Annotated crop genomes—Chapter 3	Remote sensing of plant physiology—Chapter 3
Genome-based animal breeding—Chapter 6	Microbial genomics of the rumen—Chapter 6
Plant-mediated gene silencing—Chapter 3	Sperm stem cell transplantation—Chapter 6
Biocontrol and biopesticides—Chapter 3	Solar energy—Chapter 7
Disease-suppressive soils—Chapter 5	Photosynthetic microbe-based biofuels—Chapter 7
Animal vaccines—Chapter 5	Energy storage—Chapter 7

significant long-term research to better ascertain their potential value, and to determine whether it is possible to develop them into cost-effective applications. It may be possible to capitalize on investments in research efforts already under way in these areas and make rapid progress toward applications for SSA and SA.

DISCUSSION OF TIER I AND II TECHNOLOGIES

Natural Resource Management

Soil quality was the number one issue identified by scientists from SSA and SA as important for increasing agricultural productivity in these regions. The prospect of water scarcity was the most commonly raised issue of greatest concern in the future. The committee considers the development of soil and water management applications as high priorities. Because soils and water are closely related and the climatic and socioeconomic conditions in which they exist differ regionally, approaches to their management are highly situational and should be area-specific and integrate natural and social factors. Soil and water management are integrative technologies—they require multiple methods determined for a particular site. The elements of different soil management systems described in Chapter 5, have similar objectives: to increase soil carbon content, enhance soil water infiltration, ensure the availability of water at the plant root zone, reduce soil erosion, create a positive nutrient budget in the soil, suppress the populations or activities of soilborne plant pathogens and soil-inhabiting insect pests, and encourage beneficial soil organisms. Water management techniques, described in Chapter 4, include an array of on-farm irrigation water capture, storage, and field application technologies that address the need to use water most efficiently. This includes technologies such as subsurface drip irrigation, which is highly efficient, but currently expensive for use on a large scale. However, its use in small plots might enable the growth of high-value crops to offset the added cost.

The ability to more accurately predict the onset of the tropical rainy season or drought would be a transformative development for farmers in SSA and SA, who would be able to make pivotal timing and management decisions about their farming operations. These decisions make the difference between having a good crop and no crop at all. Models, databases, and monitoring devices for weather prediction that are taken for granted in industrialized countries do not exist in SSA and SA. Moreover, in spite of intense international interest in global climate change and its influence on the climate of the large land masses encompassed by SSA and SA, data collection and the algorithms needed to enhance existing climate models are severely lacking. For this reason, weather and climate prediction are Tier I priorities for development.

The committee recommends three Tier II technologies for further exploration. One is the use of naturally occurring or synthetic nanomaterials as soil amendments, including the development of a slow-release fertilizer. There are natural and synthetic zeolites that release phosphorus and nitrogen slowly; these compounds are prototypes for further nano-molecular refinements that could confer greater control of the conditions for or timing of release and dramatically improve fertilizer efficiency.

A second area of exploration is the manipulation of the rhizosphere, which includes efforts to influence root architecture for greater carbon sequestration and increased water and nutrient uptake, and to encourage the growth of a microbial community that improves root health and crop growth. Although exploration of the rhizosphere is not new, novel molecular tools are providing greater insights to what might be the most critical processes in crop growth. The capability of manipulating this environment in the face of escalating fertilizer costs may someday transform the way that farmers approach agriculture.

A third emerging technology is the use of optical sensing of plant physiological characteristics as a tool for nutrient management and determining the state of plant health and growth. Current technology has the ability to predict yield potential midway through the growing season and to suggest future fertilizer requirements based on the amount of nitrogen being removed from the soil by a plant. Hyperspectral information collected remotely could be connected to satellite-based, information-gathering systems that would be used by both farmers and scientists. Farmers who access this information could use it for decision-making, and scientists could use it for many different purposes, including documenting changes in the landscape, and the collection of phenotypic information from plants that is important for breeding programs. Although at first glance this seems an unlikely tool for poor farmers, the use of remote sensing information to obtain indicators of a diversity of changes on the landscape (from the conditions of crops to the spread of plant and animal diseases) has the potential to become an increasingly practical and valuable decision-making tool.

Using Genetic Diversity for Crop and Animal Improvement

It is imperative that modern breeding systems for the crops and animals of importance to farmers in SSA and SA become the focus of intensive international efforts, because they represent the best tools available for plant and animal improvement. For this reason, the committee places these technologies (described in Chapters 3 and 6) on the Tier I list. High-quality reference sequences and annotations for genomes of all the relevant major crops in SSA and SA can be built on those already available for rice and sorghum and on the emerging maize genome sequence A community of researchers should be tasked with characterizing chromosomal variation in the germplasm of each crop species by using molecular markers, the locations of nucleotide polymorphisms, and haplotypes that can be linked to germplasm accessions and information associated with them. The construction of databases of this nature is pivotal if advanced molecular tools are to be used to improve crops in SSA and SA.

Modern animal-breeding approaches will require a strategy for recording and collecting important phenotypic characteristics and DNA samples from about 10,000 animals. For SSA and SA, it will be necessary to build reference genome sequences for water buffalo, indigenous breeds of cattle that exhibit superior survival traits, and economically important breeds of dairy and meat goats. Using reference genomes as a template, it may be possible, through newly developed bioinformatics approaches, to simultaneously construct a pedigree and associate economically important traits with haplotypes. The haplotypes would be used to identify animals with outstanding genetic merit.

Modern breeding systems require methodical organization and an expansive effort that could easily include dozens of scientists and technicians from in and outside of the regions for which improved crops and animals are to be raised. Although this is a significant undertaking, it is the foundation of any modern agricultural system and its benefits would be long-lived.

The committee identified one Tier II application that would contribute to crop improvement, namely site-specific gene integration, described in Chapter 3. This technology would fulfill the ultimate dream of breeders to be able to precisely replace one allele of a gene with another allele that performs better for the trait it controls, under the conditions desired, without carrying along with it other genes that have no relevance and may even be deleterious. Whereas homologous recombination (the precise exchange of one allele for another) has been fairly routine in many animal systems, it has not been possible until recently to achieve in plant systems with any useful frequency. Having such a technology available should transform breeding and also ease the path for use of safer and more precisely controlled transgenic approaches to crop improvement.

For animals, two important Tier II applications described in Chapter 6 are recommended for further exploration. Spermatogonial stem cells (SSC), the precursors of sperm, could be harvested from genetically superior males and transplanted into sires with less genetic potential. Those sires, in which the SSCs would multiply, would then be distributed to villages or small farmers. The technology could essentially provide a means for distributing superior germplasm while bypassing the need to establish the substantial infrastructure required for artificial reproductive technologies.

The second Tier II application for animals would be based on a better understanding of the microbial ecology of the rumen. Perhaps the most important limiting factor for cattle production in SSA and SA is poor animal nutrition. If it were possible to increase the efficiency of the microorganisms in the rumen that play important roles in fiber digestion and nitrogen metabolism, animal productivity (meat and milk) could be improved. Our understanding of the microbial communities in the rumen and the complex enzymology of fiber digestion has increased, but the information is incomplete. Continued work is needed to understand the enzymatic processes of ruminal fermentation. Because the techniques needed for study of the rumen are similar to those required for study of other microbial systems—including soils, food fermentations (for example, yogurt and cheese), and biofuel production—this microbial system should be further explored.

Overcoming Biotic Constraints

Biotic stresses, including the diseases of animals and crops, insect pests, and weeds, cause substantial agricultural losses to farmers in SSA and SA. Several technologies are available to address these stresses, and the committee recommends an immediate effort to build applications based on them. One of the most exciting developments in plant biology in recent years was the discovery of small RNA molecules (RNAs) that play key roles in plant development and resistance to stresses. This discovery has led researchers to create vectors containing genes that encode RNAs that target and down-regulate genes or interfere with a gene's control of critical processes related to the interactions of plants with biotic stressors. Described further in Chapter 3, research results strongly suggest that plant-mediated delivery of gene-silencing RNAs can be used to control viruses, nematodes, certain insects, and possibly also parasitic plants and fungi. If successful, the development of this technology against such selected targets as the RNA viruses affecting many crops and *Striga* (witchweed) would be a major breakthrough in plant protection.

Also described in Chapter 3 are alternative technologies to synthetic insecticides that might be particularly effective in Africa. These include classical biocontrol (releasing a pest's natural enemies to control its population) and biopesticides (toxins produced by naturally occurring pathogens of the pest). Fungi, for example, are the most common pathogens in nature; they attack thrips, aphids, and weeds, and their mode of action by direct penetration of the cuticle makes them suitable candidates for controlling sucking insects and weeds. Fungi may also be useful for controlling storage pests, and have the potential to be engineered with traits that increase their virulence. This area of science is ripe for breakthroughs and new applications.

A technology with a long history, but for which scientific understanding has been limited until recently, is disease-suppressive soils, discussed in Chapter 5. Soils in which crop-associated microbial communities are actively managed have been shown to reduce plant disease and pest problems. There are several different science-based approaches to developing disease-suppressive soils, and molecular tools are increasing the ability to document and better control outcomes in different soil environments. Given the regionality of cropping systems and different disease pressures, such new tools would be very useful in developing inoculants for commercial use in SSA and SA.

Animal vaccines are an active area of research for industrialized and developing country agriculture; this effort needs to be expanded. Existing vaccines used in industrialized countries need to be tested in the local environment, but at least some gains in meat and milk productivity might be expected by using them. Development of effective vaccines against parasitic and insect-vectored diseases would transform animal production. Several different approaches to vaccine production described in Chapter 6 offer potential.

Opportunities for Energy Production

Over the next several decades, significant public and private resources will be committed to developing renewable alternatives to fossil-based energy sources. If there were ever an opportunity for SSA and SA to leap beyond the status quo of energy supply infrastructure, now is the time. Although the regions' needs for energy transcend agriculture, the availability of additional energy for agricultural production would provide farmers with greater production capability and new opportunities.

Plant-based biofuels, like cash crops, will have a role to play in the agricultural economies of the developing world, but the committee identified two other types of energy generation—solar and photosynthetic microbes—as alternatives that merit greater exploration. These technologies, described in Chapter 7 were identified as Tier II applications because it was felt they had significant potential for SSA and SA, but were accompanied by many uncertainties.

Although many developing countries have invested in oil palm and *Jatropha* as sources of oils for biodiesel, the most productive biodiesel-producing organisms are algae and cyanobacteria. Photosynthetic microorganisms use energy from the sun to efficiently convert water and carbon dioxide into biomass, which can be converted to renewable fuels. A potential by-product of their growth is animal feed. Algae and cyanobacteria exhibit a variety of properties that make them well suited for use in biodiesel production: many species exhibit rapid growth in warm temperatures, produce high levels of oil, and can be genetically manipulated.

In addition to liquid fuels, the rural poor need electricity. Solar technologies include "third-generation" photovoltaic (PV) cells and concentrating solar (solar thermal) technologies used in conjunction with devices such as Stirling engines. Although cost and scalability are issues that need to be explored, there is already a market for PV cells and solar thermal applications in SSA and SA; expanding markets and capturing innovations for rural applications would allow these regions to be at the forefront of technology adoption.

For off-the-grid applications to achieve their potential, it will be essential to complement their use with energy-storage devices. Alternatives to batteries include ultracapacitors, which have recently been improved through the incorporation of carbon nanotubes. As energy-storage devices, they have several advantages over batteries, including very high rates of charge and discharge and low degradation over thousands of cycles. Unlike batteries, they are made of materials with low toxicity. The devices are predicted to replace batteries in the industrialized world in the future, but their role in SSA and SA could be to store locally produced electricity.

FINAL THOUGHTS: BUILDING LOCAL CAPACITY

Many of the technologies described in this report are likely to be developed into agricultural and other applications for the industrialized world by the public and private sector in industrialized countries. It is far from certain that the same will happen in SSA and SA, even though, given the low agricultural productivity in these regions relative to the world average, there is an enormous opportunity to make dramatic improvements with existing and emerging technologies. In the committee's view, the weak state of public and private capacity for research, development, and extension, if not corrected, will undermine the chances for this potential success. Even when international donors put substantial resources behind efforts to achieve rapid solutions to problems in SSA and SA, experience shows that without strong local partners, advanced science almost never succeeds in achieving sustainable results. The need for building local capacity to engage in successful partnerships has been cited in numerous high-level reports (e.g., NEPAD, 2002; IAC, 2004; Juma and Serageldin, 2007).

For both crops and animals, there is a need to strengthen the national agricultural research programs, university training, and research so that breeders can apply advances in genomics, gene discovery, and transgenic technologies. Training for more veterinarians and animal scientists is needed, and a network for carrying out routine crop and animal disease diagnostics is essential.

A long-term commitment to the development of human resources in these regions is needed at the level of technicians, extension agents, agricultural engineers, and research professionals. Although many countries in SSA and SA maintain a large number of agricultural extension agents on government payrolls, they do not have sufficient resources to get into the field or to develop and provide the information they need to support farmers. In addition to local radio, the growing access to the Internet and cell phones can be used to great advantage in these regions to transform services. The delivery of information does not need to be in only one direction. The establishment of farmer-to-farmer or peer networks could also use new tools of information technology as a powerful means of communication.

Local expertise can be built with efforts in and outside SSA and SA. One idea is to create training opportunities for young scientists in SSA and SA that are tied to research on agricultural problems in these regions by the world's most accomplished scientists (see Box 8-2). Another is to create "regional innovation communities" that would pool resources of independent research institutions to work on specific technology missions important to the region. Such communities would bring together local populations, businesses, universities, governments, and international partners in focused collaborative efforts that would allow "technologically weak countries to articulate their demand for technology, innovation policy and related institutional adjustments" and would improve the confidence of Africans in managing their own development (Juma and Serageldin, 2007). The technical community of SSA and SA can become innovators on behalf of their own farmers. The methodical effort to eradicate rinderpest from cattle in Africa is evidence of the ingenuity and determination of scientists and practitioners from the continent to solve a major agricultural problem.

The U.S. land-grant colleges and universities and their colleges of agriculture constitute a model of effective integration of research, teaching, and extension that is relevant to regional agriculture. As originally conceived, those institutions were provided with land, facilities, and recurring state and federal financing to support research and teaching that were important for farmers, ranchers, and foresters. The knowledge and technical know-how coming from their research was made publicly available through extension faculty who taught the best farming practices and maintained demonstration plots, yield trials, and diagnostic clinics. Some of these U.S. universities could become effective partners in strengthening postsecondary educational institutions in SSA and SA.

CONCLUSION

Technology is not a complete solution to the needs of farmers in SSA and SA, but for far too long these farmers have toiled without the benefits of technology that producers in the industrialized world have enjoyed. As a result, the potential effects of improvements built on new and existing technologies are great. In this study of emerging technologies, many

BOX 8-2
Bringing Talent to the Challenges of Agriculture

The Howard Hughes Medical Institute (HHMI) has helped to attract top scientists to address key problems in biology. Its approach is based on the conviction that exceptionally talented scientists will make important fundamental biological discoveries that will improve human health if they are provided the resources, time, and opportunity to pursue challenging questions. HHMI supports 298 investigators and approximately 30 international scholars, who are selected through rigorous national competitions and who include 12 Nobel Prize winners and 122 members of the U.S. National Academy of Sciences. They work in more than 64 U.S. and foreign universities, research institutes, medical schools, and affiliated hospitals. HHMI supports nearly 700 postdoctoral scientists and provide training opportunities for more than 1,000 graduate students each year.

A program similar to that of HHMI but dedicated to research on the constraints facing agriculture in SSA and SA could breathe life into the agricultural sciences in these regions. A core of 20 to 30 investigators in international laboratories would create the foundation of such a program; sufficient financial resources would need to be provided to allow the research to become a primary activity of the laboratories. The fellows could be identified by competition and be periodically reviewed to document the quality and productivity of their research. A major goal of such a program would be to make funds available to the best and brightest young students of SSA and SA to train in labs of their choice, with the aim that they would return to their home countries with some funding of their own to establish laboratories and become future academic and scientific leaders.

Over the long term, competitive grant programs are needed in SSA and SA directed at scientists at early stages in their careers, with funding going to the scientists not the institution. The possibility of mid-career sabbatical grants would also prevent stagnation and bring new ideas back into their home programs. The long-term outcome of such an effort would be the creation of a core of well-educated, well-trained scientists that share a common bond and have the interest and dedication to build comparable research institutions in their home countries.

technological tools were identified that could be put to use to improve agricultural productivity and empower farmers to control their growing environments, their results, and their opportunities for income. The specific applications that will be based on those tools will require further articulation and a road map of the research and development needed to bring them to fruition. The committee hopes that the worldwide scientific community will join the effort to apply the tools to the needs of SSA and SA so that one day they will achieve the self-sufficiency in food production of which they are capable.

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NEPAD (New Partnership for Africa's Development. 2002. CAADP (Comprehensive African Agriculture Development Programme). Available online at *http://www.fao.org/docrep/005/y6831e/y6831e00.htm* [accessed April 1, 2008].

Appendixes

Appendix A

Committee Statement of Task

A multinational, multidisciplinary committee will study the potential for new scientific information and technological tools to assist farmers in Africa and South Asia in the production of food and fiber. The study will consider the potential impacts of existing and nascent technologies and explore novel, possibly far-reaching, solutions to problems facing developing country farmers, including research pursuits that are only in a conceptual stage. The committee will organize workshops to bring agricultural scientists together with scientists working on advanced technologies and technological systems in different disciplines. The study committee will develop a framework for ranking the ideas that emerge from the workshops and prepare a consensus report that presents its findings, including categories of specific needs and the scientific and technological breakthroughs that could address those needs. The report will discuss the relative merits of different research approaches and technological directions, including the probable time frame and level of effort required to achieve particular breakthroughs and applications, and the relative potential of different technologies to positively impact farming in the developing world.

Appendix B

Biographic Sketches of Committee Members

Brian A. Larkins, *Chair*, is the Porterfield Professor of Plant Sciences at the University of Arizona. He previously was the Associate Vice Chancellor for Research and Distinguished University Professor of Life Sciences at the University of Nebraska, Lincoln. Dr. Larkins is an expert in seed biology. He characterized the zein seed protein genes of maize and illuminated the events leading from gene expression through deposition of zein proteins into protein bodies of the maize kernel, with significant implications for protein nutrition of humans worldwide. Dr. Larkins was elected to the National Academy of Sciences in 1996. He was a member of the National Research Council (NRC) Subcommittee on Environmental Impacts Associated with Commercialization of Transgenic Crops: Issues and Approaches to Monitoring. Dr. Larkins was an associate editor of *Plant and Cell Physiology* from 2002 to 2005. From 1991 to 1992, he was President of the International Society for Plant Molecular Biology and from 1998 to 1999, the President of the American Society of Plant Physiologists. Dr. Larkins earned a B.S. (1969) in biology and a Ph.D. (1974) in botany, both from the University of Nebraska, Lincoln, and he was a Postdoctoral Research Associate in Biochemical Genetics and Plant Physiology at Purdue University from 1975 to 1976.

Steven P. Briggs is a professor of cell and developmental biology at the University of California (UC), San Diego. His research looks at post-transcriptional determinants of plant innate resistance to infectious disease using protein profiling by tandem mass spectrometry combined with plant gene engineering. His formal training is in plant biology, but his interests encompass the broader issues of systems biology and regulatory problems in a variety of organisms. Dr. Briggs was elected to the National Academy of Sciences for being the first to isolate and characterize the mode of action of a plant disease resistance gene, Hm1, from maize. Before joining the UC San Diego faculty, Dr. Briggs was the Senior Vice President for R&D Platforms at Diversa Corporation, and before that, the President and Chief Executive Officer of Novartis Torrey Mesa Research Institute, and global Head of Genomics at Syngenta AG. Dr. Briggs received his Ph.D. and M.S. in plant pathology from Michigan State University, and his B.S. in botany from the University of Vermont.

Deborah P. Delmer recently retired from her position as the associate director of food security at the Rockefeller Foundation, where she was the science and policy advisor for research related to the advancement of agriculture in developing countries. The focus of her work with the Rockefeller Foundation was agricultural development in Africa. She particularly highlighted abiotic stresses, such as poor soil quality, metal toxicity, and drought, and biotic stresses such as pests, pathogens, and parasitic organisms, as two central problems facing African farmers. She has discussed the need for plant biologists to devote more energy to the realm of translational science, much like the health sciences have recently done. Dr. Delmer was formerly a professor and chair of the Department of Plant Biology at the University of California, Davis (1997-2001). She identified the first cellulose synthase gene in flowering plants. Her research has provided fundamental insights into the enzymatic mechanisms by which cellulose and other complex cell wall polysaccharides are synthesized. Dr. Delmer was elected into the National Academy of Sciences for work that pioneered research in cellulose biosynthesis. Dr. Delmer received her Ph.D. (1968) in cellular biology from the University of California, San Diego, and A.B. (1963) in bacteriology from Indiana University.

Richard P. Dick joined Ohio State University's College of Natural Resources as an Eminent Scholar in Soil Microbial Ecology in 2004. His research interests are focused on soil ecology and the role of management in affecting soil functions within ecosystems. Dr. Dick studies the biochemical properties and processes in the soils in combination with microbial community analysis by using techniques that measure enzyme activities, microbial biomass, functional diversity, stable isotope probing, and phospholipid profiling (PLFA) of the microbial community structure. Dr. Dick's research has led to the development of soil-enzyme assays that can be used as rapid indicators of the effects of soil management and pollution on soil biology. Land managers and public and regulatory personnel can use those assays to identify degraded soils and to determine when remediation of soils is complete. He has supervised many graduate students from developing countries and had a leadership role in a large U.S. Agency for International Development (USAID) agricultural capacity building project in Senegal. Dr. Dick is currently working on a large National Science Foundation (NSF) grant (biocomplexity) on the regulation of hydrological and C cycles by native shrubs in sub-Sahelian Africa. Dr. Dick earned his doctorate in soil science from Iowa State University in 1985. He joined Oregon State University as an assistant professor in that year and attained the rank of associate professor in 1991 and of professor in 1996. In 2004 he was awarded an endowed chair as an Ohio Eminent Scholar, and he is currently a professor of soil microbial ecology. He is a Fellow of the Soil Science Society of America and the American Society of Agronomy and was awarded the Senior Research Fulbright Scholar Award in 2000 to conduct research in West Africa.

Richard B. Flavell is the Chief Scientific Officer of Ceres, Inc., a California-based plant genomics company. He also is currently an Adjunct Professor in the Department of Molecular, Cellular and Developmental Biology at the University of California, Los Angeles. From 1987 to 1998, he was the Director of the John Innes Centre in Norwich, England, a premier UK plant and microbial research institute. Dr. Flavell is an expert in cereal plant genomics, having produced the first molecular maps of plant chromosomes to reveal their constituent sequences. In 2004, he chaired a scientific and management review of the International Rice Research Institute in the Philippines. He currently serves on the International Biofortification Program Advisory Committee of the World Bank's Consultative Group on International Agricultural Research (CGIAR). He served previously as Secretary to the Board and Executive Committee of ISAAA (International Service for the Acquistion of Agri-biotech Applications). In 1999, Dr. Flavell was named a Commander of the British Empire for his contributions to plant and microbial sciences. Dr. Flavell received his Ph.D. from the University of East Anglia and is a Fellow of EMBO and of the Royal Society of London.

Jonathan Gressel is professor emeritus of plant sciences at the Weizmann Institute of Science in Israel. He and his research group have actively developed crops, biocontrol agents, and agrotechnologies to facilitate control of parasitic weeds (such as *Striga*) with colleagues in Mexico and Kenya. He is the author of over 265 scientific papers and book chapters and author, co-author, or editor of 6 books. His most recent books are the *Molecular Biology of Weed Control* (2002), and *Genetic Glass Ceilings: Transgenics for Crop Biodiversity* (2008). Dr. Gressel is a past-president of the International Weed Science Society. He was chairman of the scientific program committee for the 3rd International Weed Science Congress, held in June 2000 in Brazil. Dr. Gressel received his Ph.D. (1963) in botany and horticulture and M.Sc. in botany from the University of Wisconsin, and his B.Sc. from Ohio State University.

Tsegaye Habtemariam is the Dean of the College of Veterinary Medicine, Nursing, and Allied Health at Tuskegee University. Prior to his appointment as dean, Dr. Habtemariam served as associate dean for Research and Graduate Studies; Director of the Center for Computational Epidemiology, Bioinformatics, and Risk Analysis; Director of Biomedical Information Management Systems; and Professor of Epidemiology and Biomedical Informatics. Dr. Habtemariam has conducted more than a dozen international workshops in Africa, the Caribbean, and the United States in order to train scientists in science-based risk analysis of animal disease. He has served as a consultant for the Pan American Health Organization and the World Health Organization; was elected honorary member of the American Veterinary Epidemiology Society (2004); and served on the National Advisory Committee in Microbiological Criteria in Foods (2000-2002). Dr. Habtemariam received his Ph.D. (1979) in epidemiology and MPVM degrees from the University of California, Davis, a D.V.M. (1970) from Colorado State University, and a B.S. in animal sciences from H.S.I. University, Ethiopia. Dr. Habtemariam has a broad knowledge of animal diseases that affect developing countries.

Rattan Lal is a professor of soil sciences at Ohio State University (OSU). He also directs the OSU Carbon Management and Sequestration Center and the South Asia Initiative. Dr. Lal worked for 17 years at the International Institute of Tropical Agriculture in Ibadan, Nigeria, where he chaired the International Committee on Tropical Deforestation and Land Development. He is the chief editor of the *Encyclopedia of Soil Science*, and he has received numerous awards for his work on soils, including the American Society of Agronomy's Environmental Quality Research Award (2004). Dr. Lal received his Ph.D. (1968) in soils at Ohio State University, M.Sc. (1965) in soils at the Indian Agricultural Research Institute in New Delhi, India, and B.Sc. (1963) in agriculture at Punjab Agricultural University in Ludhiana, India. He grew up on a farm in Punjab, India. Dr. Lal has a vast understanding of the soil conditions in many regions of the world, in particular South Asia and Africa.

Alice N. Pell is the Vice Provost for International Relations and Director of the Cornell International Institute for Food, Agriculture and Development (CIIFAD). As director of CIIFAD, most of her research focuses on tropical farming systems, with an emphasis on Africa, the centerpiece being an interdisciplinary project on the relationship between poverty and environmental degradation in the densely populated Kenyan highlands. Prior to that appointment, she was a Professor in the Department of Animal Sciences at Cornell University. Dr. Pell's research areas and teaching fields include rumen microbiology, forage evaluation, modeling, and nutrient cycling. Dr. Pell recently completed two terms as a member of the NRC's Board on Agriculture and Natural Resources. She served as a member of the NRC Subcommittee on Dairy Cattle Nutrition and the Committee on Animal Nutrition. Dr. Pell received her undergraduate degree and a summa cum laude on her thesis in architectural science from Radcliffe College at Harvard University; her master's degree in education from Harvard Graduate School of Education; and her master's and Ph.D. degrees in animal science from the University of Vermont.

Raymond J. St. Leger is a professor of entomology at the University of Maryland. His research focuses on understanding the fundamental biology of insect pathogenic fungi and exploiting their entomopathogenic properties for agricultural benefit. In 1996, he supervised a Centro Nacional de Investigaciones de Café (CENICAFE) project on coffee pest management in Columbia. In 2001, he collaborated with the Biocontrol Institute of China to develop effective mycoinsecticides against grasshopper pests. He currently works with the coffee federation of Columbia to produce a fungus that targets the broca beetle, a major pest of coffee. Dr. St. Leger is a member of the Society of Invertebrate Pathology, Society of Microbiology (UK), American Mycological Society, American Society of Microbiology, and the Genetics Society of America. In 1998 he was a finalist for the Office of Technology Liason's Invention of the year for a novel insecticide. In 2002 he won the faculty research award for the College of Life Sciences. He received his B.S. (1978) in biology from Exeter University (UK), his M.S. (1980) in entomology from the University of London (UK), and his Ph.D. (1985) from the University of Bath (UK). Dr. St. Leger is an expert on insect biology and novel methods to protect plants from insect pests.

Robert J. Wall is a research physiologist with the Biotechnology and Germplasm Laboratory at the U.S. Department of Agriculture and an adjunct faculty member at the University of Maryland. Dr. Wall's work in genetic engineering has focused on producing healthy transgenic animals by efficient means. His lab has produced genetically engineered cattle that are resistant to infection by a mastitis causing bacterium, demonstrated that a synthetic genetic switch can be used to turn off an oncogene (thus reversing the hyperplasia caused by a virally induced cancer), and included matrix attachment region (MARs) sequences in gene constructs to double the production of functional transgenic animals. In 1988, Dr. Wall was a member of NRC's Panel for Review of Agricultural Sciences Research Proposals Under the A.I.D. Research Grants Program for the Historically Black Colleges and Universities. In 2005, Dr. Wall was recognized with the Agricultural Research Service Beltsville Area Senior Research Scientist Award for his outstanding research accomplishments in the introduction of recombinant DNA molecules into the genome of agricultural animals. Dr. Wall received his Ph.D. in 1981 from Cornell University.

Appendix C

Responses from Sub-Saharan African and South Asian Scientists

To understand the agricultural constraints facing farmers in sub-Saharan Africa and South Asia, the committee asked for direct input from scientists in those regions. The committee staff sent letters to more than 200 scientists by e-mail in late May 2007 (see Box C-1).

The committee is grateful to the 45 respondents below who provided valuable insight on the most serious constraints in agriculture in sub-Saharan Africa and South Asia.

Nur Abdi, Global Forum on Agricultural Research
Anne Starks Acosta, Forum for Agricultural Research in Africa
Sampson Agodzo, Kwame Nkrumah University of Science & Technology
Mpoko Bokanga, African Agricultural Technology Foundation
Boniface Bouan, Centre National de Recherche Agronomique de Côte d'Ivoire
Claudio Bragantini, affiliation unknown
Joyce Cacho, The Corporate Council on Africa
Tim Chancellor, Natural Resources Institute
Kazhila Chinsembu, University of Namibia
Remi Cole, The New Partnership for Africa's Development
Thomas W. Crawford, Jr., International Center for Soil Fertility and Agricultural Development
Dr. Mohammed El Mourid, International Center for Agricultural Research in the Dry Areas, Tunis
Kenedy Etone Epie, International Institute of Tropical Agriculture
Mary Jean M. Gabriel, Department of Agriculture, South Africa

Les Hillowitz, CropLife Africa Middle East
Assetou Kanoute, affiliation unknown
Dyno Keatinge, International Crops Research Institute for the Semi-arid Tropics
Monica Kapiriri, Non-governmental Organisations Committee
Saidou Koala, International Crops Research Institute for the Semi-arid Tropics
Elisa Lenssen, Harvard University
K.B. Liphadzi, Limpopo Department of Agriculture
Chebet Maikut, Eastern Africa Farmers Federation

BOX C-1
Letter Inviting Comment about the Most Serious Constraints on Agriculture in Sub-Saharan Africa and South Asia

Dear Colleague:

I am writing on behalf of a National Research Council committee exploring emerging technologies to benefit farmers in sub-Saharan Africa and South Asia. In this one-year study funded by the Bill & Melinda Gates Foundation, the committee is tasked with looking over the future horizon to find new areas of science and technology that, if developed into applications for agriculture, might have a major impact on the productivity and income of farmers in those regions.

As a first step, the committee will identify major agricultural problems and constraints in these regions, and seeks your help and opinion in this regard. What do you see as the priority problems that require technological solutions in order for farmers in sub-Saharan Africa, India, Pakistan, Bangladesh, and Afghanistan to be more successful and productive? Which problems are so limiting that their solution would be transformative to these producers?

The committee is very aware that farmers face complex problems that are intertwined with social, political, and economic circumstances, and that technology is not a solution by itself. Technological innovations are tools that are successful only when they work in a complementary environment.

Nevertheless, the committee's assignment is to envision tools that, in the right set of circumstances, could give farmers more options for producing much more value from the land than they currently achieve. Such tools might dramatically increase crop and animal yields, provide the means to make value-added products, allow farmers more free time to pursue other economic activities, or give farmers greater flexibility in

Khaled M. Makkouk, International Center for Agricultural Research in the Dry Areas
Nouri Maman, Institut National de la Recherche Agronomique du Niger
Mkhululi Mankazana, affiliation unknown
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deciding what to grow and when to harvest. These are a vision of ideas that might be advanced with the help of technology.

Guided by the Foundation's request to focus our vision on technological tools that could be developed in 15-20 years, the committee felt there was a need to first correctly identify and define the most serious agricultural problems in these two regions. In addition to working from a series of international and national reports, we are asking colleagues like you from academic institutions and international organizations to help us focus our efforts.

We will be most appreciative if you could send us, by e-mail or fax, a brief description of five agricultural problems that you believe should be priorities for the committee. Your input will be most helpful if we receive it by June 30, 2007. At this point in the study, we are primarily focusing on understanding the problems, but if you have a vision of a powerful technological solution for a problem, please feel free to include a description of that in your reply as well.

Although the process of gathering information for the study might be accomplished more formally and methodically, time constraints require us to make this informal approach. We believe that our recommendations will be used by the Gates Foundation as an important reference in its future investments in world agriculture.

Thank you for considering this request to identify five major problems in agriculture in Africa and South Asia. We look forward to your earliest reply. If you have important papers or documents that could help us understand critical issues, I would be much obliged if you could send them to me for distribution to the committee.

Sincerely,
Michael Ma
Visiting Program Officer

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Appendix D

Contributors

The Committee on a Study of Technologies to Benefit Farmers in Africa and South Asia and staff appreciate the contributions of several individuals and organizations to the work of the committee. Some of these contributions were in person at an open session of the committee; others occurred later during the data collection and writing. The committee is grateful to the following individuals for sharing their time and expertise:

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Appendix E

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Scientific Advances in Animal Nutrition: Promise for a New Century (2001)
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The Scientific Basis for Estimating Emissions from Animal Feeding Operations: Interim Report (2002)

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