

A WORLD BANK STUDY



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Tom Walker, with Tom Hash, Fred Rattunde, and Eva Weltzien



WORLD BANK GROUP

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Foreword

Drylands—defined here to include arid, semi-arid, and dry sub-humid zones—are at the core of Africa’s development challenge. Drylands make up 43 percent of the region’s land surface, account for 75 percent of the area used for agriculture, and are home to 50 percent of the population, including a disproportionate share of the poor. Due to complex factors, the economic, social, political, and environmental vulnerability in Africa’s drylands is high and rising, jeopardizing the long-term livelihood prospects for hundreds of millions of people. Climate change, which is expected to increase the frequency and severity of extreme weather events, will exacerbate this challenge.

Most of the people living in the drylands depend on natural resource-based livelihood activities, such as herding and farming. The ability of these activities to provide stable and adequate incomes, however, has been eroding. Rapid population growth has put pressure on a deteriorating resource base and created conditions under which extreme weather events, unexpected spikes in global food and fuel prices, or other exogenous shocks can easily precipitate full-blown humanitarian crises and fuel violent social conflicts. Forced to address urgent short-term needs, many households have resorted to an array of unsustainable natural resource management practices, resulting in severe land degradation, water scarcity, and biodiversity loss.

African governments and the larger development community stand ready to tackle the challenges confronting dryland regions. But while political will is not lacking, important questions remain unanswered about how the task should be addressed. Do dryland environments contain sufficient resources to generate the food, employment, and income needed to support sustainable livelihoods for a fast-growing population? If not, can injections of external resources make up the deficit? Or is the carrying capacity of dryland environments so limited that out-migration should be encouraged as part of a comprehensive strategy to enhance resilience? And given the range of policy options, where should investments be focused, considering that there are many competing priorities?

To answer these questions, the World Bank teamed up with a large coalition of partners to prepare a study designed to contribute to the ongoing dialogue about measures to reduce the vulnerability and enhance the resilience of populations living in the drylands. Based on analysis of current and projected future

drivers of vulnerability and resilience, the study identifies promising interventions, quantifies their likely costs and benefits, and describes the policy trade-offs that will need to be addressed when drylands development strategies are devised.

Sustainably developing the drylands and conferring resilience to the people living on them will require addressing a complex web of economic, social, political, and environmental vulnerabilities in Africa's drylands. Good adaptive responses have the potential to generate new and better opportunities for many people, cushion the losses for others, and smooth the transition for all. Implementation of these responses will require effective and visionary leadership at all levels from households to local organizations, national governments, and a coalition of development partners. This book, one of a series of books prepared in support of the main report, is intended to contribute to that effort.

Magda Lovei

Manager, Environment & Natural Resources Global Practice

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Acknowledgments

This book is one of a series of thematic books prepared for the study, “Confronting Drought in Africa’s Drylands: Opportunities for Enhancing Resilience.” The study, part of the Regional Studies Program of the World Bank Group Africa Region Vice Presidency, was a collaborative effort involving contributors from many organizations, working under the guidance of a team made up of staff from the World Bank Group, the United Nations Food and Agriculture Organization (FAO), and the Consultative Group for International Agricultural Research Program on Policies, Institutions, and Markets (CGIAR-PIM). Raffaello Cervigni and Michael Morris (World Bank Group) coordinated the overall study, working under the direction of Magda Lovei (World Bank Group).

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About the Authors

Tom Walker is an agricultural economist and holds a master's degree from the University of Florida, as well as master's and PhD degrees from Stanford University. Working with international agricultural research centers and universities, he has over 30 years of overseas experience in South Asia, Latin America, and Sub-Saharan Africa. Relying heavily on longitudinal village studies and household panel surveys, he has written extensively on the economic development of dryland agriculture. Multiple interdisciplinary research investigations with biological and physical scientists have significantly enhanced his experience. In 2015 he edited a book, published by the Center for Biosciences and Agriculture International (CABI), that reports on the collaborative effort of over 200 biological and social scientists in documenting varietal change and the performance of crop improvement programs in 30 countries in Africa.

Tom Hash served ICRISAT for 25 years in various capacities related to cereal breeding, including leading activities on molecular marker development, and use of molecular markers in diversity assessment, QTL mapping, and marker-assisted selection of sorghum and pearl millet based at ICRISAT. He developed the first public sector-bred product of DNA marker-assisted selection (in any crop) to be released for cultivation in India—the pearl millet hybrid HHB 67 Improved. This hybrid has been rapidly adopted by the seed industry and farmers as a high yielding, disease resistant version of HHB 67. In West Africa, he worked on strengthening conventional breeding efforts in the region by enhancing disease screening capabilities, integrating marker-assisted breeding tools into on-going population improvement and hybrid development activities, and improving linkages with the developing seed industry.

Fred Rattunde recently retired after more than three decades of service as a plant breeder with Iowa State University, the University of Hohenheim, and ICRISAT. He has experience in oat, rye, sorghum, pearl millet and groundnut breeding; seed system development; and participatory research for dryland agriculture enhancement. His PhD degree from Iowa State University and postdoctoral fellowship at the University of Hohenheim focused on breeding methodologies. At ICRISAT, he spearheaded a sorghum breeding program for West and Central Africa that emphasized use of photoperiod sensitive Guinea-race

sorghum germplasm for variety, seed parent and hybrid development. This work produced the first commercial Guinea-race hybrids and proved that photoperiod-sensitive hybrids based on Guinea-race germplasm can give major yield advantages under low- as well as high-productivity conditions. In recognition of this work he and Eva Weltzien were jointly awarded the Justus von Liebig Award for World Nutrition (2015). His earlier research carried out in India focused on recurrent selection for improvement of early-maturity and dual-purpose sorghums.

Eva Weltzien recently retired from ICRISAT after serving for 28 years in various capacities related to sorghum breeding and genetic resource utilization. She obtained a PhD degree from the Technische Universität München, Germany in 1986 and did a postdoctoral fellowship in oat breeding at Iowa State University in Ames, Iowa, USA. Her research career is devoted to the improvement of dryland cereals in tropical and subtropical regions. Her work focuses on the effective use of sorghum, pearl millet and barley genetic resources, participatory research methods, and seed system enhancement. A strong emphasis of her work has been on “working in context,” targeting products to gender-specific production systems and creating new opportunities for farmers based on their specific conditions. She pursued this work by building multidisciplinary and multi-institutional teams. Her accomplishments have been recognized through numerous awards, including the Justus von Liebig Award for World Nutrition (2015) and the King Baudouin Award for pearl millet research at ICRISAT (1996).

Executive Summary

Dryland areas of Sub-Saharan Africa contain one-half of the region's population and three-quarters of its poor. Challenged by a meager natural resource base and suffering from a lack of assets and income, people living in the drylands are vulnerable to shocks, especially those resulting from droughts and other extreme weather events. Despite numerous efforts to improve their circumstances and lift them out of poverty, there have been few if any sustained large-scale successes.

In this context, the World Bank and other partners launched a study entitled "Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience" (henceforth referred to as the Africa Drylands study). The objective was to set out a practical framework for understanding vulnerability and resilience in drylands, as a way of informing the design of policies and programs that can help break the recurrent cycle of crises that for years have plagued the drylands. This book, one of several prepared as thematic background pieces to inform the larger Africa Drylands study, assesses the potential for improvements in dryland crop productivity to play an influential role in improving households' adaptive capacity to manage drought. The results of the assessment are organized into four topical areas: (1) characterization of dryland agriculture, (2) description of viable prospects for improving crop productivity, (3) discussion of the effectiveness of closely related risk-management policies to complement these technological options and of climatic change that threatens their performance, and (4) identification of the five top prospects in each dryland zone. The most promising technologies identified for each zone were used in the umbrella modeling exercise carried out for the larger Africa Drylands study.

Characterization of Dryland Agriculture

Drylands are generally unfavorable for agriculture. The harsh agro-climatic conditions restrict the potential of many crops, and fields are chronically exposed to unpredictable shocks that can decimate production to the point of causing complete crop loss. Dryland agriculture is diverse, with mixed cropping predominating as a way of protecting against risk. The biggest challenge to dryland agriculture

is posed by the uncertain availability of water, both in terms of quantity and timing. Although the effects of uncertain and highly variable rainfall can be mitigated through the use of irrigation, irrigation is relatively underdeveloped in the drylands, as it is across the region as a whole.

With irrigation still relatively underdeveloped, crop cultivation in the drylands takes place mainly in rainfed systems. About 95 percent of the area cropped in Sub-Saharan Africa is cultivated during the rainy season without irrigation. The bulk of the rainfed area, equivalent to 100 million hectares, can be classified as drylands, where rainfall is seasonal and undependable. In the drylands, drought-induced production shortfalls periodically precipitate the need for large-scale humanitarian assistance to help poor people maintain consumption without pronounced depletion of their meager assets.

After the uncertain availability of water, the second biggest challenge to dryland agriculture in Africa is low soil fertility. Low soil fertility is not unique to dryland cultivation, but it needs to be addressed, because it is overwhelmingly viewed as the main production problem in Sub-Saharan Africa (Gibbon, Dixon, and Flores 2007; Waddington et al. 2010).

As a result of drought, low soil fertility, and a host of lesser constraints, productivity in dryland farming systems is generally low, and production tends to fluctuate considerably from year to year. Across all of Sub-Saharan Africa, total factor productivity in agriculture increased very little during the three decades 1960–90. Not until the mid-1980s did significant numbers of African farmers begin adopting more intensive technologies, leading to a modest acceleration in productivity growth (Fuglie and Rada 2013).

Prospects for improving crop productivity were assessed separately for each of four dryland zones. Data from the HarvestChoice database were used to define a series of dryland zones. Dryland agriculture is defined as having an Aridity Index (AI) between 0.05 and 0.65. The AI expresses the ratio of rainfall to potential evapotranspiration. Alternatively, it can be viewed as the ratio of the supply of water to the crop to the demand for water by the crop. Higher values of the index indicate wetter growing conditions; lower values are synonymous with drier conditions. For purposes of the assessment described in this report, the drylands were disaggregated into four zones: (1) Arid, (2) Semi-arid, (3) Dry Sub-humid, and (4) Wet Sub-humid. The agro-climatic characteristics of each of these zones, as well as the dominant cropping systems found within each zone, are described in the report in some detail.

Viable Prospects for Improving Crop Productivity

Technological prospects for improving productivity in Africa's dryland cropping systems were assessed separately in three areas: (1) genetic improvement, (2) crop management, and (3) land management (this final category was defined broadly to include a number of miscellaneous intensification strategies).

Prospects for Genetic Improvement

One source of technical change that could reduce the vulnerability and increase the resilience of many of the people living in drylands is improved germplasm. Many of the households that depend on farming as a primary livelihood source continue to grow traditional varieties, either land races that reflect generations of selection behavior by farmers themselves, or improved varieties and hybrids developed by scientific breeding programs but introduced many years ago and no longer competitive with newer varieties. While land races and older improved varieties and hybrids can have characteristics that are valued by farmers and consumers, they may not be the best option.

Adoption of improved cultivars for major food staples started later and proceeded more slowly in Sub-Saharan Africa than in other developing regions, but Sub-Saharan Africa is slowly catching up. Across the entire region, improved varieties and hybrids are increasingly finding a home in farmers' fields at a slow but steady rate. Other studies show that adoption of modern cultivars has had a clear impact on productivity. According to Fuglie and Marder (forthcoming), 30–40 percent of productivity growth related to technological change in Sub-Saharan Africa since 1980 can be attributed to adoption of improved cultivars.

Many of the improved varieties being grown in Sub-Saharan Africa are quite old, however. Focusing on the same set of 20 major crops, about 3,600 improved varieties have been released in Sub-Saharan Africa since 1970; of these, more than 1,000 varieties could be found in farmers' fields in 2010. The largest age-cohort of the improved varieties being grown by African farmers in 2010 was released in the 1990s. With the exception of banana, yams, and rice, most of the area planted to improved varieties was and is located in dryland regions.

Prospects for genetic gains are discussed in detail for the leading food crops grown in the drylands, including pearl millet, sorghum, maize, cowpea, and groundnut. Breeding priorities differ by aridity zone. In drier environments, drought tolerance and heat tolerance are the main priorities, while in wetter environments yield potential, input responsiveness, and insect resistance are more important.

Progress in breeding for dryland environments in Sub-Saharan Africa has been slowed by the historically low rate of public investment in genetic improvement. Research intensities for genetic improvement in Africa are low relative to global benchmarks, and the rate of varietal releases is correspondingly low. Private investment has been low as well, due to the lack of demand for seed of hybrids, which offer the most attractive commercial opportunities for profit-oriented seed companies. Still, the emergence of commercially viable private seed industries in India, as well as southern Africa, shows that hybrids can succeed in dryland agriculture when the conditions are right.

Prospects for Improved Crop Management

Intensification of dryland agricultural systems requires the introduction of improved crop management practices. Introduction of improved crop management practices in turn almost always is accompanied by increased use of improved inputs such as fertilizer, herbicide, and insecticide. In contrast to adoption of improved cultivars, however, adoption of any single improved crop management practice often takes place in a relatively limited area, because the performance of that particular management practice depends on spatially varying agro-climatic, edaphic, and socioeconomic conditions.

Programs such as Sasakawa Global 2000 that have attempted to introduce standardized blanket recommendations for input-intensive crop management technologies on a large scale have rarely lived up to expectations, registering success with only a few crops and in a few countries. These programs have made clear what most crop management specialists already know: the intensification potential of dryland agricultural systems in Sub-Saharan Africa can be realized only with precise targeting of crop, land, and water management technologies, combined with adaptation to local conditions.

The potential contribution to intensification of dryland agriculture is discussed in detail for a series of promising crop management technologies, including (1) conservation agriculture, (2) microdosing fertilizer, and (3) seed treatments.

Prospects for Improved Land Management

Land management practices offer good prospects for increasing productivity in drylands. To be effective, however, land management practices must be regionally and even locally adapted. Their feasibility and desirability in specific situations is conditioned by topography, soil type, rainfall pattern, and socioeconomic characteristics. Because one size does not fit all, top-down government approaches that emphasize heavy subsidization and compulsory transfer of what administrators believe is the best practice to improve land management and minimize soil erosion have been a prescription for disaster in several settings, including the Sahel and India's drylands.

The potential contribution to intensification of dryland agriculture is discussed in detail for a series of improved land management practices, including (1) contour bunding, (2) rock bunding and planting pits, (3) ridge tillage (and the related practice known as *amenagement en courbes de niveau*), and (4) water harvesting and on-farm storage. Discussed as well is the potential contribution of several other approaches and practices, including (1) intercropping, (2) integration of trees into dryland cropping systems, (3) use of animal traction, and (4) response farming.

Effectiveness of Risk-management Policies to Complement Technological Options

Technological interventions such as those discussed in this book can help reduce vulnerability and increase the resilience of farmers in the drylands by increasing

and stabilizing production in the face of drought and other shocks. The protection afforded by technology can be complemented by protection in the form of financial risk management instruments, most notably crop insurance.

In theory, crop insurance is a policy option that directly addresses the problem of systemic risk from yield variability, which could make it especially valuable in dryland agriculture. Aside from directly protecting farmers from yield losses caused by drought, disease, and pests, crop insurance indirectly enhances resiliency in the production environment, because farmers can adopt technologies they perceive to be profitable without having to worry as much about the vagaries of weather. The increased income generated by the profitable technologies can be reinvested in the farm or the household to further limit sensitivity to risk and to improve coping capacity. In practice, however, crop insurance that is voluntary and oriented to the individual producer is vulnerable to consistent and sizable losses, because of moral hazard and adverse selection.

The 1980s witnessed a surge in interest in modifying crop insurance schemes so that they could benefit smallholder farmers in developing countries. Over time it soon became apparent, however, that voluntary insurance programs that paid out premiums based on farmer-specific yields were not economically sustainable. To begin with, they were characterized by high administrative costs, because of the need to monitor the situation on each farm individually. In addition, because premiums were kept low to keep coverage accessible to farmers with limited ability to pay, they were often subject to losses.

Over the past 25 years, some progress has been made in overcoming the problem of weak demand for weather-index insurance in developing countries, but on the whole it remains to be seen whether insurance can be profitable. Evidence continues to accumulate indicating that credit constraints, limited financial literacy of farmers, and basis risk will always limit the demand for weather-index insurance among smallholders. Still, some observers believe that with enough trial-and-error experimentation it may become possible to overcome these obstacles, to the point that weather-index insurance could eventually make a substantive contribution to risk management in dryland agriculture.

Likely Impacts of Climate Change on Crop Productivity in Drylands

The likely impacts of climate change on crop productivity in the drylands are difficult to predict with certainty. Recent modeling work suggests that the impacts, specifically of global warming, are likely to be relatively modest. Breeding for drought tolerance has always been a major component of international crop improvement programs, and breeding for heat tolerance, as well as agronomic research designed to identify practices to manage heat and drought stress, are viewed as relatively small departures from “business as usual.” As a result, the possibilities seem good that technical change will be able to keep pace with climate change, meaning that radical interventions to deal with the impacts of climate change will be needed only under highly specific circumstances.

Five Top Prospects in Each Dryland Zone

The principal objective of this book—assessing the prospects for raising crop productivity in the drylands of Sub-Saharan Africa—is an ambitious undertaking, especially when the assessment is expected to focus on the ability of improved cropping technologies not only to increase productivity but also to reduce sensitivity to drought. Ex-ante assessments made a generation ago continue to provide valuable insights about the prospects for productivity gains in dryland environments and have served as a useful reference point for validating the findings of the current assessment. In particular the assessment carried out by Matlon (1990) of technology prospects for sorghum and pearl millet in West Africa is extremely valuable. Many of the promising dryland cropping technologies described by Matlon (1990) have changed over time, but in most cases their essential substance and many distinguishing features have stayed the same.

Based on the results of the current assessment, five technologies judged to have the most potential to contribute to improved crop productivity were identified for each aridity zone. For each technology, an estimate is presented of the size of the area in West and East Africa over which the technology could potentially spread by 2030, as well as an estimate of the investment that likely would have to be made to achieve adoption (the investment consists of research costs, extension costs, and adoption costs).

It is important to note that this rather mechanical exercise of identifying the five most promising technologies for each zone and associating with each one a notional adoption cost was carried out for a specific purpose. The cost estimates—based on expert opinion but admittedly very subjective—were used as inputs into the umbrella modeling exercise carried out for the larger Africa Drylands study, which uses an economic analytical framework to ask the question: “By 2030, if the most promising crop production technologies were to be fully adopted throughout the drylands in areas in which they are profitable, how many households could be made more resilient?”

Prospects in the Arid Zone

Yield-stabilizing and land-conserving technologies are the most relevant for the Arid Zone. In contrast, prospects for the widespread uptake of yield-increasing technologies that rely on the intensification of input use are quite bleak, because the incremental benefits generated by such technologies often do not cover the additional input costs. The five most promising technologies for the Arid Zone are (1) agro-forestry, (2) pearl millet improved varieties, (3) pearl millet hybrids, (4) seed treatment, and (5) cowpea improved varieties.

Prospects in the Dry Semi-arid Zone

Land-conserving technologies are the most relevant for the Dry Semi-arid Zone. Land-conserving technologies have good prospects in densely populated farming areas where land degradation is visible and its consequences are appreciated by farmers—conditions that are present in many dry semi-arid zones. Prospects for

widespread diffusion of improved varieties are more mixed. Uptake of improved varieties has been more extensive in dry semi-arid zones than in the arid zones, but overall adoption levels remain low. The five most promising technologies for the Dry Semi-arid Zone are (1) sorghum improved varieties, (2) fertilizer (3) cowpea improved varieties, (4) soil conservation practices, and (5) groundnut improved varieties.

Prospects in the Wet Semi-arid Zone

Yield-increasing and labor-saving technologies are the most relevant for the Wet Semi-arid Zone, where they can generate substantially higher payoffs than in drier zones because of the generally higher yield potential of the crops being grown. For this reason, improved technologies in general are likely to be more attractive in the Wet Semi-arid Zone. More specifically, yield-increasing technologies are more likely to be accepted in areas of land scarcity, and labor-saving technologies are more likely to become popular in sub-regions of land abundance. The five most promising technologies for the Wet Semi-arid Zone are (1) maize improved varieties and hybrids, (2) input intensification, (3) mechanization, (4) sorghum hybrids, and (5) improved land management.

Prospects in the Dry Sub-humid Zone

Yield-increasing, labor-saving, and land-saving technologies all have considerable potential to contribute to improved crop productivity in the Dry Sub-humid zone, although it is somewhat difficult to generalize because of the tremendous heterogeneity of the cropping systems found in that zone. Improved germplasm, improved crop management practices, and improved land management practices all offer prospects of significant productivity gains, and because these gains will occur at high yield levels, considerable investment in these technologies is justified. The five most promising technologies for the Dry Sub-Humid Zone are (1) maize hybrids, (2) groundnut improved varieties, (3) input intensification, (4) improved cropping systems, and (5) conservation agriculture.

Summary and Conclusions

Over the past five decades, crop productivity growth in the drylands of Sub-Saharan Africa has lagged behind crop productivity growth in other developing regions, such as Asia and Latin America, where adoption of improved seed-fertilizer technologies started sooner and has continued to spread to larger areas. Since the end of the recurring Sahelian drought in 1984, crop productivity growth in Sub-Saharan Africa has accelerated, but overall production gains in many crops and countries continue to come more from area expansion than from yield gains. The challenge is to accelerate the growth of smallholders' yield in the drylands of Sub-Saharan Africa via increased application of inputs, especially fertilizer, and technological change.

The fact that agricultural productivity in Sub-Saharan Africa was practically stagnant during the 1970s and has grown only modestly since the mid-1980s suggests that yield-enhancing, risk-reducing technologies have not been available to many African smallholder households. Even when new technologies have been introduced, often it has been difficult to determine their usefulness, because in an environment characterized by frequent droughts, generally poor soil, and widespread micro-variation, it is difficult to assess with accuracy the impacts of technological change. For that reason, any effort to forecast the diffusion and impacts of prospective technologies is fraught with uncertainty.

In spite of these difficulties, there are grounds for optimism that the pace of crop productivity growth in the drylands will be able to match or even exceed the trend in the recent past. The assessment whose results are summarized in this book suggests that prospects for achieving crop productivity gains are positively associated with agricultural potential, which in dryland regions is determined mainly by growing-season rainfall. Prospects for improving productivity and increasing production are considerably brighter in the Wet Semi-arid and Dry Sub-humid Zones than in the Arid and Dry Semi-arid Zones. The higher payoffs generated by improved technologies in the more favorable zones justify higher levels of investment in research extension and adoption. Because it pays for farmers in the Wet Semi-arid and Dry Sub-humid Zones to invest more heavily in agriculture, they have a wider array of options to choose from than do farmers in the Arid and Dry Semi-arid Zones. Generally speaking, the emphasis in the two drier zones should be on managing risk and promoting resiliency, and the emphasis in the wetter zones should be on raising yields and increasing production.

As discussed in this book and corroborated by the results of the umbrella modeling exercise carried out for the larger Africa Drylands study, successful uptake of improved crop production technologies can make a significant contribution to reducing vulnerability and increasing resilience for households living in the drylands that depend on agriculture as a principal livelihood source.

Abbreviations

ACN	<i>Aménagement en courbes de niveau</i>
AGRA	Alliance for a Green Revolution in Africa
AI	Aridity Index
ARC	Agricultural Research Corporation (Sudan)
ASARECA	Association for Strengthening Agricultural Research in Eastern and Central Africa
CA	conservation agriculture
CG	Consultative Group
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Center
CIRAD	French Center for International Cooperation on Agronomic Research for Development
CRED	Centre for Research on Epidemiology of Disasters
CRP	Collaborative Research Project
DIIVA	Diffusion and Impact of Improved Varieties in Africa
DRC	Democratic Republic of Congo
EM-DAT	Emergency Events Database
ESA	East and Southern Africa
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Corporate Statistical Database
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Crops Research Institute for the Semi-arid-Tropics
IER	<i>Institut d'Economie Rurale</i>
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPM	integrated pest management
ISC	Sahelian Center
MAS	marker-assisted selection

MVs	modern varieties
NGO	nongovernmental organization
OPVs	open-pollinated varieties
R&D	research and development
SAT	semi-arid tropics
SSA	Sub-Saharan Africa
USAID	United States Agency for International Development
WCA	West and Central Africa

Introduction

Dryland areas of Sub-Saharan Africa contain one-half of the region's population and three-quarters of its poor. Challenged by a meager natural resource base and suffering from a lack of assets and income, inhabitants of the drylands are vulnerable to shocks, especially those resulting from droughts and other extreme weather events. Despite numerous efforts to improve the circumstances of dryland inhabitants and lift them out of poverty, there have been few if any sustained large-scale successes.

In this context, the World Bank and other partners launched the study on “Confronting Drought in Africa’s Drylands: Opportunities for Enhancing Resilience,” whose objective was to set out a practical framework for understanding vulnerability and resilience in drylands, as a way of informing the design of policies and programs to that can help break the recurrent cycle of crises that for years have plagued the drylands. This book, one of several prepared as thematic background pieces to inform the larger study, focuses on the potential for improvements in dryland crop productivity to play an influential role in improving households’ adaptive capacity to manage drought.

Agriculture—used here to refer to farming in general and crop cultivation in particular—is one of the two main livelihood strategies practiced in dryland regions of Africa (the other is livestock-keeping). In the countries of East and West Africa in which drylands represent a significant proportion of the land area, agriculture is economically important, with crop production typically contributing 10–30 percent of gross domestic product (GDP) and up to 75 percent of agricultural GDP.

Drylands are generally unfavorable for agriculture. The harsh agro-climatic conditions restrict the potential of many crops, and fields are chronically exposed to unpredictable shocks that can decimate production to the point of causing complete crop loss. Dryland agriculture is diverse, with mixed cropping predominating as a way of protecting against risk. The biggest challenge to dryland agriculture is posed by the uncertain availability of water, both in terms of quantity and timing. Although the effects of uncertain and highly variable rainfall can

be mitigated through the use of irrigation, irrigation is relatively underdeveloped in the drylands, as it is across the region as a whole.

With irrigation still relatively underdeveloped, crop cultivation in the drylands takes place mainly in rainfed systems. About 95 percent of the area cropped in Sub-Saharan Africa is cultivated during the rainy season without irrigation. The bulk of the rainfed area, equivalent to 100 million hectares, can be classified as drylands, where rainfall is seasonal and undependable. In the drylands, drought-induced production shortfalls periodically precipitate the need for large-scale humanitarian assistance to help poor people maintain consumption without pronounced depletion of their meager assets.

As a result of the many constraints, productivity in dryland farming systems is generally low, and production tends to fluctuate considerably from year to year. Across all of Sub-Saharan Africa, total factor productivity in agriculture increased very little during the three decades 1960–90. Not until the mid-1980s did significant numbers of African farmers begin adopting more intensive technologies, leading to a modest acceleration in productivity growth (Fuglie and Rada 2013).

Drought in Sub-Saharan Africa was the cause of 17 of the 100 most damaging natural disasters that occurred worldwide in the twentieth century (CRED 2014). However, drought has not resulted in widespread famine and mortality since 1985, largely due to more responsive governments, better integrated markets, and increasing humanitarian efforts. Nonetheless, the total number of people affected by drought has not declined over time because both rural and urban populations in the drylands of Sub-Saharan Africa are increasing and the incidence of drought has not diminished.

The larger study for which this book was prepared uses a conceptual framework under which three factors—exposure to drought, sensitivity to drought, and coping capacity—jointly determine household vulnerability and resiliency. This book focuses on the potential for improvements in dryland crop productivity to improve the capacity of agriculture-dependent households to better manage drought. From the outset, it should be recognized that this is a complex topic that is not easily quantified.¹

Yield growth in dryland crops does not have a direct impact on exposure from natural hazards, but it can help to insulate production during mild and moderate rainfall shortages, thereby reducing sensitivity to drought.² Multiple technologies can contribute to maintaining production in times of drought. Short-duration varieties in almost all dryland crops have the potential to escape late season drought. Improved drought-tolerant varieties in maize have the capacity to give higher yields than traditional varieties when drought occurs. Heat-stress tolerant millet varieties are characterized by more stable production than traditional varieties when temperatures rise during drought events. Well-adapted cereal hybrids have the ability to withstand adverse production conditions better than traditional varieties. Land and water management practices such as minimum tillage, use of planting pits, and porous rock bunding can enhance

soil-available water for field production, facilitate in-field drainage, and may even result in greater groundwater recharge in drought environments. Agronomic practices such as the placement of small doses of fertilizer near seeds at planting and the judicious use of intercropping systems can increase resource use efficiency when drought threatens production.

Although the nexus between improved crop productivity and drought sensitivity is difficult to assess, some examples in the literature point to the widespread mitigation consequences of improved techniques that raise productivity and reduce variability. One of the best documented cases is the Maradi region in Niger. Compared to other administrative divisions in Niger, Maradi is characterized by substantially higher adoption of natural regenerative forestry in millions of millet-growing fields. These parkland systems of low-density trees and crops have enhanced crop and household resiliency during drought (Mortimore et al. 2001). Another well-documented success story comes from the Mossi Plateau in central Burkina Faso, where diffusion of appropriate land management and soil conservation practices has substantially reduced sensitivity to drought (Reij, Tappan, and Smale 2009).

Increased crop productivity also indirectly leverages households' adaptive capacity to manage risk. Yield growth benefits many households by increasing net consumers' food production and net producers' commercial sales. Drought adaptation case studies have shown that poor households are more vulnerable than richer households (Reardon, Matlon, and Delgado 1988). Agriculture dependent households, which may have 65–75 percent of their household income concentrated in crop production, generally have few coping options. Increasing crop productivity may not provide a complete pathway out of poverty (Harris and Orr 2014), but it can be instrumental in contributing to growth and diversification of the economy (Johnson and Mellor 1961). At the household level, rising crop productivity stimulates the accumulation of assets that enhance coping capacity. At the economy level, growth from crop productivity engenders the structural change necessary for increased diversification and enhanced non-crop agricultural income. Off-farm sources of income play a larger role in household welfare as the economy expands.

Over the past five decades, crop productivity growth in the drylands of Sub-Saharan Africa has lagged behind crop productivity growth in other developing regions, such as Asia and Latin America, where adoption of improved seed-fertilizer technologies started sooner and has continued to spread to larger areas. Since the end of the recurring Sahelian drought in 1984, crop productivity growth in Sub-Saharan Africa has accelerated, but overall production gains in many crops and countries continue to come more from area expansion than from yield gains (Fuglie and Rada 2013). Most cultivated land still receives little or no mineral fertilizer (Morris et al. 2007). In efficient agricultural settings, the difference between potential yield and farm yield is usually about 30 percent of farm yield. In the drylands of Sub-Saharan Africa, the difference between potential yield and farm yield typically ranges from 200 to 400 percent (Fischer, Byerlee, and

Edmeades 2014). The challenge is to accelerate the growth of smallholders' yield in the drylands of Sub-Saharan Africa via increased application of inputs, especially fertilizer, and technological change.

This book presents the findings and conclusions of an effort to assess the challenge posed by the lack of dynamism in crop productivity in dryland regions of Sub-Saharan Africa and identify opportunities for improving productivity. The results of the multi-dimensional assessment are organized into four topical areas: (1) characterization of dryland agriculture, (2) description of viable prospects for improving crop productivity, (3) discussion of the effectiveness of closely related risk-management policies to complement these technological options and of climatic change that threatens their performance, and (4) identification of the five top prospects in each dryland zone. Several of these prospects were used in the umbrella modeling exercise that underlies the Africa Drylands study.

Africa's drylands display substantial variation in rainfall and soils that condition the performance of options for improved productivity. In chapter 2, dryland zones are delineated and described. Drought and low soil fertility are ubiquitous in African dryland agriculture. Their importance is the central message conveyed in chapter 2.

Specific prospects for improving crop productivity are described in chapter 3 (varietal change), chapter 4 (crop management), and chapter 5 (land and water management). Although the assessment is forward looking, the discussion of prospects is heavily grounded in lessons learned in the past. Valuable insights can be gained not only from past successes, but also from past failures; some approaches, technologies, and technology packages, even if they did not work out, nevertheless are helpful in revealing what is likely to generate practical impact in future. Lessons from India's Semi-arid Zone, a production environment that shares many features with the drylands of Sub-Saharan Africa, also serve as an important touchstone.

An evaluation of potential for improving crop productivity Africa's drylands would be incomplete without considering closely related policies and climatic trends that condition the outcomes of the technological prospects described earlier. The viability of crop insurance in general, and index-weather insurance in particular, is discussed in chapter 6 together with a summary assessment of the threat of and response to global climatic change in chapter 7.

The results of the assessment carried out for this book were compared to the results of an earlier assessment conducted by Matlon (1990). Described in chapter 8, the comparison generated many useful insights that helped to validate the continuing relevance of some technologies and confirm the limited potential of others. It provided a firm foundation for synthesizing the main findings, forecasting the uptake of technologies to 2030, and highlighting the main messages that emerged during the preceding analysis. Chapter 8 presents estimates of projected adoption patterns for 20 technologies judged to have the most potential to improve crop productivity across the four main dryland zones, and it presents

rough estimates of the research, extension, and farmer adoption costs that will have to be incurred to achieve the projected adoption patterns. The expected adoption trajectories and the associated research, extension, and farmer adoption costs were used as inputs into the umbrella modeling exercise that was carried out for the larger Africa Drylands study.

Notes

1. That agricultural research can generate outputs that impart stability to crop production and household income is widely accepted. For example, it is well known that plant breeders have been successful in developing improved varieties that resist and/or tolerate important diseases. Salient examples in dryland agriculture in Sub-Saharan Africa include leaf streak in maize, downy mildew in pearl millet and sorghum, mosaic virus and brown streak in cassava, rust and leaf spot in groundnut, and stem and leaf rust in wheat. Differences in varietal resistance to disease are often readily visible when infestation occurs. When maintenance breeding is effective, varietal resistance can essentially “solve” this source of production instability (Dubin and Brennan 2009). Because higher rainfall events frequently induce disease infestation, resistance allows farmers to fully capitalize on good growing season conditions. In contrast, varietal sensitivity to drought depends on its timing and severity. Drought tolerance is difficult to screen for and its sources are polygenic.
2. Although the mechanisms by which new varieties and practices can lessen sensitivity to drought are numerous, it is important to point out that maintaining and increasing dryland crop productivity is not effective in protecting households from extreme single-season and repetitive multi-year droughts. Even the best dryland practice cannot produce much if any cereal grain during catastrophic drought, defined as receipt of 50 percent or less of expected seasonal rainfall. For example, agronomists at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) had to apply a life-saving irrigation of 5 centimeters to ensure crop production at their Patancheru Station during the 1972 “never in a 100 years” drought in peninsular India (ICRISAT 1973). Pearl millet and sorghum breeders at ICRISAT’s then-new Niamey Station in Niger did not report yields during the severe 1984 drought, but they did state that the 45-day period with no rain in the middle of the growing season was useful for screening tolerant material (ICRISAT 1985).

Dry Spells, Poor Soils, and Dryland Zones

Drought is the defining feature of dryland agriculture. In contrast, low soil fertility is not unique to dryland cultivation. Low soil fertility needs to be addressed, however, because it is overwhelmingly viewed as the main production problem in Sub-Saharan Africa (Gibbon, Dixon, and Flores 2007; Waddington et al. 2010).

Drought

Although drought can visit farmers' fields at any time in the rainy season, it is conventionally categorized as early season drought, mid-season drought, or late season drought. In temperate agriculture, where farmers plant in the spring into a full profile of soil moisture after a snow melt, early season drought is seldom a cause for concern. In contrast, dryland farmers in Sub-Saharan Africa have to sow their crops into bone-dry soil at the start of the rainy season. Delayed onset of the rains or unexpected periods of early season drought may spell crop failure or court greater risk of terminal drought at the end of the rainy season.¹

Highly variable early season rainfall leads to seasonal peaks in labor demand that cannot be satisfied in thin local markets for hired labor. Labor demand peaks during sowing and weeding. Analysis of farm household data from village-level studies over several years in Burkina Faso and Niger indicates that the date of first sowing extends over several weeks. Planting sorghum and pearl millet takes over 40 days in the Arid Zone of the Sahel and 80 days in the Semi-arid and Dry Sub-humid Zones of the northern Guinean savanna. Delays in planting are attributed not only to undependable early season rainfall, but also to the large areas sown (on average 5–6 hectares) and the time-consuming nature of hand sowing (ICRISAT 1989). When farmers pursue extensification strategies, extension recommendations to plant early and on time with higher population densities fall on deaf ears. Farmers attempt to maximize returns to scarce labor at the time of planting and weeding. Extensification is the strategy of choice throughout Sub-Saharan Africa (Baudron et al. 2012) (see box 2.1).

Researchers have not been able to improve substantially on the traditional hill planting practiced on millions of hectares of pearl millet-growing area in the Arid Zone. Even though farmers have developed an optimal planting system to mitigate the effects of early season drought, they are still at the mercy of the elements (see box 2.2).

Although early season drought exacts a heavy toll on dryland production, output is more sensitive to mid-season drought stress, which occurs at flowering or panicle initiation in cereals. Unlike in India's Semi-arid Tropics (SAT), rainfall in West Africa's semi-arid tropics, especially in the Sahelian and Sudanian Zones, declined in the 1970s and early 1980s. The most marked decreases in rainfall occur in August, when the presence of mid-season drought is a potential source of abiotic stress (ICRISAT 1990).

Box 2.1 Extensification versus Intensification in the Drylands of Sub-Saharan Africa

The fact that it has been easier for farmers to plant more cropland than to intensify production per unit of area is transparent in any accounting of the sources of agricultural growth in Sub-Saharan Africa. From 1961 to 2008, agricultural output grew at 2.53 percent (Fuglie and Rada 2013). Area expansion accounted for 65 percent of growth; increasing yield contributed 35 percent. In the drylands, area expansion has figured more prominently than for Sub-Saharan Africa as a whole. For the typical and important dryland crops of millet, sorghum, groundnut, and cowpea, area expansion accounted for 75–87 percent of growth in crop production between 1961 and 2010. The share of agricultural growth attributed to area expansion for the United Nations Food and Agriculture Organization's (FAO) revised scenario of poverty reduction to be realized will need to shrink to 25 percent by 2050; that is, intensification needs to become more important over time (Alexandratos and Bruinsma 2012).

As seen in this book in a summary description of International Food Policy Research Institute's (IFPRI) HarvestChoice database, the Arid, Dry Semi-arid, Wet Semi-arid, and Dry Sub-humid Zones all contain many subregions where population density is still low, thereby indicating considerable land abundance. By 2000, median population density of the numerous subregions in each dryland zone was below 50 persons per square kilometer. The 25th percentile in population density occurred between 10–20 persons per square kilometer in all dryland zones. Conversely, about 1,500 of the total of 4,700 subregions are relatively dense, suggesting land scarcity. For these, population densities exceed 100 persons per square kilometer. Many of these subregional observations occur in Ethiopia.

It is easy to make a mental leap from extensification to a vision of large-scale commercial farms as the answer to Sub-Saharan Africa's productivity problems. However, there are still few success stories to report of large-scale production of food crops in Sub-Saharan Africa (World Bank 2009). More recent well-known failures include wheat in Nigeria and Tanzania and, much earlier in the twentieth century, groundnut in Tanzania (Deininger and Byerlee 2011). Without subsidies or favorable discriminatory policies, large-scale enterprises

box continues next page

Box 2.1 Extensification versus Intensification in the Drylands of Sub-Saharan Africa *(continued)*

have not been able to compete in food-crop production in Sub-Saharan Africa (Poulton et al. 2008). Moreover, uncultivated arable land is heavily concentrated in only a few countries such as the Democratic Republic of Congo (DRC) and Mozambique, which lack infrastructure and institutional development for its exploitation.

Production of sorghum in rainfed, mechanized conditions accounts for about 3.5 million hectares in the Sudan, but input use is negligible. Productivity is low and stagnant at 0.5 tons per hectare (ARC Sudan 2011). Nutrient depletion will increasingly be a production problem.

Some of the smaller attempts at large farm production at a level of only a few hundred hectares have also not borne fruit. For example, several dozen farmers migrated to Mozambique in the early 2000s in response to the economic crisis and land expropriation in Zimbabwe. They invested in the production of food and export crops such as tobacco but few have been able to make a living at farming in the high-potential production areas neighboring the border with Zimbabwe. These highly experienced farmers could not find crops that were sufficiently profitable to grow in Mozambique. Nor could they compensate for the high cost and unavailability of inputs stemming from the lack of adequate infrastructure.

Because Sub-Saharan Africa has high rates of urbanization, labor supply for agriculture will become increasingly constrained in many areas, so mechanization in production will eventually figure prominently in food production in operations such as land preparation and harvesting. However, rural populations are expected to increase in most countries to 2040; these people will still depend on agriculture as their primary source of employment (Losch, Fréguin-Gresh, and White 2011). It is difficult to envisage how success in food production by capital-intensive, large-scale enterprises will enhance the food security and resiliency of poor semi-subsistence farming families.

Box 2.2 Planting is Risky in the Drylands

Drought risk at planting can be acute in the Sahel. Screening germplasm for superior emergence and stand establishment requires an understanding of the determinants of patchy plant populations. Immediately after the Sahelian Center opened in Niger in 1984, plant physiologists conducted diagnostic research in farmers' fields on the determinants of stand establishment in pearl millet, the dominant cereal cultivated in the Arid Zone of the south Sahel (ICRISAT 1985). Farmers use a hoe to sow 40–300 good quality seeds per hill in the hopes that 1 to 3 plants will ultimately survive. Although seed quality is good, only 25 percent of seeds germinate. The outer seedlings that emerge protect the inner ones from the potentially erosive effects of wind in the form of sand blasting. Farmers plant into a dry profile when the first rains wet the top layer of soil. If rain is not received 10–15 days after the seedlings emerge, the germinated plants will die, not because of drought per se but because of lethal soil temperatures that range from 50–55°C and bake the tiny seedlings. Early season drought forces farmers to replant. Replanting is equivalent to delaying the onset of the rainy season, which in the Sahel increases the risk of terminal drought: later onset of the rainy season means a shorter grower season.

If drought in dryland agriculture was localized and not characterized by high positive covariance, its impacts would not be that severe. But drought is highly covariate over space, which makes risk management difficult. Drought occurs in widespread areas at the same time. Recurring droughts take place in Southern Africa about two to three times per decade (Tschirley et al. 2005). In 1992, drought in South Africa, Zambia, and Zimbabwe was sufficiently severe to cause the yield level of maize to drop below 1.0 MT per hectare in the FAO Corporate Statistical Database (FAOSTAT) for Sub-Saharan Africa as a whole for the first time in many years. Production in 1992 of 800 kilogram per hectare in Southern Africa was only about 35 percent of output in 1991 and 1993. More recently, the ratio of harvested to planted maize area plunged to 50 percent in 2004/05 in central Mozambique and Zambia (Cunguara 2008; Shipekesa and Jayne 2011). About half the fields did not produce sufficient grain to harvest during a severe covariate drought.

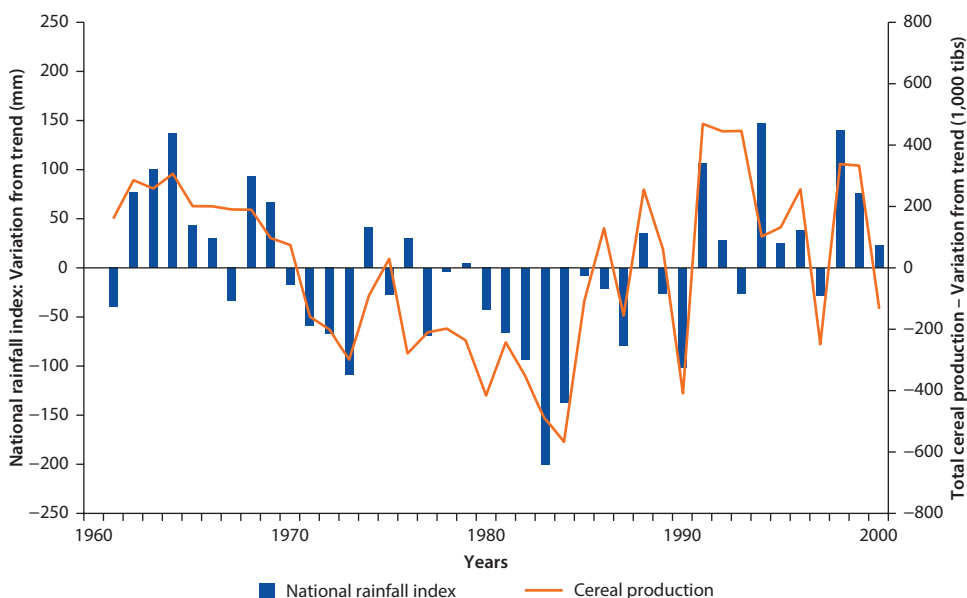
Not all countries within a region are necessarily affected by drought at the same time. For example, north Mozambique faces different weather conditions than the bulk of the Southern Africa region, and has traditionally been a small exporter of maize (Tschirley et al. 2005). Increasing crop productivity in non-covariate subregions like north Mozambique would also help to stabilize food production. Unfortunately, the drylands of north Mozambique have not even begun to attain their production potential. Maize yield has been stagnant since Independence and, surprisingly, for the two decades since the cessation of hostilities in 1992.

As alluded to above, below average rainfall was observed in the 1970s and continued to the mid-1980s throughout much of the Arid and Semi-arid Zones of Africa, extending from Senegal in the west to Sudan in the east. Chronic drought partially explains the decline in the export trade of groundnut from West Africa to Europe following Independence in the 1960s. But chronic drought is not new to West Africa and the Horn of Africa. Prolonged rainfall shortages between 1910 and 1920 in Niger make the 1970s Sahelian drought look rather mild by comparison (ICRISAT 1990).

The relationship between drought and production is vividly illustrated in figure 2.1, which was borrowed from the companion background report on prospects for irrigation (Ward with Torquebiau and Xie 2016). Deviations from mean rainfall and mean cereal production are charted annually from 1960 to 2000. Differences in production track the differences in rainfall both downward and upward.

The severity of the 1984 drought is apparent in figure 2.1. Indeed, rainfall in the early 1980s was sparser than rainfall in the early 1970s. The high association between rainfall and cereal production variability captured in figure 2.1 is not unique to Burkina Faso. Comparable data in other countries in well-defined droughts show the same tendencies in West Africa, East Africa, and Southern Africa. But in a few countries, most notably Nigeria, Guinea, and Uganda, production and rainfall variability are not significantly correlated. Drought may be less of a problem in those countries than in Burkina Faso. However, those coun-

Figure 2.1 Relationship between Cereal Production and Rainfall, 1960 to 2000, Burkina Faso



Source: Ward with Torquebiau and Xie (2016).

tries have been able to drought-proof one facet of their economies: the aggregate production data, especially estimates on cereal yields and production, which show limited variability over time (Walker 2008).

The 1984 drought was arguably the worst since 1920 in much of West Africa. In terms of dryland agriculture, it extended from the drier Sahelian Zone in the north to the wetter Guinean Zone in the south. Rainfall declines with regularity as one moves south to north from (Dry Sub-humid) Guinean to the (Arid) Sahelian Zone. International and national relief efforts focused most of their attention on the Sahelian Zone. Subsequent analysis of biweekly production and consumption data collected in case study villages in the Semi-arid Sudanian and Arid Sahelian Zones suggested that the geographic emphasis on the Sahelian Zone was misplaced (Reardon, Matlon, and Delgado 1988) (see box 2.3). Rural households in the Sahelian Zone were more effective in coping with the 1984 drought because they were able to maintain their consumption. In contrast, caloric intake fell by 20 percent in the Sudanian Zone.

Because of drought, household crop production from the 1984 harvest met only 29 percent of annual energy requirements in each zone. Consumption not only fell for households in the Sudanian Zone, but became markedly more variable across the two-week periods of 1984–1985. Additionally, in the Sudanian Zone, energy intake was least during the cropping season, when demands for energy expenditure are greatest. This contrasted with the Sahelian Zone, where consumption was consistently lowest during the hot season, when labor demands are least.

Box 2.3 Intensive Cases Studies versus Large-scale Surveys in Analyzing Coping Strategies

Although heavily laden with context, intensive household panel data collection at frequent seasonal intervals across years is needed to understand how poor households cope with drought-induced production shortfalls and how their coping ability can be improved to enhance resiliency. In-depth, multi-year, drought-response case studies, such as Reardon, Matlon and Delgado (1988) and Bidinger et al. (1991), are highly complementary to nationally representative surveys on the reliance of broad coping options in risk management (Heltberg, Oviedo, and Talukdar 2013). The single-interview survey approach provides broad information on sources of risk and household response, but data from surveys are insufficient to inform policy on how risk management could be improved to enhance resiliency. In the words of the authors,

... beyond providing broad diagnostics, the information culled from these surveys largely disappoint the aspiration to inform policy. This is mostly because these surveys shed so little light on the obstacles to risk management, that is, the reasons that people and societies often fail to take commonsense precautions in the face of known threats. Without major innovation in this area, shock and coping surveys will likely remain more useful for broad diagnostics than for specific policy recommendations. (Heltberg, Oviedo, and Talukdar 2013, 3)

Farmers in the Sahel were better able to avoid large seasonal shortfalls in consumption by supplementing crop stocks through cereal purchases. Sahelian Zone farmers pursued income strategies that were substantially more diverse across sectors and regions than Sudanian Zone farmers. Major alternative sources of income included livestock trading and migration labor that, when combined, provided nearly two-and-a-half times the absolute income for households in the Sahelian Zone compared to those in the Sudanian Zone. Since income from both sectors is largely determined by economic conditions in the urban centers of Burkina Faso as well as in the coastal countries of West Africa, earnings levels from these sources have relatively low covariation with local crop incomes.

Pastoralism has long constituted a central element in the production strategies and cultural identity of the ethnic groups who inhabit the Sahelian Zone. This reflects not only low population pressure and thus greater access to noncultivated land available for forage production, but also a response to the higher production risks that characterize cropping in that zone. These risks create incentives to invest in movable assets, such as livestock, as a form of insurance. Sahelian pastoralists' past investment of time to establish links with regular employment outside the region was probably also a response to traditionally high interannual variation in crop income.

In contrast, farming households in the higher, and less variable, rainfall conditions of the Sudanian Zone have traditionally emphasized crop production, with smaller investments in livestock. Increasing land pressure and ecological decline in this zone have progressively eroded the importance of livestock. Land pressure has simultaneously reduced Sudanian Zone farmers' capacity to produce and store grain surpluses to buffer them from annual production shocks. Because of rapid change in production conditions, migration and the establishment of links with external employment have not yet been adequately developed to replace the insurance role formerly played by livestock and grain storage.

Low Soil Fertility

Seasoned observers of global agricultural development often rank low soil fertility as the most important constraint limiting intensification of agricultural productivity in Africa (Fischer, Byerlee, and Edmeades 2014). A recent article in *Nature* titled "No Silver Bullets for African Soil Problems" summed up the current state of soil fertility in Africa:

In relation to inherent productivity, native soil fertility is less than half that found in Europe, as the vast majority of soils are relicts of 2-billion year old granites, and have few nutrients left. Where younger, volcanic soils occur these are inherently richer in nutrients, but have their own soil fertility problems as they generally fix phosphorus strongly. Soil fertility is also extremely heterogeneous at more local scales: the difference in soil organic matter between the fields of small farms in Kenya and Zimbabwe over distances of only 50–100 meter are as large (Tittonell et al. 2005; Zingore et al. 2006) as the differences between the most fertile and least fertile soils at regional or continental scale across Africa (Windmeijer and Andriess 1993). These differences in soil fertility are partly derived from inherent differences in properties (the 'soilscape') but are strongly influenced by past management, particularly by the rates and quality of organic manures added to the soils. (Giller 2012, 41)

Indeed, microvariation in soil fertility within a field can be high. For example, diagnostic research in the Sahel found that spatially small differences in soil acidity (very low pH) were a significant determinant in explaining the variation in pearl millet stands in the Sahel within fields (ICRISAT 1986).

As reflected in the above quote, a good part of the variation in soil fertility across fields is attributable to the way farmers in West, East, and Southern Africa manage their fields. The vast majority practice the same management strategy: husband and apply all of their fertility-related resources and intensify production on fields nearer the homestead or compound. This behavior gives rise to a declining fertility gradient from the near to the far fields. With shortening fallows, the distant fields become increasingly infertile over time. With steady nutrient depletion, the fertility in some of these fields will fall below a soil-carbon threshold from which fertility cannot be restored via conventional means.

Nitrogen and phosphorus are the macronutrients most lacking in African soils.² Nitrogen needs to be supplied continuously. Sources include fertilization, green manuring, legume rotations, or leguminous tree-shrub fallows. Green manuring is impractical in African dryland conditions because the rainy season is too short for the early incorporation of green manures followed by the cultivation of a food crop in the same season. About 80 percent of African soils are deficient in phosphorus. Ironically, about 80 percent of the global reserves of phosphate rock are found in Africa (Batiano et al. 2012). In general, phosphate rock cannot be applied directly; it requires processing to be reactive and soluble. Phosphorus can be managed as a stock, but to achieve this, external inputs of inorganic phosphorus are essential (Smithson and Giller 2002). Use of phosphorus-efficient varieties and crops is only a temporary and second-best solution. Sooner or later, the soil stock of phosphorus has to be replenished.

There are no magic solutions to soil nutrient deficiencies or toxicities; mineral fertilizers are necessary to maintain productivity (Smithson and Giller 2002). Mineral fertilizers should be used in judicious amounts and coupled with improved organic matter management.

Misperceptions abound in soil fertility management in Sub-Saharan Africa (Vanlauwe and Giller 2006). In principle, nutrient mining is fine, as long as nutrient stocks are ample. That is, nutrient balances do not always have to be positive.

Soil water storage capacity conditions the incidence of drought stress. In the sandy soils of the Sahel and Southern Africa, very low organic matter and clay content translate into low available water capacity.

Highly intense rainfall can lead to runoff, low water availability to the root zone, and soil erosion. Peak rainfall intensity has been measured at rates exceeding 200 millimeter per hour in both Niger and Mali during years when annual rainfall averaged less than 400 millimeter (Hoogmoed and Stroosnijder 1984). Erosive rainfall translates into rampant runoff, especially on soils that crust.

Drought and low soil fertility can interact in ways that reduce agricultural productivity. In legumes, drought reduces moisture in the soil surface where most available phosphorus is found, which, in turn, may limit phosphorus supply to the plant. Low soil phosphorus may also restrict root expansion for more water capture, and both stresses will severely reduce symbiotic nitrogen fixation and limit nitrogen supply for grain (ICRISAT et al. 2012). Thus drought and low soil fertility can be a double whammy: drought increases the plant's sensitivity to low soil fertility and low soil fertility enhances the plant's sensitivity to drought. The scope for negative interactions is highest on the millions of hectares that are home to the parasitic purple witchweed *Striga*. Drought exacerbates infestation from *Striga* on poor soils.

In spite of these seemingly uninviting circumstances, average rates of production response to fertilizer application in Sub-Saharan Africa are similar to those in other regions of the world (Yanggen et al. 1998). The problem is that despite the "normal" production response rates, fertilizer use in many parts of Sub-Saharan Africa remains limited. Low fertilizer use can be explained by lack of

accessibility, high farm gate prices, and low liquidity at the start of the planting season (Desai and Gandhi 1990; Duflo, Kremer, and Robinson 2011; Morris et al. 2007). Strategies and tactics for increasing fertilizer use in crop production in Sub-Saharan Africa are thoroughly discussed in Morris et al. (2007).

Defining Dryland Cropping in Sub-Saharan Africa

In assessing prospects for technological change that contributes to intensification and/or to resiliency in African drylands, it is useful to review the relative importance of the major dryland agro-ecologies and the countries and crops located within them. Dryland agriculture is defined for three broad regions: the Arid, Semi-arid, and Dry Sub-humid Zones. In other words, dryland production is confined to rainfed cropping that is not found in the Wet Sub-humid and Humid Zones of Sub-Saharan Africa. Considerable evidence is presented herein that in some instances it makes sense to further distinguish between Dry and Wet Semi-arid Zones.

The data. A spatially detailed HarvestChoice database from circa 2000 and 2005 was the foundation for defining dryland agriculture.^{3,4} The database covers all of Sub-Saharan Africa. Forty-three countries and 547 subregions with positive cropped area are identified. For this report's purposes, it is important to recognize that the spatial distribution and performance of crops in the HarvestChoice database are founded on a mixture of descriptive information on "what is" combined with a large dose of "what should be," broadly based on the indicative potential from crop suitability assessments.

The dryland zones. For the purposes of this book, dryland agriculture is defined as having an Aridity Index (AI) between 0.05 and 0.65. The AI expresses the ratio of rainfall to potential evapotranspiration. Alternatively, it can be viewed as the ratio of the supply of water to the crop to the demand for water by the crop. Higher values of the index indicate wetter growing conditions; lower values are synonymous with drier growing environments.

The two threshold values that define the boundaries for the definition of dryland crop production warrant more explanation. Below the lower boundary of an AI of 0.05, all field crops require some irrigation to produce grain. Above an AI of 0.65, seasonal moisture deficits do not constrain crop production. Too much instead of too little rain is more likely to be the problem when the estimated AI exceeds 0.65. Surpassing this upper boundary may be associated with negligible drought risk but erosive rainfall events, waterlogged fields, and leached soils may be inimical to heavy yields.

Between 0.05 and 0.65, four AIs (3, 4, 5, and 6) refer to dryland crop production in the HarvestChoice database. Each is separated by an interval of 0.15. The last category (AI = 7) reflects rainfed production, which is reckoned to be too wet to be termed dryland. Therefore, cropped area can be disaggregated into three broad categories: (1) irrigated area that may be found in any of the AI Categories (1–7); (2) dryland area (AI Categories 3–6); and (3) wet rainfed (AI Category 7).

Table 2.1 Composition of Rainfed Crop Area, circa 2000, Sub-Saharan Africa

<i>Description of Dryland Zone</i>	<i>AI Category (class)</i>	<i>Average Length of Growing Season (days)</i>	<i>Average Rainfall (mm)</i>	<i>Share of Rainfed Cropped Area (%)</i>
Arid	3	46	272	11
Dry Semi-arid	4	99	546	18
Wet Semi-arid	5	154	809	18
Dry Sub-humid	6	196	1,051	21
Non-drylands: Wet rainfed	7	267	1,520	33

Source: Constructed from the HarvestChoice database (2014).

In 2000, about 140 million hectares were well described with crop names in the HarvestChoice database. Only about 4–5 percent of cropped area was irrigated. Two-thirds of rainfed area could be called dryland (AI Categories 3–6) and one-third could be termed wet rainfed (Category 7).

As expected, the means for the dryland categories exhibit wide variation in the length of the growing season and rainfall (table 2.1). On average, AI 3 is extremely dry, as the length of the growing season and the mean rainfall are only sufficient to accommodate a very short-duration grain legume or cereal. Surprisingly, this very dry rainfall and short growing season regime contributes an 11 percent share to the total rainfed area in Sub-Saharan Africa. This area is denominated the Arid Zone and is synonymous with the Sahelian Zone of West Africa.

Not surprisingly, African countries with proportionally more land cultivated in the Arid Zone have been highly susceptible to recurring drought (see box 2.4). However, intensification of arid agriculture is possible. Produced with a seasonal cropping rainfall of only 250 millimeters, wheat in western Australia is a good example of sustained productivity growth in both potential and farm yield (Fischer, Byerlee, and Edmeades 2014).

In terms of area, Categories 4, 5, and 6 are about equally important in dryland cropped area. Category 4 (the Dry Semi-arid Zone) is typical of the conditions prevailing in the southern Sahel, where pearl millet intercropped with cowpea is one of the dominant cropping systems. Category 5 (the Wet Semi-arid Zone) describes the Sudanian Zone, where sorghum is the most common cereal. Category 6 (the Dry Sub-humid Zone) reflects the agroclimatic characteristics of the wetter Guinean Zone, where maize is the dominant cereal.

Categories 4 and 5 pertain largely to the semi-arid tropics and, for the purposes of this report, are referred to as the Semi-arid Zone; Category 6 mostly indexes the sub-humid tropics and sub-tropics, and is called the Sub-humid Zone.

With a four to six month growing season and 800 mm mean rainfall, there are clearly geographic regions, such as those with more fertile soils within the wetter Semi-arid Zone, that have good prospects for sustainable intensification. With a growing season extending to almost nine months and a mean rainfall exceeding 1,500 mm, it is easy to see why regions in Category 7 are not included as drylands.

Box 2.4 Historical Incidence and Severity of Drought in Sub-Saharan Africa

Analysis of the Emergency Events Database (EM-DAT) natural disaster database compiled by the Centre for Research on Epidemiology of Disasters (CRED) at the Catholic University of Louvain in Belgium confirms conventional thinking that the historical incidence and severity of drought in Sub-Saharan Africa are significantly greater in the more arid than in the wetter dryland zones. Since 1900, 278 country-specific, drought-identified natural disasters have occurred in Sub-Saharan Africa. More than 350 million people have been affected. Most of the droughts took place after 1965 when their reporting increased.

Estimating the ratio of the cumulative number of persons affected since 1965 to the national population in 2010 provides a simple aggregate index of the severity of drought over time. Among large countries in Sub-Saharan Africa, the severity index ranges from 1.9 in Niger to 0.02 in Nigeria. Only one severe drought is recorded in the EM-DAT database for Nigeria since 1960. Three million people were affected by drought in 1981.

Among countries with large dryland areas, Nigeria is an outlier. Most dryland countries are characterized by estimated ratios higher than 0.5, and 10 countries have had more people affected than their national population in 2010.

Among the three broadly defined dryland zones, the proportional allocation of area in the Arid Zone displays the strongest correlation (0.69) with the drought severity index. Most countries with a concentration of Arid Zone cropping show high drought severity estimates. Some, such as Namibia and Chad, do better than others in the sense that they have lower estimated drought severity ratios relative to the importance of the Arid Zone in their cultivated area.

In spite of the high association between Arid Zone cropping and drought severity, several countries have high drought severity ratios and little Arid Zone cropping. Malawi, Mozambique, and Zimbabwe are typical of such outliers. Poor rural households in these countries appear to be especially sensitive to drought or rural households are unduly exposed in higher rainfall regions where precipitation is highly variable. In these countries, many households derive on average 65–75 percent of their income from crop production.

Profiling the dryland zones. Productivity aspects of the dryland zones are described in table 2.2 together with the Non-dryland Rainfed Humid Zone for comparison. All dryland zones are endowed with problematic soils. Low nutrient capacity, deep sands, and leaching are edaphic constraints endemic to the Arid Zone. At the other end of the rainfall spectrum, the non-dryland Humid Zone suffers from problems of aluminum toxicity, low nutrient capacity, and phosphorus fixation. The incidence of cracking clays is higher in the Semi-arid Zone. Overall, the soil estimates in table 2.2 point to the inference that low soil fertility is likely to be more problematic in the Arid Zone than in the other dryland zones. Moreover, problematic soils are as likely to be found in the non-dryland Rainfed Humid Zone as in the dryland zones. Within the dryland zones in the Semi-arid and Sub-humid Tropics, it is not transparent that higher rainfall is associated with superior soils for crop production.

Table 2.2 Characteristics of Dryland Crop Zones in Sub-Saharan Africa (excluding South Africa)

Characteristic	Crop Zone				
	Dryland				Non-dryland
	Arid	Dry Semi-arid	Wet Semi-arid	Dry Sub-humid	Rainfed Humid
Problem soils (% area)					
Aluminum toxicity	0.2	1.2	5.8	21.1	39.2
Calcareous	9.3	10.3	5.9	2.4	1.0
Cracking clays	7.0	13.0	11.8	4.8	1.9
Low nutrient capacity	57.6	29.6	14.8	21.5	43.1
Nitrogen leaching	47.9	24.1	10.3	7.6	11.2
Phosphorous fixing	0.1	0.6	2.6	6.6	13.1
Sands	62.8	37.9	24.1	15.2	15.9
Density per square km					
Population	31.9	58.3	92.4	65.9	119.5
Cattle	19.4	25.7	29.3	22.0	16.8
Goats	24.2	39.6	43.1	18.9	30.8
Productivity indexes					
Maize yield (tons/ha)	0.72	0.99	1.48	1.54	1.45
Total factor productivity (% growth from 1961–2008)	-0.04	0.09	0.25	0.34	0.23

Source: Constructed from the HarvestChoice database and weighted by cropland area except for the total factor productivity estimates, which are aggregated by the country's importance in cropland area in each zone and are based on country estimates in Fuglie and Rada (2013).

The productivity estimates in table 2.2 support the soil inferences. (Maize is the crop that is the most common to the four dryland zones in terms of number of observations in the HarvestChoice database.) Yields in the Arid and Dry Semi-arid Zones are inferior to the two higher rainfall dryland zones, where maize productivity is 1.5 tons per hectare. This mean level of productivity is also achieved in the non-dryland Rainfed Humid Zone.

Two inferences can be drawn. First, productivity differences support the separation of the semi-arid tropics into two zones based on rainfall. The Dry and the Wet Semi-arid Zones can have markedly different prospects in terms of production potential. Second, the parity in maize yields in the higher rainfall zones suggests that the scope for intensification in the Wet Semi-arid Zone is as ample as it is in the Dry Sub-humid Zone.

The total factor productivity estimates in table 2.2 convey the same message: historical growth in technological change has been stagnant in the Arid Zone, positive but small in the Dry Semi-arid Zone, and higher but by only about one-third of 1 percent and not substantially different in the three higher rainfall zones (Fuglie and Rada 2013).

Two drivers of crop productivity are population and livestock density. Additionally, both cattle and goats enhance options for coping with drought. For both of these reasons, prospects are brighter for yield growth with rising

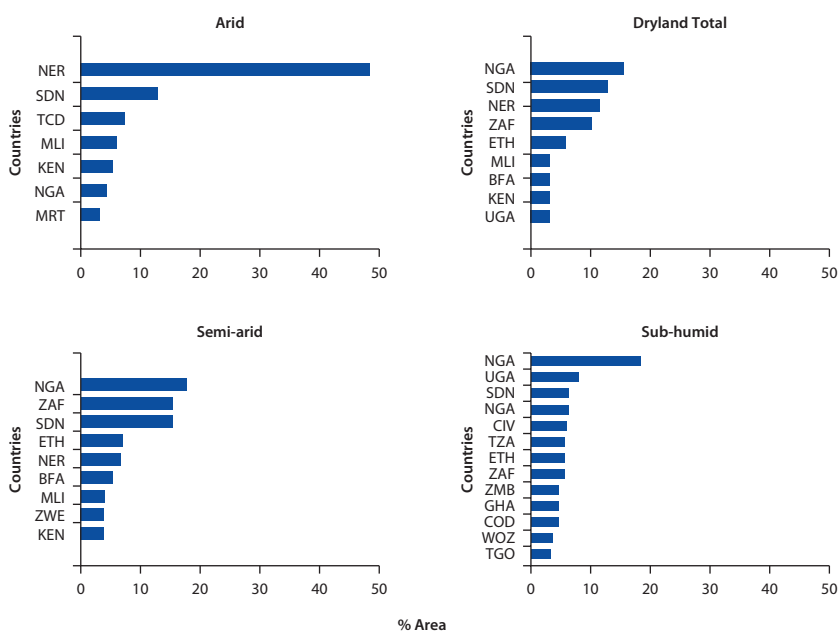
population and livestock densities. Among the dryland zones, population density is highest in the Wet Semi-arid Tropics; among all zones in table 2.2, livestock densities are also highest in the Wet Semi-arid Tropics. Because of disease, livestock levels decline with rainfall in the Sub-humid and Humid Tropics, where animal traction has spread more slowly than in the semi-arid tropics (Pingali, Bigot, and Binswanger 1987; Starkey 2000).

In summary, the estimates in table 2.2 give lie to the notion that the scope for intensification is linearly related with rainfall. Annual rainfall matters up to a threshold of about 800 mm but beyond that, threshold differences in production potential are not that transparent for most cereals, oilseeds, and pulses commonly cultivated in Sub-Saharan Africa.

The dryland countries and important subregions. As rainfall increases across the drylands of Sub-Saharan Africa, the distribution of cropland becomes less concentrated across countries and subregions. Almost half of the cropped area in the Arid Zone is found in Niger (figure 2.2) (also see box 2.5). Four of Niger's administrative divisions figure in the top five subregions in cropland in the Arid Zone. Zinder alone accounts for 16 percent of harvested area. Only Sudan (SDN) contributes more than 10 percent of cropped area in the Arid Zone. The combined extent of the next five countries (Chad (TCD), Mali (MLI), Kenya (KEN), Nigeria (NGA), and MRT (Mauritania)) is less than the total area cropped in the Arid Zone in Niger (NER).

More countries and subregions contribute to crop area in the Semi-arid Zone. The dominant countries are Nigeria, South Africa (ZAF), and Sudan, with an

Figure 2.2 Distribution of Countries by Cropped Area Across the Dryland Zones and Total



Source: Constructed from the HarvestChoice database.

Box 2.5 Institutional Response to Recurring Drought in Niger

With 13 documented droughts since 1900, Niger is arguably the poster country for drought-induced production shortfalls in Sub-Saharan Africa. Human suffering caused by drought is visible, palpable, and engenders an institutional response. Following recurring rainfall shortages in the Sahel from 1970 to 1973, the Government of Niger took positive steps to drought-proof its agriculture sector. Its emphasis shifted from industrialization to ensuring food security and self-sufficiency (Pender et al. 2008). Many irrigation projects were established and managed by the *Office National des Amenagements Hydro-Agricoles*. United States Agency for International Development (USAID) invested in a large project to supply farmers with the seed of food security crops, such as millet, sorghum, and cowpea. The project was also designed to reinforce the research capacity of the *Institut National de Recherche Agricole* du Niger, which was created in 1975. Later, Niger partnered with International Crops Research Institute for the Semi-arid-Tropics (ICRISAT) to establish an international agricultural research station at Sadore with an emphasis on maintaining and improving productivity in a harsh dryland environment.

In spite of several successes (Mortimore et al. 2001; Reij, Tappan, and Smale 2009), Niger has had to avail itself of large-scale humanitarian assistance three times since 2000 in response to recurring droughts and plagues of locusts (rangeland grasshoppers). As many as 3.5 million people are still at risk (FAO 2012a).

Sedentary agriculture in the southern Sahelian drylands of Niger is the most challenging environment in Africa's semi-arid tropics for improved cropping techniques, broadly defined as new varieties and management practices, to make a difference in poor people's lives. The potential for intensifying production is limited by the sometimes present drought and the always present poor soils. Technological change is anything but abrupt: it is reckoned in tens or at most 100–200 kilograms per hectare.

In other dryland regions of Africa, new varieties and crop management practices can contribute to intensification that leads to marketed surplus, lower prices, and enhanced food security. In those regions, generally droughts are more intermittent and less severe, strains of downy mildew infesting cereals are less virulent, insects do not attack cowpea with the ferocity of Maruca (pod borer), and sandstorms and plagues of locusts are rare occurrences. In Niger, productivity gains are still possible, but productive agricultural research is likely to have more leverage on increasing risk benefits and reducing vulnerability than on intensification (ICARDA and ICRISAT 2013; van Ginkel et al. 2013).

aggregate relative importance that approaches Niger's magnitude in the Arid Zone. More than 17 well-defined subregions contribute more than 1 million hectares of area to the 65 million hectares of cultivated area in the Semi-arid Zone.

Nigeria tops the list of cropped area in the Sub-humid Zone, which extends to many countries in Sub-Saharan Africa. To arrive at the 90th percentile in cropped area of this dryland zone, one has to sum the contributions of

16 countries. Cropped area in the Sub-humid Zone is more spatially fragmented than corresponding areas in the Arid and Semi-arid Zones. Only three sub-regions could be considered large, with a cropped area exceeding 1 million hectares. Two of these, Northern Province in Zambia and Katanga Province in the Democratic Republic of Congo (DRC), are characterized by substantially more cultivated area in the non-dryland Rainfed Humid Zone than in the Dry Sub-humid Zone.

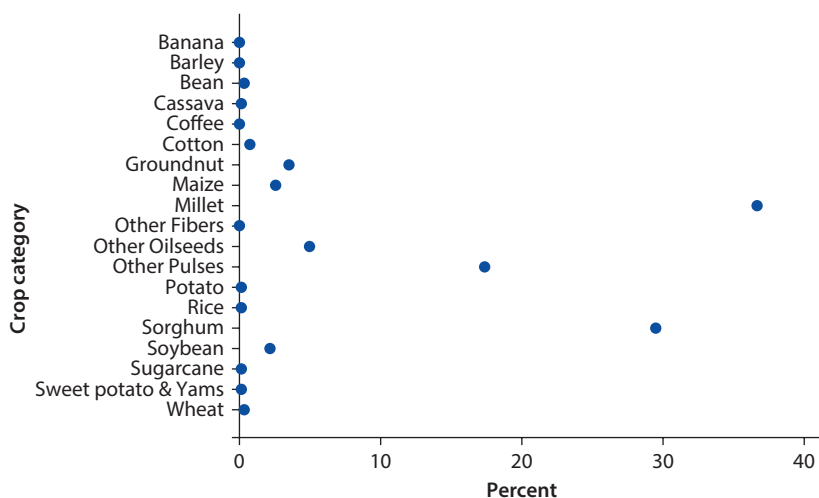
The subgraph in the upper right quadrant of figure 2.2 reinforces the relative importance of four countries in the drylands of Sub-Saharan Africa: Nigeria, Sudan, Niger, and South Africa. Cropped area across the three dryland zones is also sizable in Ethiopia. Mali, Burkina Faso, Kenya, and Uganda, with 3–4 percent shares of total cultivated dryland area, comprise the second tier of countries ranking high on relative importance.

The dryland crops. Similar to the distribution of countries in dryland cropping, the distribution of crops becomes less concentrated as aridity decreases across the dryland zones (figure 2.3). Only three crop categories (millet, sorghum, and other pulses) account for over 80 percent of cultivated area in the Arid Zone (figure 2.3a). Pearl millet is the prevalent millet species and cowpea is the dominant pulse.

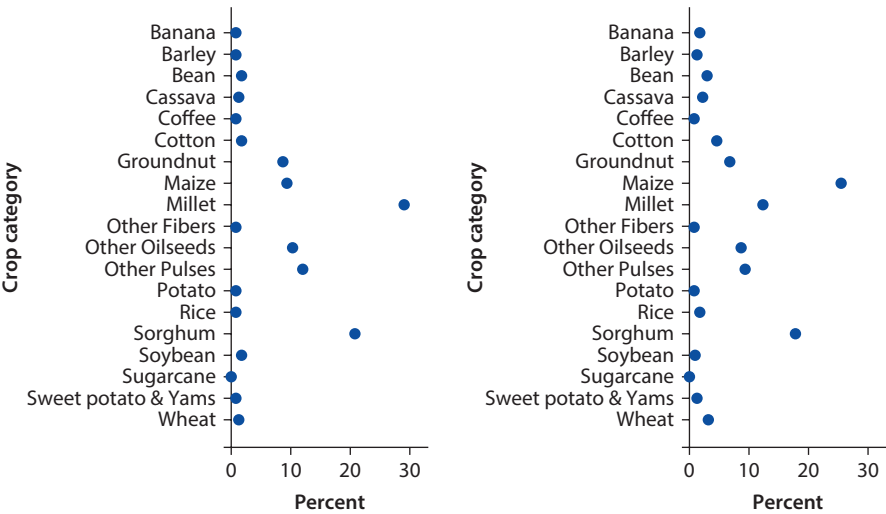
Millet retains its primacy in the drier parts of the Semi-arid Zone, but, in the wetter semi-arid tracts, millet is replaced by maize (figure 2.3b). In contrast, the relative importance of sorghum does not change as growing-season rainfall increases in the Semi-arid Zone. Groundnut also seems invariant to changes in rainfall in the Semi-arid Zone. Nevertheless, crop diversity is greater in the wetter (AI = 5) than in the drier regions (AI = 4) of the Semi-arid Zone.

Figure 2.3 Share of Area (%) by Crop Category by Dryland Zone

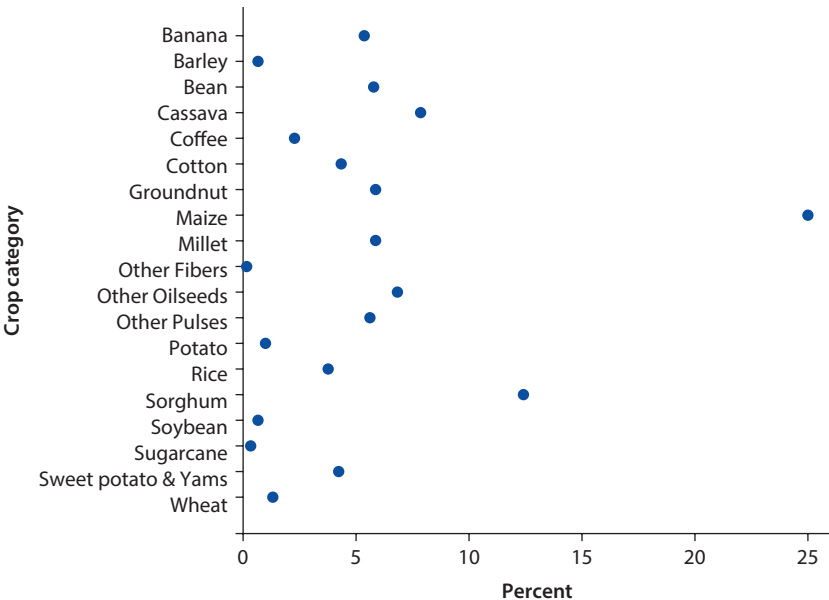
a. Share of Area in % by Crop Category in the Arid Zone



b. Share of Area in % by Crop Category in the Dry Semi-arid Zone and the Wet Semi-arid Zone



c. Share of Area in % by Crop Category in the Dry Sub-humid Zone



Source: Constructed from the HarvestChoice database.

As expected, opportunities are ample for crop diversification in the Sub-humid Zone. Maize is the leading crop by a wide margin, but almost all food crop species can be found in this wettest of dryland zones (figure 2.3c). Sorghum is a distant second to maize, and some millet is still produced.

Table 2.3 Relative Importance of Crops in Dryland Areas, circa 2000, Sub-Saharan Africa

<i>Crop</i>	<i>Share of Total Dryland Cropped Area (%)</i>
Sorghum	19.69
Millet	18.44
Maize	16.80
Other pulses	9.86
Other oilseeds	8.25
Groundnut	6.42
Cassava	3.30
Cotton	3.09
Bean	3.01
Banana	2.23
Sweet potato and yam	1.74
Upland rice	1.71
Wheat	1.54
Soybean	1.23
Coffee	1.00
Barley	0.64
Potato	0.55
Other fiber	0.31
Sugarcane	0.18

Source: Constructed from the HarvestChoice Database; You, Wood and Wood-Sichra (2007).

Maize, sorghum, and millet were the most extensively cultivated crops in dryland agriculture in the early 2000s when the HarvestChoice database was compiled (table 2.3). These three cereals accounted for about half of cultivated area (table 2.3). If these data were updated to 2010 or 2013, it is likely that maize would figure as the leading cereal because its recent growth in production exceeds sorghum and millet, which have weaker demand. Maize outperforms millet and sorghum in the Wet Semi-arid and Dry Sub-humid Zones as long as fertilizer is applied.

Dryland characteristics of several of the entries in table 2.3 warrant comment. Cowpea in West Africa is the dominant crop in “Other pulses.” Rice is labeled as upland rice because it is the principal production type in dryland agriculture and because supporting data are available to describe its production characteristics. Cotton is the most important cash crop in dryland agriculture. It can be a force for intensification of food crops within cotton-growing households. Excluding South Africa, over 90 percent of wheat production in Sub-Saharan Africa takes place in Ethiopia, which also accounts for the lion’s share of barley production.

Many food crops are predominantly grown in the drylands in Sub-Saharan Africa. Ten of the 19 commodities in table 2.4 equaled or exceeded the mean level of 84 percent. Of the 19, only banana, cassava, coffee, rice, and sugarcane had a dryland share of harvested area that was less than 40 percent. Sweet

Table 2.4 Relative Importance of Dryland Cropping in Sub-Saharan Africa

<i>Crop</i>	<i>Dryland (AI 3–6) (%)</i>	<i>Rainfed Wet (AI 7) (%)</i>	<i>Irrigated (%)</i>	<i>Total Cropped Area (ha)</i>
Banana	38.2	61.7	0.1	5,269,893
Barley	55.5	44.1	0.4	1,044,183
Bean	52.6	47.3	0.1	5,148,596
Cassava	28.7	71.3	0.0	10,343,873
Coffee	35.7	64.1	0.2	2,526,521
Cotton	69.9	22.3	7.8	3,984,223
Groundnut	71.3	23.7	5.0	8,124,154
Maize	59.8	38.4	1.8	25,330,029
Millet	92.6	7.3	0.1	17,959,054
Other fiber	81.9	18.1	0.0	343,829
Other oilseeds	72.6	27.4	0.0	10,255,960
Other pulses	85.2	14.4	0.3	10,432,527
Potato	47.5	51.0	1.5	1,038,216
Rice	24.1	43.8	32.1	6,408,267
Sorghum	84.8	10.4	4.8	20,929,856
Soybean	69.2	29.8	1.0	1,606,805
Sugarcane	16.0	41.7	42.3	1,020,741
Sweet potato/yam	32.8	57.7	9.5	4,778,065
Wheat	54.5	25.0	20.5	2,546,549
Total	n.a.	n.a.	n.a.	139,091,341

Source: Constructed from HarvestChoice database; You, Wood and Wood-Sichra (2007).

Note: n.a. = not applicable.

potato's dryland share would be higher except it is combined with yams, which are almost exclusively produced in the humid tropics of West Africa. Rice and sugarcane are the most heavily irrigated crops. Wheat also has a sizable share of irrigated area. Cassava is mainly cultivated in the non-drylands under wetter, rainfed conditions as is banana. Potato area is about equally split between the drylands and the wet rainfed sub-humid tropics.

There are not many countries in which the same crop is grown extensively under both rainfed and irrigated conditions. Sudan is one, with large areas of rainfed sorghum in the smallholder and mechanized subsectors and a smaller but still sizable irrigated subsector. Nigeria is another, with appreciable areas of upland, lowland rainfed, and irrigated rice.

The six cereals in tables 2.3 and 2.4 are planted in an array of cropping systems; however, sole-cropping is common and so is intercropping with grain legumes including pulses and oilseeds. Cereal/cereal intercrops, such as maize/pearl millet in West Africa, are also popular in well-defined areas. Intercropping cereals with roots and tubers like sweet potato and cassava is rare. Sequential cropping of dryland species is also not common. Upland rice is mainly sole-cropped. Relay cropping of cowpea after the sowing of pearl millet is possible and increasingly common in the Dry Semi-arid Zone.

Based on the estimates in tables 2.3 and 2.4, five crops each account for more than 5 percent of the total cropped area in the Arid, Semi-arid, and Sub-humid Zones of Sub-Saharan Africa. The so-called “big five” are maize, millet, sorghum, groundnut, and cowpea. More than half of their harvested area comes from the drylands. The emphasis in the next chapter is on their prospects for genetic improvement.

Notes

1. Risk of early season drought is higher in West Africa's Semi-arid Tropics than in India's Semi-arid Tropics (ICRISAT 1985). For the same level of long-term average rainfall, the onset of the rainy season is more undependable in West Africa's Semi-arid Tropics. In contrast, end-of-season rainfall is more reliable in West Africa's Semi-arid Tropics.
2. Like the dryland soils in India's Semi-arid Tropics, soils in African drylands are also likely to be deficient in micro-nutrients, especially sulfur, boron, and zinc (Sahrawat et al. 2007). Researchers and fertilizer providers have recognized the likelihood of these deficiencies and have started to include these elements in their blends. Testing for single-element responses to sulfur, boron, and zinc is also becoming more common in fertilizer trials.
3. See <http://harvestchoice.org/products/data>
4. The database on the spatial distribution and performance of crops contains 5-minute (approximately 10-kilometer) resolution grid maps across Sub-Saharan Africa (You, Wood, and Wood-Sichra 2007). Each of the pixels or 290,000 observations range in area from 5,860 to 8,586 hectares. Cultivated area for major crops was allocated geographically from spatially explicit data, including production statistics, land use data, satellite imagery, biophysical crop “suitability” assessments, population density, and distance to urban centers, as well as any prior knowledge about the spatial distribution of individual crops.

Prospects for Genetic Improvement

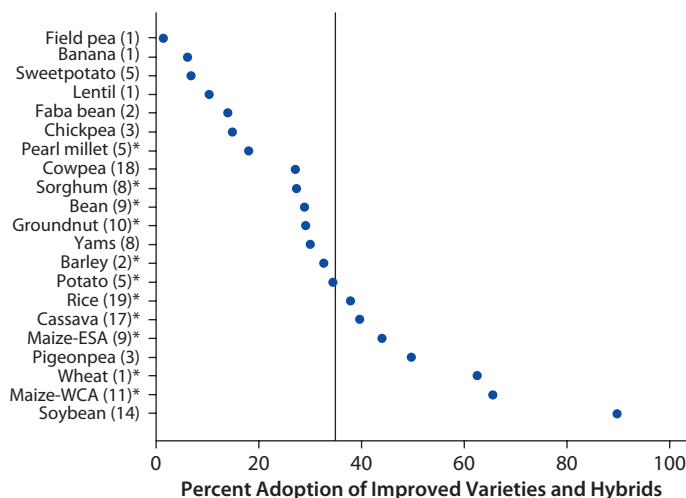
One source of technical change that could reduce the vulnerability and increase the resilience of many of the people living in drylands is improved germplasm. Many of the households that depend on farming as a primary livelihood source continue to grow traditional varieties, either land races that reflect generations of selection behavior by farmers themselves, or improved varieties and hybrids developed by scientific breeding programs but introduced many years ago and no longer competitive with newer varieties.¹ While land races and older improved varieties and hybrids can have characteristics that are valued by farmers and consumers, they may not be the best option.

Maintaining and Accelerating the Pace of Varietal Change

Data on the adoption of improved cultivars in Sub-Saharan Africa are notoriously scarce. Adoption data are best collected through surveys carried out in farmers' fields, which are technically challenging to carry out and costly. The discussion that follows draws heavily on two snapshots of varietal adoption, Evenson and Gollin (2003) for 1998 and Walker and Alwang (2015).

In 2010, the level of adoption of improved cultivars for 20 major crops was estimated at 35 percent in the dominant producing countries for each crop (figure 3.1). For the 10 crops designated with an asterisk in figure 3.1, a benchmark of the level of national adoption existed for 1998 (Evenson and Gollin 2003). For those crops, the growth of modern cultivar adoption between 1998 and 2010 was equivalent to an annual linear increase of 1.45 percent.

These data suggest that adoption of improved cultivars for major food staples started later and proceeded more slowly in Sub-Saharan Africa than in other developing regions, but Sub-Saharan Africa is slowly catching up. Across the entire region, improved varieties and hybrids are increasingly finding a home in farmers' fields at a slow but steady rate. Other studies show that adoption of modern cultivars has had a clear impact on productivity. According to Fuglie and

Figure 3.1 Adoption of Modern Varieties by Crop, 2010 (% of area harvested)

Source: Constructed from Walker et al. (2014).

Notes: Numbers of countries in the area-weighted mean adoption estimate for each crop are in parentheses. Asterisks refer to crops included in the 1998 Evenson and Gollin (2003) initiative. Maize is divided into its two major regions, East and Southern Africa (ESA) and West and Central Africa (WCA).

Marder (2015), 30–40 percent of productivity growth related to technological change in Sub-Saharan Africa since 1980 can be attributed to adoption of improved cultivars.

Many of the improved varieties being grown in Sub-Saharan Africa are quite old, however. Focusing on the same set of 20 major crops, about 3,600 improved varieties have been released in Sub-Saharan Africa since 1970; of these, more than 1,000 varieties could be found in farmers' fields in 2010. The largest age-cohort of the improved varieties being grown by African farmers in 2010 was released in the 1990s. With the exception of banana, yams, and rice, most of the area planted to improved varieties was and is located in dryland regions.

While adoption data are collected at the national level and cannot easily be disaggregated by aridity zone, the general patterns are believed to be valid for dryland production systems, which comprise a large share of crop output in Sub-Saharan Africa (the one notable exception is rice, production of which is concentrated in more humid environments and in irrigated zones). To provide insights into the opportunities and challenges associated with the promotion of improved germplasm in the drylands, the following sections focus on the adoption performance and prospects for genetic change of the three cereals and the two grain legumes that are most widely cultivated in the drylands of Sub-Saharan Africa. Many of the results have previously been reported in the recently concluded DIIVA study (Diffusion and Impact of Improved Varieties in Africa) Project (Walker et al. 2014).

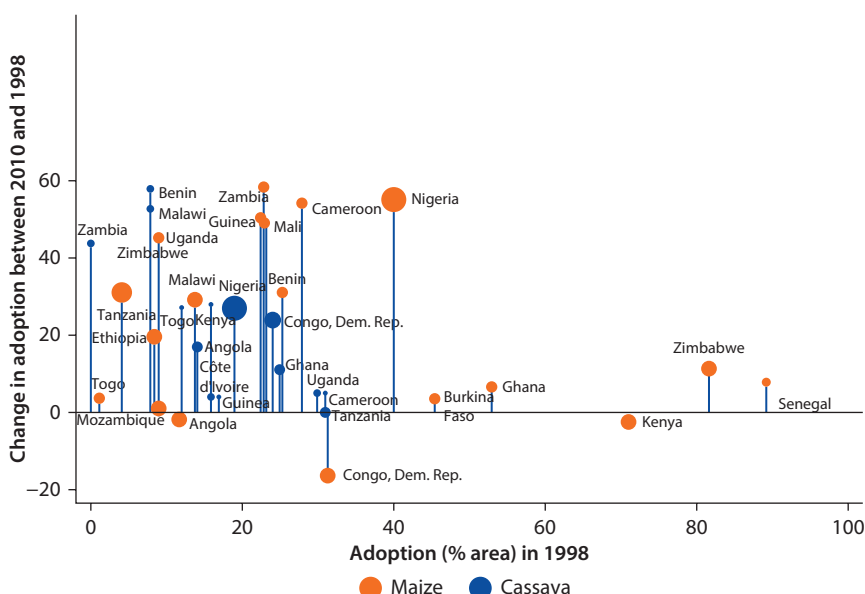
Maize. Demand for maize is by far the highest of any coarse cereal produced in dryland environments, where it is grown by many smallholder households as

a staple food, as a cash crop, or both. Because maize lends itself readily to hybridization, meaning that plant breeders can more easily protect their intellectual property by securing the parental inbred lines, substantial resources have been invested in maize breeding in East and Southern Africa breeding since Independence, both in the public and in the private sector. In West Africa, maize similarly is characterized by markedly higher research intensity than other leading crops such as sorghum or pearl millet, although the level of private investment in West Africa pales in comparison to that in East and Southern Africa.

In 2010, slightly more than one-half of the area planted to maize in Sub-Saharan Africa (55 percent) was planted to improved varieties and hybrids. The 55 percent figure is based on national adoption estimates from 19 countries that between them contain over 90 percent of the total maize-growing area in Sub-Saharan Africa. In the late 1990s, in the same set of countries the area planted to modern varieties and hybrids was assessed at 40 percent of the total area planted to maize (Hassan, Mekuria, and Mwangi 2001; Manyong et al. 2003; Morris, Mekuria, and Gerpacio 2003).

Country-specific adoption estimates for maize are presented in figure 3.2 for 1998 and 2010, together with those for cassava, the other primary staple food crop in Sub-Saharan Africa. (The size of the balloons in the figure reflects the size of maize- or cassava-growing area.) In most countries, adoption of improved varieties and hybrids increased between 1998 and 2010, and, in some countries the increases were substantial. Increased uptake of maize improved varieties and

Figure 3.2 Adoption of Maize and Cassava Improved Cultivars, 1997/98 versus 2009/10



Source: Figure 4.1 in Walker et al. (2014).

Note: The size of the balloon is proportional to the size of the harvested area in each country.

hybrids was especially pronounced in Zambia and Malawi. Maize improved varieties and hybrids also contributed to a positive adoption experience in Ethiopia. Not visible in figure 3.2 is the fact that increased adoption in the West African countries and in Tanzania and Uganda was mostly fueled by the spread of improved open-pollinated varieties (OPVs), as opposed to hybrids.

So-called “spillover” varieties are varieties or hybrids that have been released and adopted in several countries. Spillover varieties have been especially common in West Africa. For example, Obatanpa, derived from quality protein materials and first made available for adoption in Ghana in 1992, has found a home in farmers’ fields in five other countries in West Africa.

Increases in the area planted to improved germplasm have been associated with increased availability of modern cultivars. Of the 3,000 entries in the DIIVA 20-crop output database, which covers the period between 1970 and 2010, out of approximately 3,000 entries representing cultivars that have been improved by a breeding program, maize accounts for about 1,000. In the most recent decade between 1999 and 2010, the availability of maize hybrids has increased markedly in several countries in East and Southern Africa. Since 1999, more than 100 new maize hybrids have been released in Kenya and Zambia (De Groote, Gitonga, and Mugo 2011). In contrast, since 1980 improved maize cultivars have been released at a slower albeit steady pace in West Africa, where private sector breeding activity is limited and farmers rely on improved varieties developed in the public sector.

The association between varietal releases and varietal adoption is statistically significant, but the relationship is not strong, at least not in the 19 maize-growing countries for which data are available from both the 1998 and 2010 benchmarks. In addition, the relationship is somewhat inconsistent: a high rate of varietal releases does not guarantee a high rate of adoption, but a low rate of varietal releases is frequently associated with low adoption outcomes.

What accounts for observed differences between countries in rates of varietal release? One explanatory factor is the level of investment in R&D, including the number of research scientists working in the area of plant breeding. In East and Southern Africa, increases in scientific effort as measured by the number of full-time equivalent (FTE) scientists has translated into positive changes in varietal output for several countries. Across the nine maize improvement programs in East and Southern Africa, the median gain in scientists recorded between 1998 and 2010 was 7.0 FTE, and the number of maize scientists working in Zimbabwe and Tanzania more than doubled. During the same period, most countries in West Africa did not see substantial shifts in scientific strength, with the exception of Nigeria, where the number of maize scientists more than doubled. The marginal increase in scientific capacity that occurred in West Africa is consistent with a small rise in varietal output observed in that region since 1980 (Walker et al. 2014).

Relative to other cereals and other staple food crops, maize was favorably endowed with scientific capacity in 2010. Maize improvement programs were characterized by a moderately high research intensity of 15 FTE scientists

per million tons of production. This mean estimate of research intensity applied to both major maize-growing regions in Sub-Saharan Africa in 2010. Similar to most other crops included in the DIIVA Project, research intensity in maize has not markedly increased over time, however, because increased scientific capacity did not keep pace with rising production. In West and Central Africa, estimated research intensity actually declined between 1998 and 2010.

The DIIVA Project results bear testimony to the large economic impacts that can result from intensification of maize production via varietal change in higher-potential environments, such as the tropical highlands. For example, plot-level data collected through a large, nationally representative survey in Ethiopia show a 50–60 percent yield advantage of modern cultivars, mainly hybrids, over traditional varieties (Zheng et al. 2013). In the Ethiopia case, in return for absorbing a 25 percent increase in the cost of production, the average smallholder adopting household realized income gains of about US\$20. These field- and household-level impacts translated at the national level into an annual gain in economic surplus approaching US\$200 million and are estimated to have led to a reduction in the incidence of rural poverty of about 1 percentage point.

In summary, maize crop improvement efforts have paid off handsomely in many African countries in recent years. The level of investment in maize breeding research has exceeded the levels of investment in breeding research on other coarse cereals, varietal output has been very high, adoption has increased in many countries, and the impacts in terms of higher yields and improved incomes have been pronounced and well documented in several countries.

This story about scientific input, varietal output, adoption outcomes, and impact in and from maize crop improvement would not be complete without identifying several areas for improvement and challenges that have not been met. These challenges pertain to:

- Widespread non-adoption in countries such as Angola and Mozambique;
- Lagging adoption in marginal sub-regions within countries;
- Slow rates of varietal turnover even in countries like Kenya where varietal output has been high;
- Absence of private investment in hybrid research and seed production in West Africa; and
- Inertia in public sector policy to facilitate the conditions for sizable impacts from varietal change.

Sorghum and pearl millet. Sorghum and pearl millet are treated together in this section because the zones in which they are produced (mainly in West Africa) overlap and because they share a common experience in terms of scientific capacity, varietal output, adoption outcomes, and impacts. In addition, in many public breeding programs the same scientists also work on both crops. Investment by the private sector in the genetic improvement of these two cereals is extremely limited, mainly because there is very little demand for commercial hybrids.

Sorghum and pearl millet both were part of the 1998 global benchmark described in Evenson and Gollin (2003), but coverage of the two crops was skewed towards smaller producing countries in East and Southern Africa. This makes it difficult to draw inferences about progress achieved since then in the adoption of modern sorghum and pearl millet varieties.

As reported in the DIIVA study, in 2010 improved varieties of pearl millet were being cultivated on 18 percent of the total growing area in five of the most extensive pearl millet-producing countries in West Africa (Ndjeunga et al. 2012). In the same year, uptake of improved varieties of sorghum was somewhat higher at 27 percent, but adoption in the smallholder dryland sector was lower at 20 percent. In Sudan, about 0.5 million hectares of sorghum are irrigated and are overwhelmingly sown to improved varieties and hybrids; the large, commercial, rainfed, mechanized subsector accounts for another 3.5 million hectares, with an estimated 45 percent adoption level (Zereyesus and Dalton 2012).

With the salient exception of the improved pearl millet cultivar SOSAT C-88 released in Mali in 1988, most of the improved varieties of sorghum and pearl millet that have been taken up by farmers date from after 1990. Varieties released earlier, mainly in the 1970s and 1980s, did not find much favor with farmers, because the earlier varieties increased the risk of losses to birds, diseases, and insect pests and/or did not respond to farmers' needs for high grain quality combined with good biomass production (Matlon 1990). SOSAT C-88 is prized for its early maturity, insect tolerance, grain color, and quick cooking time (Ndjeunga et al. 2011). Its main weakness is low fodder production.

Almost all of the sorghum and pearl millet improved cultivars that have been adopted on a significant scale are varieties. The one exception has occurred in Sudan, where several hybrids have become popular. The most notable of the Sudanese sorghum hybrids is Hageen Dura-1. Hageen Dura-1 is the most visible output of a multiphase breeding program, coordinated by International Crops Research Institute for the Semi-arid-Tropics (ICRISAT) and funded by the United Nations Development Programme (UNDP), which supported millet improvement work in Burkina Faso, Mali, Niger, Nigeria, Senegal, and Sudan during the late 1970s and early 1980s.

Several factors have contributed to slow rates of breeding progress and low levels of adoption of modern sorghum and pearl millet varieties in West Africa. In most countries within the region, germplasm improvement research has been underfunded, and varietal output consequently has been meager. Only 300 improved cultivars of sorghum and pearl millet are listed for West Africa in the DIIVA Project's varietal releases database, slightly less than 10 percent of the total number of varietal releases for all crops. Since sorghum and pearl millet occupy about 30 percent of total cultivated area in West Africa, if the number of varietal releases had been proportional to size of the area planted, one would have expected to see about 900 releases.

The rate of varietal releases in sorghum and pearl millet has not only been low, it has also been irregular. Releases of improved cultivars for sorghum and pearl

millet have been unevenly distributed across countries and punctuated by long gaps. Of the approximately 300 releases recorded in West Africa since 1970, 104 took place in Mali. Meanwhile, in Nigeria, the second largest producer of pearl millet in Sub-Saharan Africa, only 11 improved pearl millet varieties were released. And in Senegal, which has more than 1 million hectares under cultivation, not a single improved pearl millet cultivar was released between 1986 and 2011.

The low and uneven rate of varietal releases in sorghum and pearl millet observed in West Africa can be attributed in large part to underinvestment in research. The number of scientists working in plant breeding research in West Africa is strikingly low. Research intensities for sorghum and pearl millet are typically 10–50 percent of the research intensities for maize. Among the DIIVA Project countries, only Sudan has a research intensity for sorghum that rivals the research intensities found in maize-growing countries, especially those in East Africa. The most extreme case is Nigeria, which has only 1.5 FTE scientists per million tons of sorghum production.

In assessing scientific capacity available for the improvement of coarse cereals in the public plant breeding programs of Sub-Saharan Africa, it is important to consider not only the number of scientists, but also their age. In 2010, in the five DIIVA Project countries in West Africa, two-thirds of the scientists employed in national agricultural research services and working on sorghum and pearl millet (65 percent) were over 50 years old. The skewed age configuration in the public crop improvement programs is likely to have negative consequences in future years, because opportunities are being lost for experienced scientists to mentor younger colleagues.

The low rate of varietal releases in sorghum and pearl millet observed in recent decades may also have deeper roots: it may be to some extent a legacy of underinvestment in research on these two crops during the colonial era. During the 1960s when many African countries achieved independence, the cupboard was bare in terms of a research foundation for future breeding efforts in sorghum and pearl millet. Of the 98 varietal releases in the DIIVA 20-crop database that date back before 1970, only three are sorghum or pearl millet varieties.

Research initiatives that with hindsight turned out to have been misguided also delayed the development of improved sorghum and pearl millet cultivars suited to the circumstances of African smallholders. For example, a great deal of effort was invested in working with photoperiod-insensitive sorghum hybrids introduced from India. These were seen as attractive because of their high grain yield potential, even though they scored poorly with respect to grain and fodder quality and stover production. A number of cultivars developed using these materials were released in West Africa, but they never became popular, because their cultivation cycle had to be synchronized with the cultivation cycle of traditional Guinean types to escape bird, insect, and disease damage. In general, exotic materials have not performed well in West Africa.

Of the over 1,000 improved cultivars listed in the DIIVA adoption database, the aforementioned SOSAT C-88, a short-duration pearl millet variety, was the

most extensively cultivated improved variety of any crop. In 2010, SOSAT C-88 was cultivated on just over 1 million hectares, mainly in Nigeria, Mali, Niger, and Burkina Faso. It was selected in Mali from a cross of two local landraces, one early and one late (Niagado and Kumar 1989). In trials, SOSAT C-88 outyielded its parental lines by 30 percent.

Groundnut. Groundnut is cultivated in more countries and subregions of Sub-Saharan Africa than any other food crop, aside from maize. As a grain legume that fixes nitrogen, it figures prominently in intercroops and is frequently grown in rotation with cereals. As an oilseed with diverse end uses, it faces good demand prospects in national and international markets. Although groundnut is grown throughout Sub-Saharan Africa, the bulk of groundnut production takes place in the semi-arid and sub-humid tropics of West Africa in the southern Sahelian, Sudanian, and northern Guinean Zones.

During the colonial era, groundnut was viewed as an export crop, and trade flourished between West Africa (especially Senegal) and Europe. That trade was adversely affected by the Sahelian drought and lower than normal rainfall in the 1970s and early 1980s and by increasing non-tariff barriers in the form of more stringent requirements relating to acceptable levels of contamination by *Aspergillus flavus*, a fungus that is the causal agent in aflatoxins in food crops, mostly in groundnut and maize (F. Waliyar, personal communication 2013).

In 2010, in the 10 most important groundnut-producing countries included in the DIIVA Project database, about 29 percent of groundnut area was planted to improved varieties released since 1970 (Walker et al. 2014). Regionally, the uptake of modern varieties has been higher in East Africa than in West Africa. Uganda is an emerging success story of varietal change in groundnut. In four of the five groundnut study countries in East and Southern Africa, Rosette-resistant ICGV-SM 90704 and drought-tolerant ICGV 83708 ranked first or second in the adoption of improved varieties (Ndjeunga, Mausch, and Simtowe 2015).

In West Africa, in 2010 about one hectare in four was planted to an improved groundnut variety. Groundnut improvement efforts in West Africa are subject to many of the same problems that afflict sorghum and pearl millet improvement efforts. With only five scientists per million tons of production, groundnut ranks in the lowest quintile of mean estimated research intensity among the 20 crops of the DIIVA Project. The low level of investment in research perhaps not surprisingly has been reflected in a low rate of varietal releases. Since 1990, only 40 improved cultivars of groundnut have been released in Burkina Faso, Mali, Niger, Nigeria, and Senegal. Fourteen of these releases are very recent, as they occurred between 2010 and 2012 (Ndjeunga et al. 2012).

Efforts to promote adoption of improved cultivars in groundnuts face considerable challenges. Because groundnut is a self-pollinated crop with limited scope for heterosis, the private sector cannot make money on varietal generation and seed production without the establishment of plant breeders' rights, which remain weak in most African countries, if they exist at all. In addition, because each groundnut plant produces a relatively small number of seeds, seed multipli-

cation is expensive, and seed is a precious commodity. Unless seed multiplication activities are actively supported by public agencies or nongovernmental organizations (NGOs), prospects are limited that a newly released improved groundnut variety will diffuse rapidly.

Adoption of improved varieties of groundnut is often discouraged as well by the fact that farmers are frequently unable to implement changes in crop management practices needed to realize the full genetic potential of the new cultivars. Although research shows that improved varieties of groundnut are often responsive to higher levels of crop management, especially application of phosphate and calcium, farmers in West Africa typically do not change their management practices when they replace a local variety or an older improved variety with a new improved variety.

As if the challenge was not already daunting, newly released improved groundnut varieties must compete with improved varieties developed during the colonial era and released decades ago. The short-duration variety 55–347, which was bred in Senegal in the 1950s, remains the leading groundnut cultivar in that country and also in Nigeria, where it is sown on 15 percent of the area planted to groundnuts (Ndjeunga et al. 2013). Likewise, the variety 47–10, released in Mali in 1957, still accounts for over 40 percent of the groundnut growing area in Mali.

The phenomenon of very old improved varieties of groundnut enduring in farmers' fields is not unique to West Africa. In peninsular India, the most popular improved variety of groundnut is still TMV-2, which was released in Tamil Nadu in the early 1940s (Kumara Charyulu et al. 2015). Existing groundnut cultivars have staying power in farmers' fields because the crop is highly self-pollinated, the average productivity of seed is low, the seeding rate is high, and the rate of degeneration from outcrosses, mutation, or viruses is negligible. As a result, even when a new variety is released that outperforms the farmer's current variety, the low seed multiplication ratio translates into very slow diffusion.

Two factors that can help groundnut breeders respond to the challenges posed by seed-related constraints are strong market demand and wide adaptability. Groundnut improvement efforts have excellent potential for generating spillover benefits across countries, as suggested by several of the examples cited above. Fleur 11, a recent introduction from Asia, similarly is spreading in three of the five DIIVA study countries in West Africa.

Cowpea. Cowpea is the most extensively produced pulse crop in Sub-Saharan Africa. In 2010, more than 11 million hectares were planted to cowpea in Sub-Saharan Africa, mostly in West Africa. With a combined area of 9 million hectares, Nigeria and Niger are the largest African and global producers of cowpea.

Cowpea is prized for both its grain and its hay. It is called “the poor man's meat” in the Sahel and is one of the lowest-cost sources of protein among the pulse crops that are cultivated in Sub-Saharan Africa. Cowpea is often grown in combination with pearl millet, almost always under rainfed conditions.

Cowpea is the shortest duration grain legume cultivated in Sub-Saharan Africa. This makes it inherently less vulnerable to drought, but it cannot always escape drought completely. It does reasonably well when grown in soils that are low in phosphorus, although yields are depressed by lack of phosphorus, especially in times of drought. More than any other pulse crop, cowpea is heavily attacked by insect pests during the growing season and after harvest. Cowpea is highly drought-tolerant, with deep roots that help stabilize the soil and dense foliage that shades the soil surface, thereby preserving moisture. Largely because of drought and insect attack, cowpea on-farm grain yields in Sub-Saharan Africa reach only 10–30 percent of their biological yield potential (Ehlers and Hall 1998).

In 2009, across 18 cowpea-producing countries in the DIIVA Project, about 27 percent of the area planted to cowpea was planted to improved varieties. Most of the improved varieties express one or more desirable traits that have commanded breeders' attention: resistance to the parasitic weed *Striga*, drought tolerance, dual-purpose types for crop-livestock systems, suitability for intercropping with cereals, and diverse disease and pest resistances (Alene and Mwalughali 2012). In addition, extra-early cowpea varieties that mature in 60 days have been developed for the very short growing season that is characteristic of northern Nigeria and southern Niger.

Despite the availability of numerous improved varieties of cowpea with diverse traits that respond to farmers' needs, cowpea ranks poorly compared to other crops with respect to adoption (see figure 3.1). Many of the same challenges that have affected germplasm improvement efforts for pearl millet, sorghum, and groundnut apply as well to cowpea. Of the six pulse crops tracked by the DIIVA Project, cowpea is characterized by the lowest level of research intensity (6–7 scientists per million tons of production) and the lowest level of output intensity (17 released varieties per million hectares of cultivated area). The rate of varietal releases in cowpea peaked in the 1990s at 65 but declined to only 32 in the 2000s. Part of this decline is attributed to the closure of a regional breeding program in Southern Africa when funding became tighter in the late 1990s and early 2000s (Alene and Mwalughali 2012). Several larger West African producers, such as Burkina Faso, Nigeria, and Senegal, have not been able to maintain the rate of varietal releases recorded during the 1980s and 1990s.

Unlike groundnut, cowpea research has not been able to draw on a foundation of research results produced during the colonial period. Furthermore, because cowpea is relatively unimportant in developed country agriculture, little cowpea breeding work has been done in developing countries, so there are few opportunities to capture spill-in benefits by importing exotic germplasm. As a result, cowpea improvement got off to a very slow start. The DIIVA varietal releases database contains only 11 improved varieties that were released in Sub-Saharan Africa prior to 1980.

A number of improved cowpea varieties released in West and Central Africa are being grown in more than one country, showing that they have wide

Table 3.1 Weighted Average Percent Adoption by Crop Across AI Zones, 2010²

Zone	Maize	Sorghum	Pearl millet	Cowpea	Groundnut
Arid		26.0	12.9	18.8	19.2
Dry Semi-arid	61.3	23.6	19.3	26.5	31.6
Wet Semi-arid	66.6	22.4	21.5	33.9	24.6
Dry Sub-humid	53.7	23.1	25.0	39.4	31.5
Non-dryland Wet Rainfed	52.2	23.1	25.1	39.8	31.4

Source: Constructed from Walker et al. (2014) and HarvestChoice database (circa 2005), excluding South Africa.

adaptability. Examples include IT82E-32 (covering 23 percent of the total cowpea area in Ghana, 11 percent in Benin, and 2 percent in Cameroon) and VITA-7 (accounting for 22 percent of total cowpea area in Guinea and 13 percent in DRC) (Alene and Mwalughali 2012). The adoption level for variety IT81D-1137 is estimated at 17 percent in DRC and 14 percent in Benin. These varieties are attractive to farmers because of their high yield potential, disease tolerance, and short duration. In total, 20 varieties were being cultivated in two or more countries.

Improved varietal adoption by dryland zone. When the national adoption estimates for the five crops are disaggregated by dryland zone, it is apparent that generally speaking, the level of adoption is associated with production potential (table 3.1). Several exceptions stand out, however. Sudan, with its large mechanized rainfed sector, is characterized by higher levels of adoption in sorghum than other countries. Sorghum production in Sudan tends to be located in drier zones relative to other sorghum-growing countries, so the weighted average incidence of improved cultivar adoption for sorghum does not show a trend as one moves from the drier to the wetter zones. Adoption of improved maize varieties and hybrids peaks in the Wet Semi-arid Zone, which is characterized by ample production potential (the effect is especially pronounced in regions with higher elevations). Groundnut's superior performance in the Dry Semi-arid Zone is mainly attributed to the Peanut Basin in Senegal, historically a region that specialized in production for export, although the importance of exports has decreased over time.

Prospects for New Varieties Well-adapted to the Drylands

Maize. Maize genetic improvement has a long and distinguished history in Africa, especially in East and Southern Africa. Following several decades of research, SR52, the world's first single-cross hybrid, was released in 1960 (Eicher 1995). Work carried out at the Kitale research station in Kenya during the 1960s and 1970s established the foundation for the commercial production of hybrids throughout the region.

International agricultural research centers, especially those that are members of the Consultative Group for International Agricultural Research (CGIAR), have

made important contributions to maize genetic improvement in Sub-Saharan Africa generally and in drylands in particular. The International Maize and Wheat Improvement Center (CIMMYT) and the International Institute of Tropical Agriculture (IITA) have worked extensively on improving tolerance to drought and to low nitrogen (Fischer, Byerlee, and Edmeades 2014). Working in partnership with national breeding programs, both Centers have developed stress-tolerant hybrids and OPVs that are well adapted to broad agro-ecologies. The past record of success in breeding for drought tolerance in maize bodes well for future prospects.

Looking to the future, heat tolerance is likely to command increasing attention. Diverse breeding materials in a good agronomic background are available for drought and heat tolerance, but the recent finding that tolerance to these abiotic stresses are genetically independent in maize will lengthen the gestation period in the quest for desirable genotypes (Fisher, Byerlee, and Edmeades 2014).

Genetic engineering techniques could make an important contribution to enhancing genetic progress for resource-poor maize growers. Genetically engineered hybrids with insect and herbicide resistance are increasingly used in South Africa, where no risk to human health from their deployment has been detected. Two specific genetically engineered sources of drought tolerance are raising exciting prospects for increasing yield potential in water-limited dryland production environments (Edmeades 2013). These new potential sources of drought tolerance, which were developed through a collaborative effort involving public and private breeding programs, have been made available on a royalty-free basis. The impact of genetic engineering methods, which can complement conventional breeding techniques, hinges on the public acceptance of procedures for testing and subsequent release of transgenic cultivars. If transgenic cultivars live up to breeders' expectations with respect to their agronomic performance, their non-deployment because of adverse attitudes to transgenics would impose a large opportunity cost on producers and consumers. Meeting the challenge of accelerating yield performance could be severely compromised.

Sorghum and pearl millet. Investment in sorghum research in Sub-Saharan Africa has been very modest. The one significant initiative has been the Dryland Cereal Collaborative Research Project (CRP), which is being led by the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) and the International Center for Agricultural Research in the Dry Areas (ICARDA). Seven research emphases are delineated in the Dryland Cereals CRP, six of which are relevant to African drylands (the only exception is post-rainy season sorghum in India).

Sorghum was domesticated in Africa, and the region remains a rich source of biodiversity. Five dominant types of landrace materials are found in West Africa, in Ethiopia, and in the northeastern Horn of Africa. Since 2000, ICRISAT plant breeders and their colleagues in the Malian national program have been developing hybrids based on the Guinean landrace, which offers many advantages for sorghum production (described in the next section on cereal hybrids in West Africa).

The main emphasis in African sorghum breeding is on the Sudanian Zone of West Africa, where sorghum is a leading staple, and on the northern Guinean

Zone of Nigeria, where sorghum is gaining in importance as a cash crop and marketed surplus is increasing. Secondary emphasis is on the Sahelian Zone, where improving yield stability is the most important goal. Because sorghum competes with maize in some of these zones, sorghum breeders often emphasize traits in which sorghum enjoys a comparative advantage, such as adaptation to low soil fertility, drought, and heat.

In spite of the modest levels of investment being made in Sub-Saharan Africa in sorghum breeding research, sorghum was one of the first crops to benefit from the new technologies of marker-assisted and genomic selection. Several popular improved varieties were re-released when they were identified as containing valuable traits, which were identified with the aid of biotechnology tools (see box 3.1). Similar to other field crops, genetic engineering techniques are

Box 3.1 Release of First Striga-resistant Sorghum Varieties Developed Using Marker-Assisted Selection

Sorghum farmers in Sub-Saharan Africa first began to taste the fruits of biotechnology research in 2012, when four Striga-resistant varieties were released for cultivation in Sudan. These four varieties shared genetic backgrounds with the popular but Striga-susceptible improved sorghum varieties “Tabat,” “Wad Ahmed,” and “AG8.” The four varieties were developed through a collaborative effort that had begun much earlier. In 2004, researchers from International Crops Research Institute for the Semi-arid Tropics (ICRISAT), the University of Hohenheim in Germany, and national program partners from Eritrea, Kenya, Mali, and Sudan joined forces under a project supported by the German Federal Ministry for Economic Cooperation and Development (BMZ). These researchers worked on qualitative trait loci (QTLs) for Striga resistance that had been identified under an earlier BMZ-funded project involving ICRISAT, UH, KARI-Kenya, and *Institut d’Economie Rurale* (IER)-Mali. The work was continued with the help of a 2006 competitive grant from the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA), as the national programs in Sudan, Eritrea, and Kenya, with ICRISAT backstopping, worked to fine-map the Striga-resistance QTLs. The fine-mapping and marker-assisted selection (MAS) backcrossing program was the subject of the PhD thesis research program of Ms. Rasha Ahmed, of Sudan’s Agricultural Research Corporation. Ahmed visited ICRISAT headquarters in Patancheru, India, where she carried out the genotyping required to fine-map the Striga-resistance QTLs and for the SSR genotyping of three additional generations of the MAS backcrossing program. Genotyping for the last generation of MAS was completed in 2011 at the BecA facility of the International Livestock Research Institute (ILRI)-Nairobi campus before the product lines could reach the required state of agronomic elite-ness combined with high and stable levels of host plant resistance to *Striga hermonthica*. Finally, following standard variety trials carried over three rainy seasons from 2009 to 2011, backcross lines were released that were Striga-resistant and agronomically superior, giving 180–298 percent increases in grain yield over their recurrent parents in the infested plots.

Source: ICRISAT (2012).

not expected to make a major contribution to boosting yields in sorghum (Fischer, Byerlee, and Edmeades 2014), but marker-assisted selection (MAS) should facilitate the search for resistance and/or tolerance to biotic and abiotic stresses. It will be interesting to follow the trajectory of the uptake and performance of the newly strengthened “old” improved cultivars in Sudan to see if they lead to productivity gains in sorghum improvement programs.

Pearl millet improvement efforts in Sub-Saharan Africa have focused squarely on the Arid Zone and on the drier portion of the Semi-arid Zone, where pearl millet is the leading staple and one of the few food species that can be grown. Pearl millet is the most heat-tolerant of the cereals cultivated in Sub-Saharan Africa, and its heat tolerance opens up some intriguing possibilities (see box 3.2).

Pearl millet breeders have attempted to produce a range of cultivars characterized by plasticity in flowering dates, so that the environmental profile can be filled with varieties adapted to regionally specific conditions within the Sahel. Adaptation to low fertility in the presence of climate-induced stress is highly desirable, and experience suggests that adoption of improved varieties is much more likely when farmers have access to Striga management techniques, including seed treatments, and when they are able to ensure satisfactory levels of soil

Box 3.2 Possibility of Producing Irrigated Pearl Millet During the Dry Hot Season in the Sahel

Farmers in India who grow pearl millet under “summer irrigated” conditions (sowing in February once soil temperatures are reliably above 20°C, with flowering in late March or early April, and grain harvest in early May) are able to harvest 4–6 tons of grain under conditions so hot that no other cereal can reliably produce grain at all. Commercially successful pearl millet hybrids grown in the Indian states of Gujarat, Maharashtra, Rajasthan, and Uttar Pradesh under irrigated hot-season conditions could be grown successfully across much of the northern Sudanian and Sahelian zones—provided that treated seed is available, the crop is sown at sufficiently high density, and it is fertilized adequately. Grain yields of 4–6 tons per hectare in 110 days or less, accompanied by foliar-disease free stover (6–8 tons deciwatt per hectare) should be achievable under farmers' conditions, particularly if drip-line irrigation systems are used to minimize water losses due to evaporation and limit conditions favorable for foliar disease development.

Irrigated hot season pearl millet has tremendous potential in West Africa and the Horn of Africa, particularly for local production of drought-relief food grain in a global economy where the grain surpluses that used to be available for this purpose can no longer be found. Chances of realizing this potential will be considerably enhanced if the nascent seed industries in the Sudanian and Sahelian agro-ecologies of Sub-Saharan Africa can be linked with the much stronger seed industry in India, which could be a source of the know-how and financing needed for the former to expand and mature.

fertility. Hybrids and varieties developed through recurrent selection also need to achieve adequate levels of downy mildew resistance.

In some countries, pearl millet breeders working in the public sector have attempted to establish the foundation for a private breeding industry by identifying germplasm pools for heterosis and generating parental lines and experimental hybrids.

Grain legumes: groundnut and cowpea. Genetic improvement efforts for eight grain legumes grown in Sub-Saharan Africa are taking place under the Grain Legume CRP, whose activities are comprehensively described in ICRISAT et al. (2012). Here, attention is restricted to the two most important grain legumes grown in drylands: cowpea and groundnut.

Groundnut has long been grown in West Africa as an export crop, so it has a long research tradition. In contrast, research on cowpea started in Sub-Saharan Africa only in the 1980s. Compared to maize and proportional to the relative size of their production, it is not an overstatement to say that groundnut and cowpea, like sorghum and pearl millet, have been and still are starved for resources in national agricultural research programs (Walker et al. 2014).

For groundnut and cowpea, three product lines have particular potential to contribute to enhanced resiliency and intensified production in the drylands:

1. *Short-duration, drought-tolerant, and aflatoxin-free groundnut.* Groundnut is grown in Sub-Saharan Africa in widely varying rainfall regimes ranging from 350 to 1,500 millimeters. Particularly in dryland regions, short-duration, high-yielding groundnut cultivars are at a premium, due to the short growing seasons. Short-duration cultivars have the potential to escape end-of-season drought and diseases. These varieties are also useful in reducing pre-harvest infection leading to aflatoxin contamination. This product line hinges on strategic research to find five new sources of drought tolerance and aflatoxin resistance in groundnut. Investment in transgenics is also envisioned if new sources from wild relatives cannot be found. Recently, additional sources of short-duration materials have become more available. The biggest bottleneck in adoption of improved cultivars is the availability of quality seed. This can be addressed by strengthening both the formal and informal seed systems.
2. *Drought- and low phosphorus-tolerant cowpea.* Cowpea is grown principally in West Africa and is an important source of protein for many households. In dryland regions, short-duration, high-yielding cowpea cultivars are needed due to the short growing seasons and frequent spells of drought. Because of strong negative interactions between drought stress and low phosphorus, addressing drought and low phosphorus in a combined manner is necessary. The identification of gene-based markers that influence drought and low phosphorus tolerance is a key step in this combined research approach.
3. *Insect-smart production systems in cowpea.* Cowpea is highly susceptible to pod borer damage. In West Africa, the monetary value of losses from the pod borer *Maruca* on cowpea can be extensive. Mobilizing sources of resistance

from wild relatives and utilizing transgenic approaches, especially the deployment of Bt genes that are highly suited for combating Lepidopteran pests, will be the means to generate genetic components that are incorporated into a framework of Integrated Pest Management (IPM).

Cereal Hybrids in West Africa

In West Africa, when a farmer adopts a modern cereal cultivar, it is almost always an improved OPV that was developed by a public breeding program. Elsewhere in the developing world, including in many parts of East and Southern Africa, when a cereal farmer decides to adopt an improved cultivar, it is likely to be a hybrid developed by a private seed company (see box 3.3).

Box 3.3 Pearl Millet and Sorghum Hybrids in India

The experience with sorghum and pearl millet hybrids in India has potentially important lessons for the prospects for pearl millet in the drylands of West Africa. Sorghum and pearl millet hybrids became a reality in India in the mid-1960s about the time of the introduction of the semi-dwarf wheat and rice varieties that fueled the Green Revolution. Since then, about an equal number of hybrids and improved varieties have been released both nationally and at the state level (Kumara Charyulu et al. 2015). The most popular cultivars (measured in terms of area planted) have been sorghum hybrids developed in the public sector and pearl millet hybrids developed in the private sector. Several improved sorghum varieties and one or two improved pearl millet varieties were popular for a relatively short period during the 1960s, but, in general, farmers have preferred hybrids over improved varieties. Their adoption in the monsoon season has fueled considerable growth in yield over the past five decades, and they are widely regarded as success stories in dryland agricultural research (Pray and Nagarajan 2009).

Recently, pearl millet hybrids have penetrated into Rajasthan, the largest pearl millet-producing state in India, where production conditions are remarkably similar to the harsh southern Sahelian Zone in West Africa. Results from a large survey of 2,144 households suggest that over half of pearl millet-growing area in Rajasthan is planted to improved materials, mostly hybrids, in conditions of smallholder subsistence agriculture. Based on seed packaging, it was estimated that farmers were growing about 50 different hybrids (Asare-Marfo et al. 2013). The average plot planted to millet was substantially less than one hectare. Some of the hybrids were prized for their superior grain yields; others were planted for their perceived excellence in fodder production.

The fact that many different pearl millet hybrids are being grown in the sandy soils of the arid tropics of Rajasthan flies in the face of the conventional wisdom that hybrids cannot compete with traditional varieties in marginal production environments. This story is all the more compelling because the conditions under which pearl millet is grown have deteriorated

box continues next page

Box 3.3 Pearl Millet and Sorghum Hybrids in India *(continued)*

steadily over time as improved drought-tolerant maize cultivars and drought-tolerant cultivars of other crops have pushed pearl millet into areas with lower and more erratic rainfall regimes (Walker 2008). Today, maize has practically replaced millet in the wetter parts of Eastern Rajasthan. In the mid-1960s, area-weighted, mean annual rainfall in the millet-producing districts was 900 millimeters in peninsular India and Rajasthan. By the early 2000s, that same rainfall estimate had declined to 600 millimeters. Long-term average rainfall has not declined in these districts. Millet is increasingly grown in the lower rainfall districts.

The very limited engagement of the private sector in West Africa in cereal adaptive research and seed multiplication is lamentable. The absence of cereal hybrids in farmers' fields underscores the opportunity to make a major contribution to economic development and resiliency by ensuring that dryland cereal farmers in West Africa have access to well-adapted hybrids similar to maize, millet, and sorghum producers in the rest of the world.

Assuming they are well-adapted to local growing conditions, hybrids generally offer several advantages compared to improved OPVs. First, well-adapted hybrids tend to be agronomically superior, in that they have higher yield potential and higher yield stability. Second, because hybrids are commercially attractive for private firms, the supply of hybrid seed tends to be much more reliable than the seed of varieties. These benefits do not come without a cost, however, as farmers must purchase fresh seed every year, since hybrids do not "breed true," so that agronomic performance usually declines when harvested grain is saved and replanted in the following season.

While the cost of seed of hybrids is often considerably higher than the cost of seed of OPVs, the additional cost is usually modest relative to the value of the production gains derived from planting quality seed of higher- and more stable-yielding material. If the additional benefits stemming from the use of hybrid seed did not exceed the cost, farmers would not be willing to purchase the seed. In West Africa, farmers' seed rate for both millet and sorghum is low, at about 5 kilograms per hectare. Moreover, improved varieties are not immune from the need to replace seed. Generally, farmers need to buy new seed every three years to prevent declining production from seed deterioration. Finding quality government-provided seed of well-adapted varieties can be problematic.

The fate of hybrids—like that of all improved cultivars—depends on their adaptation to the conditions in the season and zone in which they are being grown. Good adaptation is a necessary condition for competitiveness. One strategy that sorghum breeders in West Africa have used to ensure that hybrids will have good adaptation to local conditions is to use as parental materials high-performing local varieties. Since 2000, international and national researchers in Mali have concentrated on the improvement of the local Guinea landrace dominant in the Sudanian Zone of West Africa (Rattunde et al. 2013).³

Yield trials were conducted over the course of two years in three aridity zones. In general, the hybrids yielded better than the other three types of material in the trial. The top three hybrids had an average yield advantage of 30 percent over their parental material, an improved variety, and the farmers' local variety. The yield advantage of the top three hybrids averaged 600 kilograms per hectare in more fertile fields and 380 kilograms per hectare in less fertile fields. Given that average productivity of the local check is around 1,000 kilograms per hectare, these are sizeable yield increases in trials managed by farmers in a participatory-testing format.

These results—and other similar results recorded in other locations—show that it is possible to develop hybrids from well-adapted landraces that express hybrid vigor. They confirm earlier work conducted on-station by Andrews (1975) that the potential for expression of heterosis is high in the dominant landrace materials found in the Guinean Zone of Nigeria. With the generation and selection of more hybrid parental material, it is likely that the gain from heterosis will be greater than 30 percent. Prospects for achieving gains in fodder production and quality are also promising. Again, the advantage of the newer Guinean hybrids stems from their superior adaptation to abiotic and biotic stresses in the Sudanian Zone, which is attributable to the fact that they are descended from materials that sorghum farmers have been growing (and selecting) for generations.

ICRISAT's Hybrid Parents Research Consortium (HPRC) in India represents a potential institutional model that could be emulated in West Africa. Public and private breeding programs both have benefitted from this innovative partnership, which since 2000 has generated more than 70 ICRISAT-related pearl millet and sorghum hybrids of which seed was or is being produced by private seed companies (ICRISAT 2013). With a great deal of breeding work having been accomplished, efforts are shifting to demonstrate that hybrids can be commercially viable. In areas where the private sector is not active, farmer groups and cooperatives are being trained in commercial production of hybrid seed.

Although there is grounds for optimism, the road to improving the availability of coarse cereal hybrids in West Africa is long and potentially arduous. Formidable technical and policy obstacles will have to be overcome along the way. On the technical side, breeders will be challenged to ensure that hybrids are endowed with durable sources of downy mildew resistance. On the policy side, attention needs to be focused on several critical regulatory issues, such as the introduction and enforcement of standards governing truthfully labeled seed.

The successful introductions of pearl millet and sorghum hybrids in India and of maize hybrids in Southern Africa offer important lessons that could provide guidance for similar efforts in dryland regions in West and Eastern Africa. As the experiences in India and Southern Africa have vividly illustrated, an emerging hybrid seed industry driven by public-private partnerships can offer farmers a range of cultivars adapted to local agro-climatic conditions and market needs.

Notes

1. To conform with conventional usage, the term *improved varieties* is used here to denote varieties that have been developed by a modern scientific breeding program. Varieties that have not been improved by a modern scientific breeding program are referred to as *traditional varieties* or *land races*. The term *improved varieties* is actually a misnomer, however, because traditional varieties and land races also have been improved during the course of many generations of deliberate selection by farmers. The term *cultivars* is used here when referring to both varieties and hybrids.
2. The adoption rates presented in table 3.1 do not show as much variation across aridity zones as might have been expected. Because the adoption rates were estimated based on national averages, differences across zones are likely to have been muted because in some cases sub-regional adoption data could not be disaggregated accurately by aridity zone.
3. The Guinea landrace materials have numerous advantages. They are photoperiod sensitive, which is highly desirable when early season rains are erratic but late season rains are reasonably assured in their timing. Photoperiod sensitivity means that on-time and delayed sowings mature at the same time and experience an equal level of pressure from harvest pests such as birds. The Guinean types also have lax panicles and related seed characteristics that deter insect pests and make the harvested output less susceptible to grain mold. The recent creation of cytoplasmic male-sterile female parents based on West African Guinea-race landraces and Guinea–Caudatum interracial breeding lines enabled production of the first series of Guinea-race hybrids.

Prospects for Improved Crop Management

Intensification of dryland agricultural systems is dependent on the introduction of improved crop management practices. Improved crop management practices in turn almost always are accompanied by increased use of improved inputs such as fertilizer, herbicide, and insecticide. In contrast to adoption of improved cultivars, however, adoption of improved crop management practices is often restricted to a limited area, because the performance of any individual management practice depends on spatially varying agroclimatic, edaphic, and socioeconomic conditions.

Programs such as Sasakawa Global 2000 that have attempted to introduce standardized blanket recommendations for input-intensive crop management technologies on a large scale have rarely lived up to expectations, registering success with only a few crops and in a few countries, for example, maize in Ethiopia and Ghana (Howard et al. 2003). These programs have made clear what most crop management specialists already know: the intensification potential of dryland agricultural systems in Sub-Saharan Africa can be realized only with precise targeting of crop, land, and water management technologies, combined with adaptation to local conditions.

Because farmers rarely adopt a technology on large areas without first experimenting on smaller areas, and because inputs related to new crop management practices are usually divisible, the lack of targeting usually does not have major implications for risk management (see box 4.1). Moreover, farmers are not compelled to accept unprofitable technology. Instead, the absence of targeting across space and time engenders a loss in economic efficiency and growth to which intensification potentially contributes.

Box 4.1 Risk and Expected Profitability in Dryland Agriculture

The fact that improved technologies are often adopted to a limited extent in dryland agricultural systems in Sub-Saharan Africa is often attributed to risk aversion on the part of farmers. Improved technologies usually cost more than the technologies they replace, and while the improved technologies may lead to higher yields when production conditions are favorable, they may lead to lower yields in seasons when production conditions are unfavorable. The greater down-side risk is often seen as a major impediment to adoption, because farmers are generally believed to be extremely averse to risk.

The empirical evidence suggests that risk is overrated as a determinant of technology adoption in developing country agriculture (Roumasset 1976; Walker and Ryan 1990). Experimental research pioneered by Binswanger in the 1980s in several countries showed that the vast majority of farmers are moderately averse to risk; that is, they are willing to adopt riskier technologies if the increase in profits more than compensates for the increase in the variance in returns.

More importantly, few technologies feature a sharp tradeoff between increased variance and/or downside risk and expected profitability. Most technologies that result in increased risk are also characterized by lower expected profitability. Since most crop management technologies are divisible and can be adopted piecemeal and sequentially in small amounts or on smaller areas, technology diffusion becomes an information-generation process. Farmers take up the new technology in increments, “learning by doing” as more and more farm-specific information is revealed about technological response over time.

The limited available studies suggest few instances of conflict between risk and expected profitability. In the 10-year longitudinal International Crops Research Institute for the Semi-arid-Tropics (ICRISAT) Village-Level Studies of 240 households in the Semi-arid Tropics of India, only one improved technology was determined to have higher expected profitability combined with higher risk (Walker and Subba Rao 1982). Hybrid sorghum was characterized by markedly higher grain yield than local sorghum in high-rainfall years and moderately higher yield in low-rainfall years, while fodder production and grain quality were lower in all years. Hybrid sorghum was highly responsive to fertilizer, which also increased financial risk, although hybrids outperformed local sorghum in low rainfall years. Averaged over 10 years with hundreds of field observations, adoption of hybrids was characterized by sufficient profitability to offset marginally increased financial costs of production to satisfy the conditions for widespread adoption in regions where rainfall was assured.

In the jargon of economists, most technologies that farmers do not adopt are stochastically inefficient, meaning their expected profitability in farmers’ circumstances is too low to warrant adoption. Few of the improved crop, land, and water management practices described in this section are characterized by increased variance of returns or downside risk. But most farmers will not adopt a new technology only because they expect it to provide added protection from the ravages of drought. The new technology must pass minimum

box continues next page

Box 4.1 Risk and Expected Profitability in Dryland Agriculture *(continued)*

thresholds for expected profitability, because it will require the farmer to make an additional investment in labor or capital.

The influence of risk in adoption decisions is often overrated because information about technological outcomes in farmers' fields is often incomplete. A salient exception is animal traction. Because of animal mortality and its indivisibility, decisions concerning whether or not to adopt animal traction are influenced by risk considerations. Animal traction is a technology whose premature and unsupported adoption can have major adverse consequences for household welfare. Because of the high seasonality in demand in dryland agriculture production, animal traction cannot be made divisible in a rental market for animal services.

Intensification of Input Use

Because of the location specificity of many crop management technologies, for purposes of this discussion it is useful to further disaggregate the three main aridity zones discussed in the larger Africa Drylands study. As characterized in the HarvestChoice database available from International Food Policy Research Institute (IFPRI), dryland cropping in Sub-Saharan Africa takes place in five distinct agro-ecologies: (1) the arid tropics and sub-tropics (representing 3 percent of cultivated drylands area), (2) the semi-arid tropics and sub-tropics (representing 56 percent of cultivated drylands area), (3) the sub-humid tropics and sub-tropics (representing 24 percent of cultivated drylands area), (4) the humid tropics (representing 2 percent of cultivated drylands area), and (5) the tropical highlands (representing 14 percent of cultivated drylands area). IFPRI's spatially fine-grained HarvestChoice database provides an opportunity to illustrate the use of targeting for intensification within each of these five agro-ecologies.

Demand for intensification of dryland agriculture comes mainly from population pressure (Boserup 1965). Technical potential to intensify is determined by a range of agro-climatic, edaphic, and socioeconomic conditions. The relationship between demand-side drivers and supply-side drivers determines the rate and nature of intensification. For example, in the presence of large numbers of livestock, technological innovations are likely to exploit crop-livestock synergies (Pingali, Bigot, and Binswanger 1987). Similarly, favorable infrastructure in the presence of rising demand is likely to result in market-led intensification.

Among the five agro-ecologies present in the drylands, the dry sub-humid tropics would seem to be the best candidate for intensification, based on the amount and distribution of rainfall, which among other things determines the length of the growing season. Many assessments of the potential for intensification of agriculture in the drylands come to this conclusion. What these assessments

overlook, however, is that the sub-humid tropics are characterized by lower human population density than some other zones and lower cattle density, the latter a consequence of the prevalence of tsetse fly, the vector for Trypanosomiasis. Population densities in the sub-humid tropics are on average only about 50 percent as high as those found in the tropical highlands, and mean cattle density is on average only 66 percent as high as those found in the semi-arid zones.

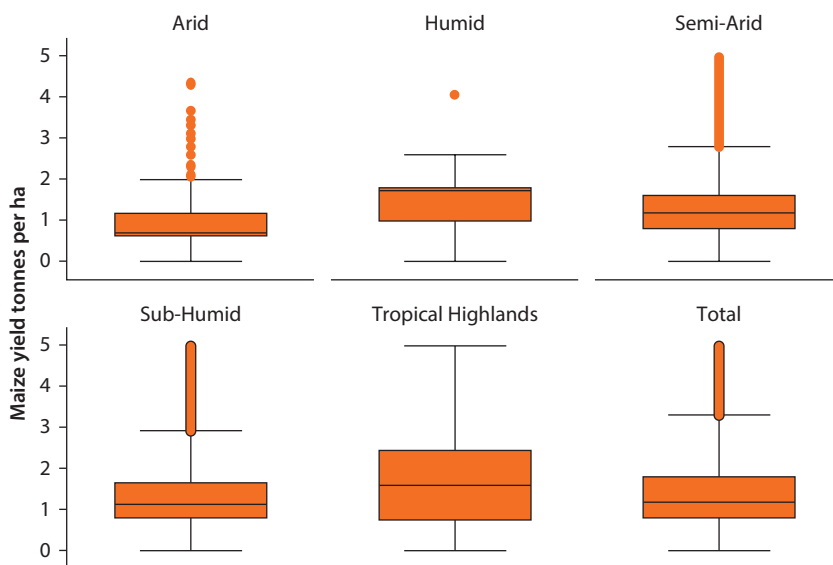
Analysis of demand- and supply-side drivers suggests that prospects for intensification in dryland agriculture in Sub-Saharan Africa should not be restricted to the sub-humid tropics, but should also include tropical highlands and large areas of the wet semi-arid tropics. In many respects, these two agro-ecologies are the most important and relevant for intensification in dryland agriculture in Sub-Saharan Africa. The tropical highlands, while quite limited in extent, best match demand- and supply-side drivers of intensification, as human population densities and cattle numbers both are very high in the highlands relative to other agro-ecologies.

The tropical highlands (including mid-altitude zones), located almost entirely in East and Southern Africa, are on average only about 1,000 meters higher than the semi-arid tropics and sub-humid tropics, but the advantages of this difference in altitude are considerable. Soil evaporation and plant transpiration rates are lower, opening up new possibilities for cropping. In addition, many tropical highlands zones feature fertile soils, especially volcanic soils.

The notion that the tropical highlands offer greater possibilities for intensification of dryland production than the other four agro-ecologies is supported by the area-weighted distribution of maize yields across the five agro-ecologies reinforces (figure 4.1). The tropical highlands are characterized by a less concentrated and more plastic distribution of maize productivity than the other agro-ecologies. For instance, in ascending order of yield, the difference between the 75th and 25th percentiles (the borders of the interior box in figure 4.1) is about 1.75 metric tons in the tropical highlands. Both the semi-arid and sub-humid agro-ecologies are characterized by a difference of about 0.8 metric tons between these two same percentiles. The less compact distribution of the tropical highlands suggests that intensification is already taking place. With the possible exception of Kenya, there is no evidence to indicate that fertilizer use has plateaued at an economically optimal level (Sheahan, Black, and Jayne 2012).

Pragmatism calls for emphasizing areas where intensification is already taking place, rather than investing in areas where the technological prospects for intensification are more remote.

When similar analysis is carried out using elevation categories instead of agro-ecologies, the same conclusion emerges: elevation appears to confer benefits to intensification in maize up to an altitude of about 2,500 masl. Coastal growing areas with an elevation less than 500 masl seem to offer especially poor prospects for intensification in maize and also for other field crops, aside from lowland rice (Fischer, Byerlee, and Edmeades 2014). This finding is noteworthy, because

Figure 4.1 Area-weighted Dryland Maize Yield Distributions by Agro-ecology

Source: Constructed from HarvestChoice (2014) with dryland production defined as an AI Category between 3 and 6; $n = 79,147$.

Note: AI = Aridity Index.

currently about 35 percent of the maize grown in dryland regions of Sub-Saharan Africa is grown in low-lying areas where yields are significantly lower than in higher elevation areas.

The potential to take advantage of elevation are of relevance mainly in East and Southern Africa, because differences in elevation are generally small in West Africa. Furthermore, higher plateau areas in West Africa tend to be infertile because of poor soils, and many farmers cultivate them only as a last resort. As a result, in West Africa targeting promising crop, land, and water management technologies is based mainly on the amount and distribution of rainfall, which determine the length of the growing season, rather than on elevation per se.

Conservation Agriculture

Conservation agriculture is based on three management principles: (1) minimizing displacement of the soil; (2) maintaining permanent ground cover, usually with crop residues; and (3) using crop rotations (Thierfelder and Wall 2009). In years past, conservation agriculture was narrowly identified with conservation tillage, but it is now understood more broadly to encompass a series of practices designed to reduce the use of external inputs and improve the sustainability of production (Wall 2007). With conservation agriculture, the number of field operations is minimized. Plowing, harrowing, and mechanical cultivation are

minimized or not carried out at all. Mulch, often cereal straw or other crop residues, is applied to the surface of the field. Planting and fertilizer are placed in a narrow traffic zone amid the mulch with specially designed equipment that rips open furrows. Weed management relies heavily on herbicides.

Rosegrant et al. (2014) recently assessed prospects for technological advances in farming, using crop modeling simulations that took into account the projections of two widely used climate change models. Among 12 technologies included in the assessment, two technologies closely associated with conservation agriculture were identified as those with the best prospects to deliver productivity gains in Sub-Saharan Africa by 2050. No-till agriculture was determined to have the potential to increase maize yields in rainfed agriculture by 36 percent, and integrated soil fertility management was determined to have the potential to increase maize yields in rainfed agriculture by 21 percent. As defined for purposes of the assessment, integrated soil fertility management shares several of the traits of conservation agriculture, particularly its heavy reliance on mulching.

Conservation agriculture is widely practiced in rainfed farming systems in the Americas and in Australia, usually in highly commercialized settings in which mineral fertilizers are applied. In the subtropical drylands, one of the most important examples of conservation tillage is associated with soybeans in the Brazilian savanna region known as the Cerrado, where heavy application of lime unlocked the potential for cultivation in a vast area characterized by highly acidic soils. Worldwide, interest in conservation agriculture has grown steadily over the years. By 2005, zero tillage, a variation of conservation agriculture, was being practiced on approximately 95 million hectares worldwide (Wall 2007).

With conservation agriculture, higher and more sustainable production is derived from several short-term and medium-term effects (Wall 2007, 139):

- Increased water infiltration into the soil due to the protection of surface structure by the residues;
- Reduced water run-off and diminished soil erosion due to the increased infiltration and the ponding effect of the residues;
- Reduced evaporation of moisture from the soil surface as the residues protect the surface from solar radiation;
- Better crop water balance, less frequent and intense moisture stress because of the increased infiltration, and reduced evaporation;
- Reduced cultivation requirements for land preparation, and thus savings in fuel and labor costs;
- Increased soil organic matter resulting in better soil structure, higher cation exchange capacity and nutrient availability, and greater water-holding capacity;
- Increased biological activity in both the soil and the aerial environment, leading to more biological control of pests.

The size of some of these effects was reported recently based on the results of a long-term experimental study of the effects of conservation agriculture carried out over eight cropping seasons in nine targeted communities in central and southern Malawi (Thierfelder et al. 2013). In the study area, few farmers own cattle, and low livestock densities mean that the use of maize straw as a field mulch carries a low opportunity cost. Rainfall infiltration was determined to be 24–40 percent greater compared with the conventional ridge and furrow system, which requires a lot of labor to construct and maintain. The adverse consequences of seasonal dry spells were substantially mitigated, as yields doubled in some of the conservation agriculture plots. Yield benefits of conservation agriculture over conventional tillage systems were especially noticeable from the fifth season onward, although in some instances higher yields from conservation agriculture were recorded almost immediately. On average, the yield advantage in conservation agriculture plots was 22–24 percent compared to control plots (Ngwira et al. 2013). Yield advantages and net return differences were greater at lower altitudes, where seasonal droughts were more frequent. Thierfelder et al. (2013, p. 147) concluded:

Conservation agriculture can be practiced in diverse environments from sandy to clay soils, nutrient rich to infertile soils and from low to high rainfall areas as long as adequate inputs (fertilizer, herbicides and labor) are available with good extension support to farmers, especially in the initial years.

Experiments conducted on research stations in Zambia and Zimbabwe provided further evidence that conservation agriculture delivers large gains in water infiltration (Thierfelder and Wall 2009). In the Zambia and Zimbabwe trials, however, drought did not occur during the period when the research was being carried out. Mainly for that reason, yields from conservation agriculture were not significantly different from those using conventional tillage, although unit production costs were lower because input use was reduced.

Giller et al. (2009) are among another group of crop scientists who are less sanguine about the prospects for conservation agriculture in the drylands of Sub-Saharan Africa. The skepticism of these self-proclaimed “conservation agriculture heretics” rests on evidence that the benefits may turn out to be smaller and the costs greater than proponents realize. For example, they point out that crop residues used for mulching tend to have a high opportunity cost in drylands, due to the scarcity of natural forage for livestock. Furthermore, they allege that conservation agriculture practices can be much more labor intensive than traditional practices, especially when herbicides are not used; that yields may be very low when fertilizer is not used; and that even when fertilizer is used, conservation agriculture may require higher doses to maintain yields on a par with those obtained through conventional tillage. Giller et al. (2009) conclude their critique by pleading for more component research in different ecological and socioeconomic conditions to better understand what benefits and costs are to be expected from conservation

agriculture. They propose a research agenda for unraveling the complexity of conservation agriculture as an integrated crop-soil-water management package (Giller et al. 2011).

The scientific controversy concerning the advantages and disadvantages of minimum tillage and mulching technologies that underlie conservation agriculture is intensifying, but it is not new. During the 1970s and 1980s, Lal's research carried out at the International Institute for Tropical Agriculture (IITA) involving the cultivation of field crops in the humid tropics with zero and restricted tillage was at the center of the debate. During the same period, major components of conservation agriculture were being tested in the semi-arid tropics at ICRISAT in India and at the Sahelian Center (ISC) in Niger. In India, researchers were unable to detect a significant yield response to conservation agriculture, and they concluded that conservation agriculture was consequently less profitable than conventional agriculture, because the continuous ground cover used as part of conservation agriculture harbored pests that required more intensive management.

The news about conservation agriculture in drylands was not uniformly bad, however. In Niger, in on-station research carried out by the International Fertilizer Development Center (IFDC), the results were more favorable. The control in those trials was the farmer practice of hill planting without fertilizer, which yielded at most 200–300 kilograms per hectare, far less than the 1.5–2.5 tons per hectare achieved with mulching, fertilizer application, and minimal tillage.

Results from ICRISAT's longitudinal Village-Level Studies underscored the high opportunity cost to retaining sorghum or pearl fodder as mulch in Burkina Faso, Niger, and India (Walker and Ryan 1990). Because fodder, hay, and straw are bulky and difficult to transport, markets for these byproducts are highly localized throughout the world. During severe drought, it is not rare to see the price of fodder rise to the price of the grain in these very thin markets. It makes sense that yield response to increased water infiltration is higher in drought-prone areas, but biomass is also a more precious commodity.

One reason why the benefits (or not) of conservation agriculture are difficult to document with consistency is that management practices are unpredictable and enormously variable. Analysis of management practices used on hundreds of plots monitored as part of the Village-Level Studies revealed that planning crop rotations is an inexact science. Only 60 percent of farmers' expected cropping season rotations were carried out as planned. Deviations between planned and actual planting patterns and crop management practices were attributed to changes in market incentives, revised rainfall expectations from early season rainfall events, and unexpected seed availabilities.

Since the early 2000s, conservation agriculture has been promoted in dryland agriculture in Sub-Saharan Africa by FAO, Sasakawa 2000, and various nongovernmental organizations (NGOs), as well as by selected IARCs and national programs. Herbicide and fertilizer often do not figure prominently in the

conservation agriculture package. Mulching—often tailored to regional-specific circumstances—seems to be the common denominator of technology transfer efforts related to conservation agriculture.

Except for a few areas in Ghana and Zambia, the acceptance of conservation agriculture in Africa has been disappointing. Adoption has been substantially less than expected. Conservation agriculture practices are currently being used on less than 5 percent of dryland cropped area in Ghana, South Africa, and Zambia. The low rate of uptake is not unique to conservation agriculture, however, because many other technologies that have enjoyed success in other parts of the world similarly have been slow to gain a foothold in Sub-Saharan Africa.

Still, there are glimmers of hope. In Zambia, where conservation agriculture is called conservation farming, early results suggest that the package is well suited to the demands and capabilities of dryland hand hoe cotton farmers and may be stimulating private input suppliers to finance more precise application of fertilizer and herbicide to this clientele (Haggbblade and Pierhoples 2010). In Zambia, conservation farming has smoothed out the seasonality of labor demand by shifting work to the dry season. Effects of greater use of purchased inputs in cotton are expected to spill over into maize production.

One thing that has become clear is that the benefits of conservation agriculture often take time to materialize. Returning once again to the example of Zambia, because of high labor requirements for land preparation in the form of planting basins, adoption generally occurs incrementally. On average, households that had initiated adoption four years earlier were characterized as having slightly less than one-half of their cultivated area in conservation farming; transferring these practices is knowledge intensive and requires sustained extension effort (Haggbblade 2009).

Efforts to extend the Zambian conservation farming practices to maize in Mozambique have not been successful, as little spontaneous diffusion has occurred outside the immediate area of project support near the border with Malawi (Grabowski 2013). Interest in conservation agriculture in Mozambique was primarily motivated by access to improved inputs, especially fertilizer that farmers applied to potatoes, a vegetable crop with a potentially very favorable fertilizer response.

Conservation agriculture is rightly viewed as offering promise for dryland regions in Sub-Saharan Africa, but it is premature to say that the prospects are sizable at this time. Daunting technical challenges must be overcome to adapt the technology to local circumstances. Foremost is the need to involve farmers more deeply in the generation of conservation agriculture technologies that in other countries have been driven by farmers more than by researchers (Wall et al. 2013). Scientists working on experiment stations can identify promising conservation agriculture technologies based on first principles, but they cannot possibly do the location-specific fine-tuning needed to adapt the technologies to meet the needs of literally thousands of diverse situations (Wall 2007).

In addition, effective targeting of conservation agriculture technologies will require synthesizing of on-station and on-farm research results, similar to what occurred in India during the 1980s (Binswanger, Virmani, and Kampen 1980; El-Swaify, Walker, and Virmani 1984). Some progress has been made in Africa with respect to synthesizing research results. For example, a recent meta-analysis on the long-term effects of conservation agriculture on rainfed maize productivity in Sub-Saharan Africa showed that prospects are brighter in drier environments on soils that are well-drained, because mulch cover in higher rainfall areas led to lower yields because of waterlogging (Rusinamhodzi et al. 2011). Much more work of this type will be needed to identify which combinations of conservation agriculture practices can make a difference in the drylands, and under precisely what circumstances.

Microdosing Fertilizer

Microdosing is a technology that involves the strategic placement of low levels of fertilizer at times and in locations where the added nutrients can optimally affect yield and plant water-use efficiency. Farmers apply small doses of fertilizer per planting hole or per plant—a full bottle cap in Southern Africa or a three-finger pinch in West Africa, equivalent to about 6 grams of nutrient (ICRISAT 2009). Application usually takes place at planting (when the fertilizer is applied directly in the planting hole) or about one month after planting (when the fertilizer is applied near each plant, basally or top-dressed). In the drylands of Sub-Saharan Africa, most microdosing initiatives have focused on maize and have featured nitrogen-based fertilizer, but other crops also have received attention, and some have responded well to microdosing. Nutrients other than nitrogen and several types of soil amendments can also be microdosed.

Microdosing in Africa began in earnest in the early 2000s. The most comprehensive experience to date has occurred in southern Zimbabwe and has involved maize, sorghum, and pearl millet (Twomlow et al. 2010). From 2003 to 2006, under the auspices of a series of drought recovery programs, every year more than 160,000 farmers received fertilizer and information on microdosing. Based on the results of earlier work dating back to the late 1990s and early 2000s, the optimal microdose was set at 17 kilograms per hectare of nitrogen, equivalent to about 25 percent of the recommended rate.

The results of this initiative were tracked through a series of on-farm trials. Data from over 1,200 paired plot trials consistently showed that microdosing increased yields by 30–50 percent across a broad spectrum of soil, farmer-management, and seasonal climate conditions. Yield gains on that order of magnitude were more than sufficient to pay for the small amount of fertilizer used:

In order for a household to make a profit, farmers needed to obtain between 4 and 7 kg of grain for every kg of N applied depending on season. In fact, farmers commonly obtained 15–45 kg of grain per kg of N input. The result provides strong

evidence that lack of N, rather than lack of rainfall, is the primary constraint to cereal crop yields and that microdosing has the potential for broad-scale impact on improving food security in these drought prone regions. (Twomlow et al. 2010)

Similar microdosing initiatives meanwhile were being implemented in dryland regions of West Africa, supported by donor-financed investments in agro-input shops, an inventory credit system, and intensive farmer training programs using demonstration plots. By 2009, about 25,000 farmers in Mali, Niger, and Burkina Faso had used microdosing to improve their cereal productivity. Value-to-cost ratios in cereals typically ranged from 2 to 4 with microdosing technology, compared to the control of no fertilizer (Tabo et al. 2007). Microdosing gave roughly equal or superior productivity outcomes to application of higher recommended doses of nitrogen and phosphorus.

The consensus among experts today is that the positive productivity consequences of microdosing are robust, although yield gains certainly are more assured when farmers use good agronomic practices. Judicious use of on-farm trials and yield-response simulation modeling can also be very effective in adapting microdosing practices to fit local circumstances. The main challenge faced by those adopting the technology is how to reduce the heavy labor requirements. The private sector could potentially play an important role in helping farmers to overcome the problem of heightened seasonal labor intensity, for example by pelletizing the correct dose per plant into easy-to-apply tablets or even coating seed with fertilizer (ICRISAT 2009).

Based on the generally positive experience to date, microdosing is being tried on a number of dryland crops in several countries and regions, such as western Sudan where use of fertilizer is still uncommon (Osman et al. 2012). Findings from research station and on-farm trials indicate that microdosing is a low-risk, affordable technology that can generate significant productivity gains in cereals and, to a lesser extent, in grain legumes.

Many microdosing initiatives have involved explicit or implicit subsidies. Economic analysis shows that microdosing can be profitable even without subsidies, but farmers need to be weaned from subsidies to make microdosing commercially viable and sustainable. Studies such as the one carried out by Pender et al. (2008) are needed to assess effective demand for the technology following the termination of donor and government subsidies. The degree to which microdosing introduces or reintroduces farmers to fertilizer in general is an important aspect of the technology, but more telling is the potential for adoption of microdosing itself, which is a risk-reducing technology compared to acceptance of recommended doses that are three to five times as costly. Ideally, adoption monitoring needs to be conducted 5–10 years after the testing programs have ended to determine the sustainability of microdosing and the degree to which it has led to increased fertilizer use intensity.

Microdosing may not always offer the best opportunity to maximize returns to farmers' labor, especially when there is scope for area expansion, but it is potentially a cost-effective means to produce more grain per hectare. Back-of-

the-envelope calculations suggest that a US\$20 million investment in microdosing in 2004 could have largely averted the need for emergency relief in Niger during the drought of 2005 (Batiano et al. 2012). Donor relief efforts totaled US\$80 million, and more local food production in 2004 would also have incurred savings for consumers from price rises in 2005.

Seed Treatments

Seed treated with fungicide and insecticide is protected from diseases and pests during germination and emergence. Protection from diseases and pests during germination and emergence reduces seedling mortality and leads to higher plant populations, resulting in most cases in higher yields. Seed treatments represent a low-cost form of technical change that should be well within smallholders' capacity to pay if treated seed are effective in protecting and increasing yield.

Seed dressings of fungicides and insecticides are commonly used in maize in Sub-Saharan Africa because they are inexpensive and effective. Treated seed is now becoming increasingly available for other coarse cereals as well, with impressive effects on performance. In Niger, observations made on paired plots (treated and non-treated) involving four pearl millet varieties planted in nine villages distributed from Maradi in the south-central part of the country to Tera in the extreme west revealed that Syngenta's Apron Star 42 WS seed treatment can increase yields of pearl millet by up to 53 percent. The wholesale cost of Apron Star 42 WS, delivered into Niamey, is just US\$2 per 10-gram sachet, which is enough product to treat 4 kilograms of seed, enough to plant 4 hectares. The retail cost of a 10-gram sachet is around US\$3.25, making seed treatment a better short-term investment than irrigation, seed, or mineral fertilizer. Similar results confirming the economic attractiveness of seed treatments have been reported in a range of cereals and grain legumes by experiment station and on-farm research in western Sudan (Osman et al. 2012).

Weeds take a heavy toll on crop productivity throughout Sub-Saharan Africa, and the drylands are no exception. In maize, yield losses from weeds in rainfed cropping systems are believed to average between 10 and 15 percent (Gibbon, Dixon, and Flores 2007). In regions affected by purple witchweed (*Striga*), maize yields are depressed by an additional 7 percent on average.

Herbicides will increasingly be used in more commercial areas to manage weeds, but herbicides are still too expensive for widespread smallholder use. One novel technology that combats weed infestation while substantially lowering herbicide costs is the use of non-transgenic varietal resistance to specific active ingredients in herbicide. Seed of varieties that have resistance can be treated with herbicides, which will discourage weed growth following germination and during the seedling emergence stage, while leaving the resistant seedlings unaffected. Compared to the use of conventional herbicides, the cost of seed treatments is very low because there is no need for spraying equipment, and because input intensity per treated hectare is substantially reduced. An example of such a

technology involves the use of seed treatments in conjunction with herbicide-tolerant maize cultivars to manage Striga (Kanampiu et al. 2003). In early tests of the technology, imidazolinone-resistant (IR) maize seed was treated with two herbicides, imazapyr and pyrithiobac. In experiment station and on-farm trials conducted over six years in East and Southern Africa, the technology provided season-long Striga control, in most cases resulting in a three- to four-fold increase in maize yield when Striga density was high.

Prospects for Improved Land Management

Land management practices offer good prospects for increasing productivity in drylands. Examples of land management practices that show promise for dryland agriculture include *aménagement en courbes de niveau* (ACN), which translates roughly as “contour bunding,” in southern Mali (USAID 2013), rock bunding in Burkina Faso (ICRISAT 1985; Kaboré and Reij 2004; Matlon 1990), and integrated land management in Niger (Pender and Ndjeunga 2008).

To be effective, however, land management practices must be regionally and even locally adapted. Their feasibility and desirability in specific situations is conditioned by topography, soil type, rainfall pattern, and socioeconomic characteristics. Because one size does not fit all, top-down government approaches that emphasize heavy subsidization and compulsory transfer of what administrators believe is the best practice to improve land management and minimize soil erosion have been a prescription for disaster in several settings, including the Sahel and India’s drylands.

Contour bunding. Contour bunding has been actively promoted as the land management technology of choice in several Sahelian countries, including Burkina Faso, from the early 1960s to the early 1980s (Reij, Tappan, and Smale 2009). In Burkina Faso, between 1962 and 1965, earthen bunding was carried out by heavy machinery on more than 120,000 hectares (ILEIA 1985). By end of the project, it was apparent that farmers were not interested in maintaining the bunds, because they perceived that the soil was too wet on the front side of the bund and too dry on the back side. Waterlogging led to crop loss during intense rainfall events. Soil erosion increased when the bunds were inevitably breached. Later throughout the 1970s and early 1980s, smaller in-field earthen bunds were executed as part of food-for-work programs largely in response to the Sahelian drought.

Stone bunding and planting pits. The failure of contour bunding to take off during the late 1970s strongly suggested that prospects for this technology were bleak. In 1979, an Oxfam project took a different approach and consulted with

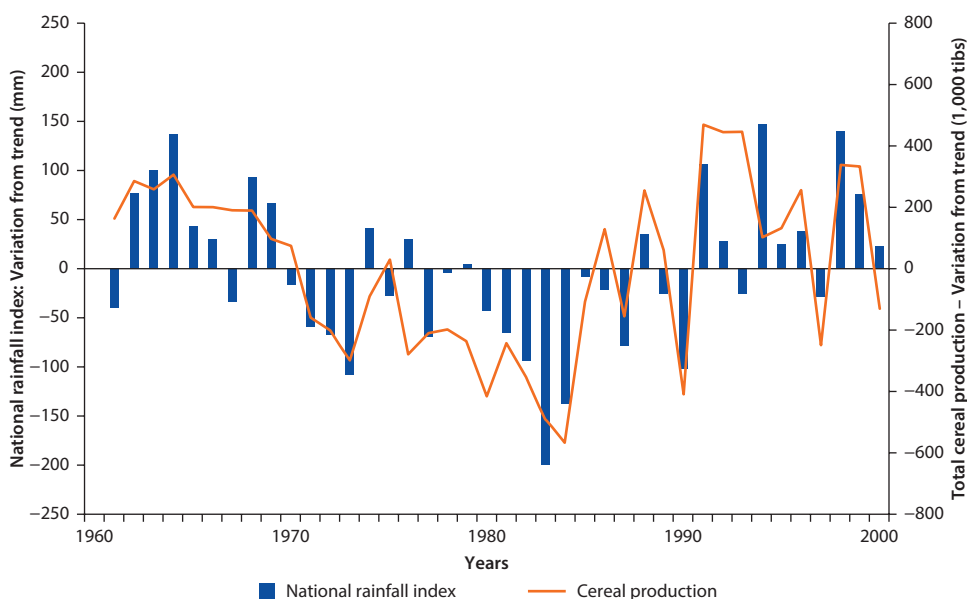
farmers on what they wanted in terms of management practices to increase productivity and reduce land degradation. Borrowing on what some farmers had done in the past, the project tested permeable rock bunding complemented with planting pits called *zai*. Similar to microdosing of fertilizer described earlier, the small micro-catchments provide an attractive place for adding animal manure.

Labor use increases with planting pits (construction of *zai* requires about 300–650 hours of labor per hectare), but *zai* can be formed in the dry season when surplus labor is often available and the opportunity cost is low. In contrast, tied ridging, another land management technology that results in increased productivity, needs to be implemented early in the rainy season when the opportunity cost of labor is much higher.

During the severe 1984 drought, with annual rainfall of less than 400 millimeters (see figure 5.1), cereal yields achieved using stone bunding and planting pits were 90 percent higher in 72 treatment plots in the six ICRISAT study villages (ILEIA 1985). These yield differences have held up over time, including in other locations. For example, in 2008 the combination of planting pits and stone bunds provided an increase in cereal yields from about 0.45 to 0.95 tons per hectare in four villages in Burkina Faso (Reij, Tappan, and Smale 2009).

Reij, Tappan and Smale (2009) estimate that 200,000–300,000 hectares have been rehabilitated in the central plateau of Burkina Faso. The cost of rehabilitation, mainly in the form of stone bunding, is about US\$200 per hectare. Additional cereal production attributable to rehabilitation (at least 80,000 tons) is sufficient to cover the annual cereal needs of about 400,000 people. The

Figure 5.1 Relationship between Cereal Production and Rainfall, 1960 to 2000, Burkina Faso



Source: Ward with Torquebiau and Xie (2016).

monetary value approaches US\$20 million per year. There appear to be hundreds of thousands of hectares in the recommendation domain (rainfall above 300 and less than 800 millimeters) that could still be rehabilitated.

The experience with stone bunding and *zai* in Burkina Faso generates several lessons about desirable characteristics in land management practices, such as:

- They need to be simple, cheap, and not too seasonally labor-demanding
- They need to demonstrate transparent productivity gains in the first year
- They should not be viewed from the technical perspective of what minimizes soil erosion in a catchment area but of what improves yield and reduces land degradation in farmers' fields.

A recent update on adoption and impact of in situ soil and water conservation practices in the Volta Basin of Burkina Faso supports the Reij, Tappan and Smale (2009) estimates. Fueled by donor and government projects, the area under soil conservation and water conservation practices increased dramatically beginning in the 1980s. Adoption has been confined largely to localities of higher population density in the 400–800 millimeter dry semi-arid zone, where demand for land and water conservation is strongest (Morris and Barron 2014).

Amenagement en courbes de niveau. The practice known by its French name of *amenagement en courbes de niveau* was developed beginning in the mid-1990s by French Agricultural Research Centre (CIRAD) scientists working in partnership with associates of the Mali *Institut d'Economie Rurale* (IER) (Gigou 1996). Designed to promote water infiltration and reduce soil erosion, the practice essentially combines ridge tillage and contour bunding. On relatively level land, the ridges are spaced widely, but on sloping land, the ridges are spaced more closely, with the closeness of the ridges increasing along with the degree of slope. Following its appearance in Mali, *amenagement en courbes de niveau* spread to Gambia, Senegal, and Cameroon, with the help of support provided through the United States Agency for International Development (USAID) Soil Management Collaborative Research Support Program (CRSP) (Kablan et al. 2008). The technology responds to larger landscape needs, but it can be applied at the level of individual fields, which adds to its economic attractiveness.

The *amenagement en courbes de niveau* practice addresses the problems that arise when intense rainfall events occur in the presence of soils that crust easily; this leads to low rainfall infiltration rates and severely erosive runoff. Crusting is most common on fine-grained clay soils, but crusts can also form on more coarse sandy soils.

Even though *amenagement en courbes de niveau* is relatively new, its performance in drylands regions of West Africa has been impressive. The technology is credited with increasing yields on a par with the yield increases made possible by stone bunding (a much more expensive technology), boosting soil carbon levels, and causing rises in groundwater tables (Kablan et al. 2008). Cereal yields of sorghum, millet, and maize have increased by as much as

50 percent, mainly via enhanced soil water availability and secondarily from earlier planting (Gigou et al. 2006).

Unconfirmed estimates by USAID suggest that by 2010, the practice had spread to cover 100,000 hectares. If this estimate is correct, ACN would seem to have bright prospects because its recommendation domain in West Africa is potentially large. Like microdosing, it is a good candidate for a rigorous and punctual verification assessment.

Water harvesting and on-farm storage. In some parts of the world, farmers protect against drought through water harvesting and on-farm storage. One approach is to capture rainwater that runs off from upland fields, store it in ponds or tanks, and later use the stored water to irrigate lower lying fields (via gravity systems) or the same upland fields (via pumping). Water harvesting and on-farm storage enjoyed a spell of success in India, where it is referred to as tank irrigation, although its popularity has waned in the face of growing population pressures (see box 5.1). In the drylands of Sub-Saharan Africa, the technology has made few inroads. Because most soils in the drylands are porous, storage ponds usually require lining to prevent seepage, which significantly raises the construction cost. More problematically, the timing of rainfall in the drylands often does not

Box 5.1 Tank Irrigation: Water Harvesting and Storage in Peninsular India

In the hard rock areas of peninsular India, thousands of small reservoirs called tanks dotted the landscape at Independence in 1947. Ranging in size from tens to hundreds of hectares, these tanks provided a very important source of supplementary irrigation for summer production of paddy. Tank irrigation enjoyed a long period of popularity; in the late 1970s and early 1980s, water from tank irrigation still accounted for about 20 percent of rice production in India (von Oppen and Subba Rao 1982).

Tank irrigation provided the means for many farmers to cultivate dryland and wetland crops in the same year. The interactions between wetland and dryland cultivation were and still are complex and contextual. Post-rainy season and summer rice were intensive in their demand for inputs, which enhanced input availability for dryland agriculture, but farmers with both types of cropping tended to concentrate all their energy on wetland production. Releases of water from the tanks were managed by village-level committees, which also were responsible for resolving disputes over water.

Tank irrigation in India eventually succumbed to a combination of factors, chiefly population growth and economic development. With population growth, arable land became increasingly scarce, causing land that formerly had been used for water storage to be expropriated and converted into farmland. At the same time, economic development led in many areas to the intensification of the road network, which impeded many of the natural watercourses and man-made canals that had long been used to channel rainfall runoff into the tanks. Deprived of their water collection networks, many remaining tanks no longer fill up, so ground water recharge is no longer taking place and water tables are falling.

coincide with irrigation needs; farmer experience, which is supported by the results of simulation modeling, leads to a sobering conclusion: throughout most of the drylands, stored water is most likely to be available when it is not needed, and when it is needed, it will not be there (Pandey 1986).

Rosegrant et al. (2014) included water harvesting as one of 12 technologies in their global scenario analysis of the impacts of technological change to 2050 for maize, rice, and wheat. In terms of its potential to raise maize yields by 2050, water harvesting was judged to be one of the least effective technologies. Based on their scenario analysis, these authors concluded that even though the technology might be adopted on as much as 50 percent of the area planted to maize throughout Sub-Saharan Africa, it was likely to increase maize yields by only 0.4 percent. This conclusion about the limited prospects for water harvesting in Africa is consistent with the findings of analysis done years earlier by Rosegrant et al. (2002), which noted that small, localized successes with water harvesting achieved in a few isolated locations have not translated into broader adoption due to a panoply of constraints. For example, small reservoirs have increased in numbers and have helped raise and stabilize productivity in the Volta Basin of Burkina Faso, but they account for only about 3 percent of all water stored for irrigation (Morris and Barron 2014). Water harvesting and on-farm storage thus seems too site specific to make a substantive and widespread contribution to improved productivity of dryland crops.

Improved Intercropping Systems

In industrialized countries, modern agriculture is almost always synonymous with monoculture. In field after field, sole cropping is the norm. Intercropping—growing multiple species in the same field—may be common in home gardens, but it is rarely practiced at scale in commercial production systems.

In contrast, in dryland regions intercropping is common. Salient examples include intercropping of maize and pigeonpea in East Africa, and intercropping of pearl millet and groundnut and pearl millet and cowpea in the Sudanian and southern Sahelian Zones. Intercropping is common in many dryland regions because many species are 20–30 percent more productive when intercropped, as compared to being grown as sole crops. Work done by Willey et al. (1983) shows that in the dryland semi-arid tropics, temporal and spatial complementarities in the timing of resource use and in exploiting space confer advantages to different species grown in proximity compared to sole crops of the same species.

Not all intercrops are characterized by these productivity advantages—farmers intercrop for many reasons—but popular intercrops can be very efficient in the use of scarce resources. Data from moisture stress studies confirm that during periods of drought, the productivity edge to an intercrop can be as large as 40–60 percent, because intercropping increases the ability of plants to exploit scarce soil moisture (Willey et al. 1983). Again, not all intercropping systems deliver such large benefits, but examples abound in the literature of many that do. The

implication is that intercropping should not be seen as a traditional, “backward” way of farming in the drylands, but instead be recognized as a potentially productive and risk-efficient cropping strategy.

Intercropping has attracted relatively modest attention from researchers. As a result, there are not many examples of new intercropping technologies moving from research plots to farmers’ fields. One of the rare instances in which a new intercropping system identified initially by researchers has enjoyed success involves maize intercropped with pearl millet; introduced in West Africa during the 1970s, the system spread rapidly and within a few years covered about 50,000 hectares (ICRISAT 1986).

Because the management requirements of intercrop systems are complex and farmers often are forced to make trade-offs between the competing needs of different crops, many researchers now believe that the most effective way to promote intercropping is expose farmers to new varieties and support their efforts to integrate these varieties into existing cropping systems. The role of researchers thus should be to provide farmers with an expanded set of options by making sure that they have access to new varieties with a range of agronomic characteristics. In this context, it is worth noting that a number of pulse crops are highly suitable for intercropping with cereals in the drylands, such as bush beans and pigeonpea. In response to growing export demand, especially from India, intercropping with pigeonpea is rapidly expanding in dryland zones in Malawi, Mozambique, and Tanzania. New medium-duration pigeonpea varieties of 6–8 months are well-adapted to the length of the growing season prevailing in dryland regions in those countries. Intercropping of short-duration maize with longer-duration pigeonpea is gaining in popularity as well.

With growing availability of ever more diverse modern varieties, coupled with strengthening demand for pulses including from export markets, intercropping is expected to become increasingly common in dryland regions of Sub-Saharan Africa.

Agroforestry Innovations Appropriate for the Drylands

In a companion book prepared as another background piece for the Africa Drylands study, Place et al. (2016) assess the prospects for tree-based production technologies to reduce vulnerability and enhance resilience among households living in the drylands of Sub-Saharan Africa. Trees and field crops can interact in several ways. Three main tree-based production systems can be distinguished. Under *forestry systems*, trees are produced in sole stands in wood lots or plantations, in which case they compete with other livelihoods activities for land. Under *agro-forestry systems*, trees are grown on the same land where crop cultivation and/or herding activities are taking place, in which case there may be mutually beneficial interactions. Under *parkland systems*, farmers manage the regeneration of naturally occurring trees, some of which are left to grow in cultivated fields or grazing areas. Because this report assesses prospects for improving crop

productivity in drylands, here the focus is on the potential for the second type of system—agro-forestry systems. (For a more in-depth discussion of all three types of systems in dryland regions off Sub-Saharan Africa, see Place et al. 2016.)

Given the potential benefits of intercropping (discussed in the previous section), it is reasonable to ask whether there are productivity benefits in drylands from agro-forestry systems and parkland systems? The answer to this question turns out to vary by tree-based system and by aridity zone.

Arid and dry semi-arid zones: In very dry zones, trees and crops can be productively cultivated in association in parkland systems. In many dryland regions in West Africa, as rainfall decreases, the productivity of natural vegetation under savannah trees declines more slowly than in areas where there are no trees (Ong and Leakey 1999). This is epitomized by the “Albida effect.” In the Sahel, millet almost always performs better and gives higher yields when planted under or in close proximity to *Acacia albida*, which sheds its leaves in the rainy season. Sown on well-drained sandy soil, *Acacia albida* has a long tap root that can exploit sources of fertility 10 or more meters below ground. Soil fertility is higher under the trees, which also shade the crop (Vandenbeldt 1992). In a parkland setting at low densities, *Acacia albida* is a significant contributor to heavier pearl millet production. Positive interactions between savannah trees and field crops, especially millet, have contributed substantially to the success of farmer-managed natural regeneration in Niger (Reij, Tappan, and Smale 2009). Regenerative savannah tree mixed cropping systems, featuring millet, cover several hundred thousand hectares in southern Niger.

Moist semi-arid zone: Years of agro-forestry research carried out at ICRISAT Center in India and at the Sahelian Center (ISC) in Niger led many researchers to conclude that in the moist semi-arid tropics, planted trees and crops should not be cultivated in proximity in the same growing season, because of stiff competition for soil moisture. The trees always win, irrespective of how they are managed, because of their superior ability to exploit soil moisture. Based on the emerging evidence in the 1980s of the limited scope for synergistic interactions in high-density, simultaneous tree/crop systems, the prospects for agro-forestry interventions seem very limited in the moister segments of the semi-arid zone (Walker 1987). Statistical analysis often is not needed to arrive at this conclusion, because a height gradient is clearly visible as one moves away from the tree species: crop height increases with distance from the tree as the competition for moisture decreases. Under these conditions, planting trees and crops separately is the most productive arrangement. The experimental results have been borne out in practice: beginning in the 1980s, even though so-called hedgerow intercropping of leguminous trees and field crops was actively promoted as having high productivity potential in rainfed tracts in Sub-Saharan Africa, the technology never took off in the semi-arid tropics. In summary, competition for soil moisture limits the role that agroforestry innovations can contribute directly to productivity growth and risk reduction in the semi-arid tropics. Leguminous trees and shrubs must be grown on field boundaries or in separate fields, rather than being

intercropped in the same field, although intercropping in the same field can confer some advantages for field crops in terms of nitrogen management.

Sub-humid and Humid zones: In zones where rainfall is relatively abundant, hedgerow intercropping has greater potential because the soil fertility gains from the tree component outweigh the losses in competition for soil moisture (Rao, Nair, and Ong 1998).

Animal Traction

Land preparation and cultivation activities in dryland regions of Sub-Saharan Africa are carried out using basic three sources of power: human, animal, or mechanical. In the absence of reliable statistics, it is impossible to know the relative importance of each source, although casual observation suggests that human power remains the most common, animal power ranks second in importance, and use of machinery still comes last.

Vast expanses of the drylands continue to be cultivated by hand, using simple instruments such as hand-held hoes. While the conventional wisdom has long held that the bulk of agricultural labor, including land preparation and cultivation, is carried out by women, recent evidence generated in a sample of drylands countries through the World Bank-supported Living Standards Measurement Surveys (LSMS) suggest that this is untrue.

Animal traction is a critical transition technology between manual and mechanical cultivation. Research on animal traction peaked in the 1980s, when pioneering studies pointed out its role and the spatial conditions where it contributes most effectively to intensification (Pingali, Bigot, and Binswanger 1987). In many parts of the drylands, animals—mainly cattle but depending on the location also horses and more rarely camels—provide traction used to cultivate lower-lying, heavier soils. In addition to providing the power to carry out land preparation activities that are too arduous to be done by hand, animals can play an important role in facilitating row planting, reducing seasonal labor bottlenecks in weed management, and enhancing options for transport. The transport function of draft animals is often critical for intensification, because it improves access to fertilizer and allows hauling of raw materials needed for construction of soil conservation works. Use of animals confers many benefits to dryland farmers, but the cost of acquiring and maintaining draft animals remains a huge barrier in many areas. Further, policies to stimulate the adoption of animal traction are not well defined.

In most dryland regions in Sub-Saharan Africa, use of machinery to carry out land preparation activities remains uncommon. Use of tractors can significantly increase the area that can be cultivated by a single operator, which can be an attractive proposition particularly in areas where agricultural labor is in short supply, but the large initial investment cost puts the technology far beyond the reach of the vast majority of dryland households. Governments in several dryland countries have attempted to introduce machinery hire services to make the

technology more accessible to smallholders, but these have almost never succeeded, due to a combination of technical, economic, and institutional factors.

Response Farming

Productivity in dryland farming could be increased significantly if farmers could better predict rainfall patterns and take advantage of wetter cropping seasons. Response farming refers to a set of practices that farmers can use to exploit meteorological and other information that becomes available during the course of the cropping season. The term “response farming” originated in East Africa, where the short and long rains afforded scope for taking corrective actions during two rainy seasons. Near- and in-season predictions have relevance in dryland zones worldwide, however, and over the years they have been used successfully in a wide range of cropping systems, ranging from millet cropping systems in the Sahel (ICRISAT 1985) to wheat cropping systems in western Australia (Fischer, Byerlee, and Edmeades 2014).

In response farming, the trick is to identify patterns from which farmers can profit as regularities emerge. For example, in the Sahel region an early start of the rains means a longer growing season; therefore, a relay intercrop of millet/cowpea is likely to be more effective than sole-cropped millet, because the relay intercrop can better exploit increased water resources from a longer growing season. In contrast, sole-cropped millet is likely to be the more profitable alternative when the onset of rains is delayed.

Although response farming is unlikely to be a large contributor to increasing productivity in the drylands of Sub-Saharan Africa, it has potential in some very specific contexts. Automatic weather stations could help make it an increasing reality, and the increasing availability and rapidly falling cost of information and communication technology (ICT) means that dissemination of information needed for decision making is becoming easier, faster, and cheaper.

Crop and Rainfall Insurance

In theory, crop insurance is a policy option that directly addresses the problem of systemic risk from yield variability, which could make it especially valuable in dryland agriculture. Aside from directly protecting farmers from yield losses caused by drought, disease, and pests, crop insurance indirectly enhances resiliency in the production environment, because farmers can adopt technologies they perceive to be profitable without having to worry as much about the vagaries of weather. The increased income generated by the profitable technologies can be reinvested in the farm or the household to further limit sensitivity to risk and to improve coping capacity.

In practice, crop insurance that is voluntary and oriented to the individual producer is vulnerable to consistent and sizable losses, because of moral hazard and adverse selection. Moral hazard refers to the negative incentives associated with the use of insurance, which enter into the picture because farmers know they will be rewarded for exerting less effort when rainfall has been poor and yields fall low enough to approach payout trigger points. Adverse selection becomes a problem when the more productive farmers with higher and more stable yields do not participate in crop insurance, which raises the cost of coverage for the remaining, relatively unproductive farmers with lower and more variable yields. Both moral hazard and adverse selection erode the actuarial basis for cost-effective crop insurance.

The 1980s witnessed a surge in interest in modifying crop insurance schemes similar to those that had enjoyed a certain success in industrialized countries so that they could benefit smallholder farmers in developing countries (Hazell, Pomareda, and Valdes 1986). It soon became apparent, however, that voluntary insurance programs that paid out premiums based on farmer-specific yields were not economically sustainable. To begin with, they were characterized by high administrative costs, because of the need to monitor the situation on each farm individually. In addition, because premiums were kept low to keep coverage accessible to farmers with limited ability to pay, they were often subject to losses. Very high loss ratios (the value of indemnities divided by premiums) exceeding 40 were incurred in some bad years; loss ratios greater than one were even recorded in normal and good weather years in a program with this design in Brazil.

At the same time, voluntary insurance programs based on farmer-specific yields had one big advantage over other designs: they minimized basis risk, which occurs when the payout of indemnities is not coincident with farmer losses (see box 6.1). Sizable basis risk erodes farmers' incentives to participate, because in the presence of basis risk insurance becomes a blunt instrument to stabilize household income and to smooth consumption.

Box 6.1 Risk Benefits from Crop Insurance

The performance of a stabilization policy depends largely on risk benefits (Newbery and Stiglitz 1981). Risk benefits measure the extent that the policy diminishes variability, which in this case are crop yield and household income. The size of risk benefits also depends on risk preferences.

Risk benefits increase with multi-crop insurance. However, extending insurance to more crops greatly increases administrative costs and requires considerable sophistication in yield determination and statistical sampling, especially in species that are not sole-cropped.

Superimposing a typical crop insurance scheme where payouts were triggered by an 80 percent of average yield in the 10-year International Crops Research Institute for the Semi-arid-Tropics (ICRISAT) study panel in India's Semi-arid Tropics (SAT) showed that a focus on the main dryland crop improved risk benefits by only 3–5 percent of mean household income (Walker, Singh, and Asokan 1986). Indeed, the results suggested that the highest potential for risk benefits was irrigated rice produced from groundwater and tank irrigation in villages where rainfall was unassured. Rice households tended to have fewer other sources of income relative to dryland crop producers, and rice was by far their dominant cropping activity. Although rice production was more stable than dryland crop production, the importance of rice in household income translated into higher risk benefits in terms of dampened fluctuations in income by participating in a representative crop insurance scheme for moderately risk-averse households, which was the central tendency in terms of risk preferences.

These results are specific to India's Semi-arid Tropics, but they illustrate the salient point that diversified farming systems and alternative sources of income in the drylands of Sub-Saharan Africa (SSA) can markedly reduce the potential benefits from and demand for formal institutional insurance. Efficient risk adjustment hinges on diversified cropping systems and sources of income.

These findings further suggest that maize monoculture as cultivated, for example, in Zambia could be the best prospect for the receipt of risk benefits from crop insurance in the drylands of Sub-Saharan Africa. Maize-growing families in Zambia rely heavily on maize production for crop income, which accounts for the bulk of their household income. Millet-growing households in the Sahelian and Sudanian Zones of West Africa, where high temperatures and low soil fertility are severe constraints to diversification, also qualify as a cropping environment where eliminating downside risk should confer sizable risk benefits. Other things being equal, risk benefits are higher and the demand for crop insurance is greater in commercial, specialized production than in more diversified smallholder systems.

Part of the interest in crop insurance that occurred during the 1980s was attributed to several advances in design that brightened its prospects. In response to the so-called “never in a 100 years drought” experienced in India in 1972, Dandekar (1976) pioneered a design that featured a homogeneous area approach to crop insurance. Payouts were still determined by crop yields, but the basis for indemnities was yield estimates made not at the level of individual farms but rather over a relatively large area (equivalent to a county in the United States). This design effectively eliminated the problem of moral hazard, because individual farmers had little ability to manipulate yield estimates made over a wider geographic area. In India, the government crop reporting service publishes reliable yield estimates that can serve as the basis for valid actuarial estimates.

Another design improvement was to move to weather-index insurance, in which the trigger for payouts is not crop yield, but rather rainfall. Because rainfall data are more readily available than yield estimates, especially with the advent of automatic weather stations, when rainfall is used as the trigger, insurance can easily be designed to be free of moral hazard and adverse selection. In addition, rainfall insurance can be structured to hedge against the problem of area variability at planting. However, rainfall is one step removed from yield, so when rainfall is used as the trigger rather than crop yields, it is possible that basis risk as perceived by farmers will increase.

Early efforts to introduce weather-index insurance in India met with little success. Bakker (1990) analyzed the results from five early pilots carried out in India in the late 1980s and concluded that the schemes were unprofitable due to weak demand, even though the cost of the insurance was partially subsidized, and despite the fact that the scheme was explained clearly to the target population. In those pilots, seemingly perfect information did not translate into participation. Bakker (1990) concluded that weather during the previous cropping year seemed greatly to influence expectations about the likelihood of weather events during the next cropping year.

Over the past 25 years, some progress has been made in overcoming the problem of weak demand for weather-index insurance in developing countries (Brown, Mobarak, and Zelanska 2014). In a survey carried out in 2010, Hazell et al. (2010) concluded that pilot schemes were being implemented in approximately 30 developing countries. Early results suggested that with effective targeting and adaptation of the design to local circumstances, the widely acknowledged problem of weak demand may not be insurmountable. This conclusion was later supported by others; for example, Brown, Mobarak, and Zelanska (2014) pointed to a number of cases in which the successful adoption of technological innovations could plausibly be attributed to weather-index insurance.

Despite these limited successes, at least one seasoned observer of crop insurance believes that weather-index insurance is not a viable option for improved

risk management in smallholder agriculture. Summarizing from 40 years of experience working with smallholders, Binswanger-Mkhize concludes:

[Poor farmers] are cash/credit constrained and, therefore, cannot advance the money before sowing time to buy insurance that pays out only after the harvest. Index insurance, therefore, cannot be scaled up. Even if a few farmers purchase it, governments still will need to run relief programmes for the uninsured. (Binswanger-Mkhize 2012, 187)

Brown, Mobarak, and Zelanska (2014) are more sanguine. They concede that credit constraints, limited financial literacy of farmers, and basis risk will always limit the demand for weather-index insurance among smallholders. They express cautious optimism, however, that with enough trial-and-error experimentation it may become possible to overcome these obstacles, to the point that weather-index insurance could eventually make a substantive contribution to risk management in dryland agriculture.

Climate Change

Short-term deviations in temperature and rainfall have exacted a toll on crop production and welfare throughout human history. During the past 50 years, persistent departures from normality include the Sahelian drought of the 1970s and 1980s, widespread rainfall shortages in southern Africa in the early 1990s, and the Millennium Drought in Australia in the late 1990s and early 2000s. The effects of these sharply defined deviations are transparent. In contrast, climatic change from global warming is a slow, cumulative process characterized by uncertain and diverse geographic impacts. Nevertheless, the contours of those impacts are becoming more visible.

Global warming has the potential to wreak havoc with the production potential of the tropical and subtropical drylands in Sub-Saharan Africa, especially where mean temperatures already exceed optimal levels for some crops. For maize, the optimal mean temperature to attain potential yield is 18 °C.

A comprehensive review of studies that have assessed the likely impacts of global warming on crop performance highlighted maize as the most important crop in Sub-Saharan Africa warranting attention (Lobell and Field 2007). Maize was singled out due to its importance in food security and due to the fact that many of the maize cultivars grown in Sub-Saharan Africa contain heat-sensitive germplasm originating from temperate materials.

Because physiological processes determining crop growth are characterized by threshold temperature effects, yield response to rising temperatures can be abrupt and discontinuous. For example, potatoes do not set tubers unless minimum daily temperatures fall below 21 °C. Similarly, sterility is induced in maize when the maximum daily temperature is greater than or equal to 38 °C.

The key question, therefore, is not whether climatic change will have deleterious impacts on crop yield in the drylands of Sub-Saharan Africa. The key question is how much productivity will be lost from rising temperatures. Fischer, Byerlee and Edmeades (2014) recently addressed this question in a survey of the burgeoning and contentious literature on the agricultural consequences of global warming. They attached greater weight to so-called regression approaches based on observed panel data, which in their view provide the most reliable

way to estimate the sensitivity of yield to small changes in temperature, rainfall, solar radiation, and other variables associated with global warming (Lobell and Burke 2010; Lobell, Cassman, and Field 2009; Lobell, Schlenker, and Costa-Roberts 2011).

Fischer, Byerlee, and Edmeades (2014) arrived at the following conclusions:

- CO₂ is expected to increase by 26 percent to 480 parts per million by 2050;
- With rising CO₂ levels, average global temperatures are forecast to increase by 2 °C by 2050;
- Predictions on differences in precipitation attributed to global warming are not that sizable and are too uncertain to warrant rigorous impact assessment at this time;
- “Best bet” estimates from regression studies and simulation modeling suggest that each 1 °C increase in temperature will cause a 5 percent decline in the yield of maize, rice, and wheat, and a 2 percent fall in soybean yield (table 7.1). Assuming no adaptation, global warming of 2 °C by 2050 thus would lead to a 10 percent decrease in cereal yield and a 5 percent decrease in soybean yield;
- These pure temperature effects are likely to be offset by gains from increasing CO₂ concentration, especially in the C3 crops, wheat, rice, and soybean, where the utilization of CO₂ in photosynthesis is not as efficient as in coarse cereals. Hence, the total yield effect is negligible in rice and wheat and is equivalent to an 8 percent loss of productivity in maize; and
- Chronic warming, especially hot spells above 30 °C, depresses yield by speeding up crop development and by reducing grain numbers and size.

Based on their review of multiple studies, Fischer, Byerlee, and Edmeades (2014) describe a set of “best bet” projected yield effects likely to occur by 2050 (table 7.1). Overall, the effects are not that large, and these authors express optimism that plant breeding and crop agronomy can be deployed to dampen the projected declines in yield from global warming.

The estimates presented in table 7.1 reflect the crop yield effects that are projected to occur assuming that a 1 degree increase in temperature leads to a 5 percent decrease in yield, *ceteris paribus* (Fischer, Byerlee, and Edmeades 2014). In an innovative assessment based on a very large experimental database, Lobell et al. (2011) found significantly larger declines in productivity when crops were drought-stressed. In addition, gains projected by standard models to occur in higher elevations as a result of climate change disappeared when crops were water-limited. Under conditions of water stress, the productivity of maize for each 1 °C increase in temperature fell by as much as 43 percent.

The Lobell et al. (2011) assessment is arguably a worst-case scenario. Treatments in the trials considered by Lobell et al. (2011) were not fertility stressed. In nitrogen-stressed fields, which are common throughout Sub-Saharan Africa, the negative interaction between drought and temperature on productivity

Table 7.1 Effect of Warming and CO₂ Increase on Crop Yields to 2050^a

Crop	Yield Sensitivity to 1° Rise Relative to 2000 Yield (%)				Overall Yield Response by 2050 Relative to 2000 Yield (%)		
	From Regression Studies	From Simulation Models	Average R and S	"Best bet" after Rounding	2 °C Warming	+100 ppm CO ₂	Sum
Wheat	-4.1	-7.7	-5.9	-5	-10	+ 10	0
Rice	-2.3	-7.4	-4.8	-5	-10	+ 10	0
Maize	-4.9	-4.1	-4.5	-5	-10	+ 2	-8
Soybean	-0.3	-3.1	-1.7	-2	-4	+ 10	+ 6

Source: Fischer, Byerlee and Edmeades (2014).

^a Assuming growing season mean temperature (T_{mean}) is + 2 °C and CO₂ increase + 100 ppm (+26%).

would presumably not be as large. Nonetheless, if global warming results in a marked increase in the incidence of very hot spells, the findings by Lobell et al. (2013) suggest that the effects of higher temperatures on maize yield in Sub-Saharan Africa could be substantially higher than the global "best bet" estimates presented in table 7.1.

Whether the confidence expressed by Fischer, Byerlee, and Edmeades (2014) is justified that the negative impacts of climate change can be dampened by research remains to be seen. Many agricultural research centers, both international and national, have committed considerable resources to screening genetic materials for tolerance to heat stress. Especially in the past 10 years, the incidence and consequences and prospects for the mitigation of and farmer adaption to global warming has commanded increasing research attention. At the same time, such work already has a long history, as work on drought tolerance and heat tolerance has always been a large component of international crop improvement programs (Hausmann et al. 2012). Fischer, Byerlee, and Edmeades (2014) go so far as to say that recent initiatives to breed for adaptation to global warming represent relatively small departures from "business as usual."

Whether or not these efforts will pay off is an open question. In the past, breeding for resistance/tolerance to heat stress has not paid enormous dividends in maize [at the International Maize and Wheat Improvement Center (CIMMYT)] or in potato [at the International Potato Center (CIP)]. A number of physiological aspects remain to be explored, however, and these could provide the basis for effective heat tolerance. In pearl millet improvement, a hybrid prized for its heat tolerance is one of the leading cultivars in the State of Rajasthan, India, which has an environment very similar to the southern Sahelian Zone (Asare-Marfo et al. 2013).

Fischer, Byerlee, and Edmeades (2014) also highlight tactical crop management as a source of innovations designed to combat the adverse effects of global warming. The possibilities in this realm are largely location-specific and rely on knowledge about timeliness of the use of inputs. Many of the changes will likely be made in the course of "normal" crop improvement, as the additionality of

global warming to agronomic research is difficult to envisage in highly specific terms (Fischer, Byerlee, and Edmeades 2014).

If high-yielding, heat-tolerant cultivars and adaptive innovations in crop management are not forthcoming, substituting more heat-tolerant cereals, such as pearl millet and sorghum, for maize is a possibility. Moving forward to 2050, however, the scope for substitution among the coarse cereals in food consumption appears to be decreasing, because as incomes rise, consumption preferences are likely to shift away from coarse cereals.

Technology Diffusion Prospects by 2030

The principal objective of this book—assessing the prospects for raising crop productivity in the drylands of Sub-Saharan Africa—is an ambitious undertaking, especially when the assessment is expected to focus on the ability of improved cropping technologies not only to increase productivity but also to reduce sensitivity to drought. Introducing drought into the equation complicates the exercise, because the future incidence of drought in the drylands, the impacts of future droughts on crop productivity, and the degree to which those two things will shape future technology development pathways are difficult to predict.

A survey of the literature revealed that ex-ante assessments made a generation ago continue to provide valuable insights about the prospects for productivity gains in dryland environments. In particular the assessment carried out by Matlon (1990) of technology prospects for sorghum and pearl millet in West Africa is extremely valuable. Many dryland cropping technologies have changed over time, but their essential substance and many distinguishing features have stayed the same.

Several parallels exist between Matlon's work and this assessment. The four dryland zones distinguished by Matlon are roughly comparable to the zones used for the Africa Drylands study. Matlon classified technologies into four groups: (1) yield increasing, (2) labor saving, (3) yield stabilizing, and (4) land conserving. Most if not all of the same technologies are covered in this background paper. Matlon's evaluation relied heavily on, but was not restricted to, 10 years of on-farm experimental research and village-level studies carried out mainly in Burkina Faso and Niger. This assessment similarly relies on empirical evidence from these two countries (and other Sahelian countries).

One respect in which the two assessments diverge is in their willingness to make projections. Matlon was quick to point out that "any attempt to offer a detailed forecast of the types of technical changes that can be expected—where, in what time frames, and with what impacts on production—would be conjectural and inevitably proven wrong by subsequent events" (Matlon 1990, 34). He

limited his remarks to the most promising technologies that were on the shelf or that were desirable if they became available by 2000. This assessment adopts a riskier approach and presents a ranking—admittedly subjective—of the five most promising technologies for each aridity zone. In addition, this study presents estimates—also very subjective—of the area within each aridity zone over which each of the technologies is likely to have been adopted by 2030. The expected areas vary from about 0.5 million hectares in some aridity zones for the fifth ranking technology to more than 5 million hectares in some aridity zones for the top-ranking technology. These area estimates refer to incremental use of each technology, that is, they represent the number of hectares on which “new” adoption will take place by 2030.

In addition to projecting the areas over which promising technologies are likely to be adopted by 2030, this assessment assigns indicative costs of adopting the technologies, expressed in terms of costs per hectare. The adoption cost estimates, which are derived based on admittedly crude estimates of the costs incurred by the public sector in promoting the technologies and the costs incurred by farmers in adopting the technologies, were used as inputs into the “umbrella modeling” exercise described in the main Africa Drylands study. It is important to take technology adoption costs into account, because farmers are unlikely to adopt an improved technology if the cost of adoption exceeds the expected benefits, that is, if the technology is unprofitable.

Prospects in the Arid Zone

According to Matlon (1990), yield-stabilizing and land-conserving technologies are the most relevant for arid zones, as epitomized by the Sahel, which was perceived as having a comparative advantage in extensive livestock production. Among available technologies, shorter-cycle pearl millet varieties that escape drought, thereby dampening downside yield risk, are the type of innovations that are desirable and economically feasible. Drought tolerance is also an important characteristic, although incorporating this trait into well-adapted materials takes time. With increasing population density, water-harvesting systems could have some potential to stabilize production, but the deep sands of the arid zone pose a daunting challenge. Expanding area under cultivation is undesirable, as it could lead to desertification in a fragile ecosystem.

The assessment done for this book mostly agrees with Matlon’s expectations for technological change in the arid zone. Prospects for the uptake of yield-increasing technologies that rely on the intensification of input use are bleak, because the incremental benefits generated by such technologies often do not cover the additional input costs. Four of the five technologies cited as most promising in table 8.1 involve farm-level investments that cost less than US\$5 per hectare.

Improved varietal change is feasible and desirable, even though productivity gains are usually modest, at 10–15 percent. Adoption of shorter-duration improved

Table 8.1 Most Promising Crop Productivity Improvement Technologies for Arid Zones, 2030

<i>Rank</i>	<i>Intervention</i>	<i>Characteristics</i>	<i>Cost (US\$/ha)</i>	<i>Basis for Expected Area</i>
1	Agroforestry	Natural regenerative forestry in millet fields in the Sahel	<5	Reij, Tappan, and Smale (2009)
2	Pearl millet varieties	Short duration plus heat tolerance in the Sahel	<1	ICRISAT and ICARDA (2012) and Walker et al. (2014)
3	Pearl millet hybrids	Heat tolerance in the Sahel	3	ICRISAT and ICARDA (2012) and Walker et al. (2014)
4	Seed treatment	With private sector products, such as Syngenta's Apron, on pearl millet seed in the Sahel	<2	Tom Hash (personal communication 2014)
5	Cowpea varieties	Drought and low phosphorus tolerance for the Sahel	20	ICRISAT et al. (2012) and Walker et al. (2014)

Note: The adoption costs for improved pearl millet and cowpea varieties are based on a seed rate of 5 kilograms per hectare for pearl millet and 40 kilograms per hectare for cowpea. It is assumed that improved varieties are available for twice their output price and hybrids for four times their output price. Output prices are taken from FAO Corporate Statistical Database (FAOSTAT; FAO 2012b).

pearl millet varieties is increasing and now stands at 18 percent for West Africa as a whole, slightly higher than the ceiling adoption rate predicted by Matlon. SOSAT C-88, released in 1988 when Matlon was drafting his assessment, has diffused to about 1 million hectares in West Africa across the arid and semi-arid zones.

Today, the most important yield-stabilizing and land-conserving technology is not water harvesting, but farmer-managed natural regeneration of tree species, which is ideally suited to the arid zone, where annual crops such as pearl millet derive complementary benefits from planting in fields with trees at low densities. The area under parkland systems, where crops and trees are grown in the same field during the same cropping season, is expanding and was estimated at about 5 million hectares in the early 2000s. This technology was just beginning to take off at the time of Matlon's assessment. Looking forward to 2030, the prospects are bright that farmer-managed natural regeneration will continue to expand. In principle, the bulk of cereal cropped area in the arid zone could be covered by this technology in 2030.

Prospects for widespread diffusion in arid zones of improved varieties of the major crops (pearl millet and cowpea) are not as bright because of the low research intensities in these crops. Low research intensities are reflected in the low rate of release of improved varieties. Because it takes about 10 years to develop and release a variety of pearl millet or cowpea, resources for improvement of these two crops would have to increase by several orders of magnitude in the very short run in order to have a substantial impact on adoption levels by 2030. Without greater investment in pearl millet and cowpea, it is unlikely that adoption of improved varieties in the arid zone will increase dramatically from current low levels. Based on the experience of India, it seems safe to say that the contribution that improved cultivars—especially hybrids—can make to productivity growth in the arid zone will be negligible unless private sector participation increases dramatically in the cereal seed industry in West Africa.

Two technologies discussed earlier in this report could make an impact on crop productivity in the arid zone by 2030. Seed priming and low-cost treatment with Syngenta Apron have given substantial yield increases in cereals, on the order of several hundred kilograms per hectare in early experimental testing in on-farm trials in Niger and western Sudan. Particularly if the cost continues to come down, these technologies could spread widely.

The five most promising technologies for the Arid Zone are shown in table 8.1, along with the area within the Arid Zone over which each of the technologies is likely to have been adopted by 2030, as well as the likely adoption cost.

Prospects in the Dry Semi-Arid Zone

In summarizing the results of his ex-ante technology assessment for the drylands, Matlon (1990) concluded that the prospects for viable technological options to improve crop productivity were very limited in the Dry Semi-arid Zone. Population density in that zone already seemed much higher than the land could sustainably support. Land degradation was rampant, driven by highly erosive rainfall and by the expansion of farming into areas that were increasingly marginal for crop production. Drought was chronic. Crop and livestock activities were not well integrated, and the density of ruminants was in any case low. Livelihood sources were non-diversified, with most households heavily dependent on income from crop production, and few households could adequately compensate for drought-induced production shortfalls. Mechanisms for facilitating temporary migration out of the region were limited.

Given the extreme threat posed by land degradation, combined with limited scope for risk management, Matlon highlighted the potential benefits of land-conserving technologies, which he felt had especially bright prospects in densely populated farming areas where land degradation was visible and its consequences were appreciated by farmers. Because many people in these zones lacked full-time employment, Matlon drew attention as well to the potential benefits of labor-intensive technologies, such as contour bunding and rock bunding. These land-conserving technologies are doubly important, because in addition to increasing yields in years of good rainfall, they have the capacity to temper yield losses in years of poor rainfall. Interestingly, while many agricultural specialists were promoting the use of tied ridging in semi-arid zones to create micro-basins, Matlon argued that tied ridging can depress yields by causing waterlogging on heavier soils. Matlon's comments proved to be prescient: different from planting pits and rock bunds, adoption of tied ridging has been very limited in the semi-arid zone.

The technologies identified by Matlon as having most promise in semi-arid zones included a number of yield-stabilizing technologies. Mainly these consisted of improved cultivars of coarse cereals, specifically short-duration sorghum and maize varieties and hybrids that can escape drought, and sorghum varieties resis-

tant to the parasitic witchweed (*Striga*). Supplementary irrigation was conspicuously absent from the list of yield-stabilizing prospects identified by Matlon as having bright potential for cereals grown in semi-arid zones. Matlon predicted—correctly, as it turned out—that supplemental irrigation would have little impact on coarse cereal production, because the high investment cost dictated that its use be restricted to high-value vegetable crops.

In the years following the publication of Matlon's assessment, considerable progress was made in confronting the threat of land degradation and addressing the limited production prospects in the dry semi-arid zone. By the early 2000s, rock bunds, planting pits, and other soil conservation practices for in-situ water and land management had spread widely in the Sahel region. Plant breeders from the CGIAR Centers, working in collaboration with breeders in national programs, succeeded in developing a series of sorghum and maize varieties with good resistance to *Striga*. With the help of biotechnological techniques, resistance to *Striga* was incorporated into several popular improved sorghum varieties in Sudan, the country with the most extensive cropped area in the dry semi-arid zone. The use of marker-assisted selection techniques to backcross *Striga* resistance into popular improved varieties in dryland Sudan was a singular achievement that is indicative of what can happen when resources are effectively utilized in multiple partnerships (table 8.2).

The assessment done for this book broadly supports Matlon's analysis of the prospects for technological change in the Dry Semi-arid Zone. The soil and water conservation practices that have become popular in the Dry Semi-arid Zone appear to be sustainable and have conferred considerable resiliency in insulating farm households from the adverse effects of drought. They offer a pathway to agricultural intensification when population densities rise and the potential for

Table 8.2 Most Promising Crop Productivity Improvement Technologies for Dry Semi-arid Zones, 2030

Rank	Intervention	Characteristics	Cost (US\$/ha)	Basis for Expected Area
1	Reintroduced improved sorghum varieties	<i>Striga</i> resistance in the Sudan	<2	ICRISAT (2012) and Zereyus and Dalton (2012)
2	Fertilizer	Microdosing in the Horn of Africa and West Africa	15	Tabo et al. (2007) and Winter-Nelson and Mazvimavi (2014)
3	Cowpea varieties	Drought tolerance and insect resistance	20	ICRISAT et al. (2012) and Walker et al. (2014)
4	Soil conservation practices	Stone bunding and planting pits (zai)	45	Matlon (1990) and Reij et al. (2004)
5	Groundnut varieties	Short-duration cultivars that escape drought	70	ICRISAT et al. (2012) and Walker et al. (2014)

Note: The adoption costs for improved pearl millet and cowpea varieties are based on a seeding rate of 5 kilograms per hectare for sorghum, 40 kilograms per hectare for cowpea, and 100 kilograms per hectare for groundnut (in shell). It is assumed that improved varieties are available for twice their output price. Output prices are taken from FAO Corporate Statistical Database (FAOSTAT; FAO 2012b). The microdosing application focuses on phosphorus and is equivalent to using 15 kilograms of Diammonium Phosphate (DAP) per hectare plus increased labor costs of application. Stone bunding and planting pits are valued at an annualized cost equivalent to 300 kilograms per hectare of sorghum grain (ICRISAT 1985). It is assumed that the farm household invests in both rock bunding and planting pits.

area expansion is diminished. Although some of the most effective soil and water conservation practices are being practiced on a relatively limited scale, experience suggests that if they are actively promoted, farmers who try them are very likely to continue using them, unlike some other soil conservation practices, which have been abandoned by farmers soon after promotion efforts have ceased. Knowledge of what drove early adoption beginning in the 1980s, combined with today's improved ability to target extension efforts based on technical and socio-economic factors, provides a firm basis for further technology transfer. It seems reasonable to anticipate that 1–2 million hectares could be under improved soil and water conservation technologies in the Dry Semi-arid Zone by 2030.

Prospects for increased use of fertilizer in the Dry Semi-arid Zone are bright as well. In the future, fertilizer use and its intensity will increase in response to greater effective demand for output and lower input prices and greater availability of inputs, both conditioned by improved infrastructure that will lower transport costs. A major factor driving increased fertilizer use in the drylands will be microdosing. Microdosing fertilizer can stimulate fertilizer spread into areas where only moderate doses are profitable and labor is readily available for their application. Tens of thousands of farm households, mainly in West and Southern Africa, have already received training in microdosing fertilizer and have acquired experience with the practice. A comprehensive assessment of the uptake of microdosing is not available at this time, but success stories in the form of sustainable adoption have been reported in several locations (Winter-Nelson and Mazvimavi 2014). By 2030, 1.5–5.0 million hectares seems like a plausible range for area coverage for microdosing fertilizer.

Prospects for widespread diffusion in the Dry Semi-arid Zone of improved varieties of the major crops are mixed. On the one hand, uptake of improved varieties has been more extensive in the Dry Semi-arid Zone than in the Arid Zone. For example, adoption of improved sorghum cultivars in Sudan was estimated at 40 percent nationally in 2010. But on the other hand, improved varieties in few other major crops cultivated in the Dry Semi-Arid zones approach the level of farmer acceptance as sorghum in Sudan. Even worse, initial progress made beginning in the late 1990s to scale up the most promising improved sorghum varieties in northern Nigeria has been eroded, as considerable numbers of farmers have since stopped growing the improved varieties. Given this setback, 40 percent seems like a formidable but attainable target for the level of improved varietal adoption by 2030.

By 2030, Bt cowpea that is endowed with resistance to pod-boring pests should be feasible. Pest resistance is more desirable in cowpea than in any other major field crop produced in the drylands.

The five most promising technologies for the Dry Semi-arid Zone are shown in table 8.2, along with the area within the Dry Semi-arid Zone over which each of the technologies is likely to have been adopted by 2030, as well as the likely adoption cost. Comparing the cost estimates in tables 8.1 and 8.2, it is apparent that adoption costs in the Dry Semi-arid Zone (in the range of US\$20–50 per

hectare) are generally much higher than the adoption costs in the Arid Zone (in the range of US\$1–20 per hectare), reflecting the much higher expected profitability of the top-ranked technologies in the Dry Semi-arid Zone, which justifies higher investments on the part of farmers.

Prospects in the Wet Semi-arid Zone

Matlon (1990) correctly recognized that the payoffs to yield-increasing and labor-saving technologies are substantially greater in the Wet Semi-arid Zone than in the Arid Zone and the Dry Semi-arid Zone, due to the higher yield potential. For this reason, improved technologies in general are likely to be more attractive in the Wet Semi-arid Zone. More specifically, yield-increasing technologies are more likely to be accepted in areas of land scarcity, and labor-saving technologies are more likely to become popular in sub-regions of land abundance.

The technologies identified by Matlon as having most promise in the Wet Semi-arid Zone included a number of yield-increasing technologies, especially those involving the application of moderate doses of fertilizer with recurrent applications of organic matter in the form of manure. Matlon argued that practices to improve soil fertility, particularly when combined with input-responsive varieties and run-off land management systems, could generate large and sustainable productivity increases and that they were likely to find ready acceptance in sub-regions of rapidly increasing population density. Interestingly, Matlon did not foresee the development and diffusion of fertilizer microdosing and *amenagement en courbes de niveau*. Still, these two yield-increasing technologies are very congruent with Matlon's description of technologies that are likely to be feasible and desirable in the Wet Semi-arid Zones.

Matlon's analysis of the prospects for labor-saving technologies centered on herbicides, tractorization, and animal traction. His assessment showed considerably more optimism for animal traction than for either herbicides or tractorization. Matlon's conclusions continue to be relevant today, and according to the assessment carried out for this book will continue to be valid through 2030 for the Wet Semi-arid Zones. However, use of herbicides in dryland regions of Sub-Saharan Africa is becoming more pervasive in some countries, such as Ghana, but the intensity of tractors is stagnant, at less than 1 per 1,000 hectares of area harvested for Sub-Saharan Africa as a whole (Fuglie and Rada 2013). In contrast, numbers of cattle, which provide the source of power for most animal traction-related technologies, have more than doubled over the past 50 years. As noted earlier, cattle density is higher in the Wet Semi-arid Zone than in the other dryland zones.

The assessment done for this book broadly supports Matlon's analysis of the prospects for technological change in the Wet Semi-arid Zone, but it differs in the sense of attributing greater potential to improved cultivars. A number of maize varieties and hybrids developed since Matlon carried out his assessment are showing tremendous potential for adoption in the Wet Semi-arid Zone by

2030. Between 2007 and 2013, more than 140 drought-tolerant maize cultivars were released by the 13 national programs participating in the Drought Tolerant Maize in Africa Initiative being led by International Maize and Wheat Improvement Center (CIMMYT) and International Institute of Tropical Agriculture (IITA).¹ About one-half of these cultivars are targeted to the Dry Semi-arid Zone, and the other one-half are targeted to the Wet Semi-arid Zone. In addition to tolerating drought, some of these cultivars are also resistant to Striga.

Other new input-responsive cereal cultivars that are well-adapted to the Wet Semi-arid Zone include Guinea sorghum hybrids and more than 100 drought-tolerant maize varieties and hybrids that have been released since 2000. By 2030, these materials are expected to have spread to one-quarter of sorghum-growing area and one-third of maize-producing area, resulting in adoption rates approaching 45 percent for sorghum and 70 percent for maize in the Wet Semi-arid Zone. Establishment of a hybrid seed industry in West Africa would provide additional stimulus to the generation and diffusion of input-responsive hybrids in both crops.

The projected diffusion of improved cultivars in the Wet Semi-arid Zone augurs well for the use of fertilizer. As farmers become more aware of the synergies between modern cultivars and improved soil fertility, use of fertilizer is likely to increase, rising over time well above the low application levels associated with microdosing. Maize should be the major beneficiary in this deepening of input use on several million hectares in the Wet Semi-arid Zone.

The assessment done for this book is optimistic about the future of land management technologies in the Wet Semi-arid Zone, but perhaps not as optimistic as Matlon was in 1990. The main benefit of ridge tillage is to decrease run-off, thus setting the stage for enhanced fertilizer response. Still, the spread of ridge tillage in the drylands of Sub-Saharan Africa is poorly documented, particularly on soils susceptible to crusting, where the technology can deliver the greatest benefits. Unlike microdosing, successful adoption of ridge-tillage techniques requires considerable interaction between farmers and extension agents with specialized knowledge to address location-specific field conditions. Scaling up is not readily accomplished with generic protocols. For that reason, extension of ridge tillage to only 1–3 million hectares by 2030 seems like a reasonable expectation.

What can be said today about the prospects for animal traction? In 1990, Matlon estimated that animal traction was practiced on 15 percent of land area cultivated to millet and sorghum in West Africa. He stressed that the provision of weeding equipment with animal traction enhances the potential for both area expansion and yield growth. Since Matlon carried out his assessment, use of animal traction has increased in many dryland tracts in selected countries in East and West Africa. Estimates vary substantially by sub-regions within countries, however, ranging from negligible to almost full adoption (Goe 1988). The assessment carried out for this book suggested that animal traction has bright prospects

Table 8.3 Most Promising Crop Productivity Improvement Technologies for Wet Semi-arid Zones, 2030

Rank	Intervention	Characteristics	Cost (US\$/ha)	Basis for Expected Area
1	Maize varieties and hybrids	Drought tolerance and/or Striga resistance	5–20	CIMMYT and IITA (2011)
2	Input intensification	Inorganic fertilizer	100	
3	Mechanization	Animal traction	60	
4	Sorghum hybrids	New hybrids from well-adapted Guinean landraces	3	ICRISAT and ICARDA (2012)
5	Land management	Ridge tillage (ACN) on soils susceptible to crusting	15–20	USAID (2013) and Doumbia et al. (2008)

Note: The adoption costs for maize varieties and hybrids are based on a seed rate of 25 kilograms per hectare. It is assumed that improved varieties are available for twice their output price and hybrids for four times their output price. Output prices are taken from FAO Corporate Statistical Database (FAOSTAT; FAO 2012b). Animal traction expenses are measured from the perspective of annualized or rental costs in employing oxen in plowing and weeding. Inorganic fertilizer is defined as using 200 kilograms per hectare of 15:15:15, one of the most common blends in West Africa. The cost of ridge tillage is annualized and includes expenses in maintaining permanent ridges.

ACN = *Aménagement en courbes de niveau*.

in the Wet Semi-arid Zone, and adoption is likely to accelerate in future (Starkey 2000). For purposes of the umbrella modeling exercise, it is projected that by 2030 use of animal traction will spread to an additional 3 million hectares. This estimate needs to be confirmed with large-scale, nationally representative survey information. Updating Goe's 1988 inventory of draft animals would be a good starting point.

The five technologies deemed most promising for the Wet Semi-arid Zone are shown in table 8.3, along with the area over which each of the technologies is likely to have been adopted by 2030, as well as the likely adoption cost. Similar to the adoption cost estimates presented in table 8.2 for the Dry Semi-arid Zone, adoption costs in the Wet Semi-arid Zone (in the range of US\$5–100 per hectare) are again much higher than the adoption costs in the Arid Zone (in the range of US\$1–20 per hectare), reflecting the much higher expected profitability of the top-ranked technologies in the Dry Semi-arid Zone, which justifies higher investments on the part of farmers.

Prospects in the Dry Sub-humid Zone

Because the Dry Sub-humid Zone is geographically diverse and characterized by tremendous within-region heterogeneity, assessing prospects for technological change in this zone is difficult. Based on the results of his ex-ante technology assessment, Matlon (1990) concluded that the prospects for the Dry Sub-humid Zone are very similar to those for the Semi-arid Zone and revolve around yield-increasing and labor-saving technologies. That said, because the agro-climatic conditions in the Dry Sub-humid Zone are different and because the cropping systems are not the same, the challenges and the opportunities differ in some respects. For example, because rainfall is relatively abundant in the Dry Sub-humid Zone and because maize is the dominant crop, when considering the traits

needed in improved cultivars to increase yields, input-responsiveness in maize is much more important than drought-tolerance in pearl millet, sorghum, and maize. Hybrids are preferred to varieties for their input-responsiveness.

Matlon saw greater scope for area expansion in the Dry Sub-humid Zone than in the Semi-arid Zone because the longer growing season allowed the planting period to be extended by several weeks. Extension of the planting period would allow more area planted using animal traction. Animal traction allows cultivation of heavier soils in low-lying areas of the toposequence, and since these heavier soils are often highly fertile, the impacts on productivity could be significant.

Matlon singled out herbicide as the perhaps the most promising labor-saving technology. He predicted that herbicide would be used increasingly as a single component, in areas where the benefit-cost calculus made it attractive.

Matlon did not consider conservation agriculture. When he wrote of biomass recycling, he was referring to the need for more integrated mixed farming systems to maintain soil quality under continuous cultivation. More specifically, *“Animal drawn carts will become increasingly important as a means to overcome labor constraints in the harvest of crop residues for animal feed and in the distribution of organic matter over farmers’ fields”* (Matlon 1990, 31).

The assessment done for this book broadly supports Matlon’s analysis of the prospects for technological change in the Dry Sub-humid Zone, although it includes several technologies that Matlon did not contemplate. With respect to improved germplasm, there is no doubt that input-responsive, drought-tolerant maize cultivars—both varieties and hybrids—have tremendous potential to deliver significant productivity gains. Additional productivity gains are likely to come from improved groundnut varieties, which have already registered considerable success in the Dry Sub-humid Zone in Malawi, Nigeria, and Uganda. New groundnut cultivars combine disease resistance with a certain amount of drought tolerance. In addition, as improved maize cultivars continue to diffuse in the Dry Sub-humid Zone, intercropping with grain legumes that more fully exploit a longer dryland growing season should become more prevalent. Fueled by the strong export demand for pigeonpea from East and Southern Africa to India, maize row-intercropped with pigeonpea is increasingly visible in national survey data. Maize/pigeonpea could easily account for 1.5–2.0 million hectares by 2030 in Sub-Saharan Africa.

New crops are also more likely to emerge in the Dry Sub-humid Zone than in the other dryland zones. Soybean is the strongest candidate at this time to take advantage of the heavier rainfall afforded by the Dry Sub-humid Zone. Soybean is no longer a novelty in many countries where it has gained a foothold, although the pace of expansion has been slow.

The productivity gains from improved germplasm are likely to be complemented by productivity gains from improved crop management technologies. Conservation agriculture would appear to hold considerable promise in the Dry Sub-humid Zone, because the relatively high amounts of rainfall in that zone and the low livestock density mean that more biomass is produced and that the opportunity cost of using that biomass for mulching and residue incorporation is lower.

Nonetheless, the prospects for conservation agriculture being taken up in manual cultivation systems do not seem bright, because conservation agriculture is too labor- and knowledge-intensive. Formally, carrying out minimum tillage on land that is already minimally tilled seems to defeat the purpose of the technology.

In East and Southern Africa, where conservation agriculture has a longer history, the area currently being farmed using conservation agriculture practices is estimated at about 600,000 hectares (Wall et al. 2013). About two-thirds of this area is in South Africa, concentrated in regions where large-scale mechanized commercial farming is predominant. Mechanization was a major driver of conservation agriculture in Zimbabwe and South Africa beginning in the 1970s and 1980s. Aside from Zimbabwe and South Africa, adoption of conservation agriculture has not exceeded 20,000 hectares in any other country. By 2030, it is reasonable to expect that conservation agriculture practices will have spread to cover 1–2 million hectares in the Dry Sub-humid Zone, significantly more than today, but still relatively modest considering the large size of the Dry Sub-humid Zone. Eventually, conservation agriculture will make inroads into the drylands of Sub-Saharan Africa, but diffusion is likely to be slow, and the impacts by 2030 will be relatively modest. As in Brazil, where large farmers in Rio Grande do Sul drove the adaptation process in the Cerrado, it may be large commercial, mechanized farmers from the South—in this case South Africa—who play a prominent role in popularizing conservation agriculture throughout the continent.

The five technologies deemed most promising for the Dry Sub-humid Zone are shown in table 8.4, along with the area over which each of the technologies is likely to have been adopted by 2030, as well as the likely adoption cost. Once again, adoption costs in Dry Sub-humid Zone (in the range of US\$10–70 per hectare) are relatively high, reflecting the much higher expected profitability of the top-ranked technologies in the Dry Sub-humid Zone, which justifies higher investments on the part of farmers.

Table 8.4 Most Promising Crop Productivity Improvement Technologies for Dry Sub-humid Zones, 2030

<i>Rank</i>	<i>Intervention</i>	<i>Characteristics</i>	<i>Cost (US\$/ha)</i>	<i>Basis for Expected Area</i>
1	Maize hybrids	Input responsiveness with some drought tolerance	5–20	CIMMYT and IITA (2011)
2	Groundnut varieties	Disease resistance with some drought tolerance	70	ICRISAT and ICARDA (2012)
3	Introduction of inputs	Herbicides	20	CIMMYT and IITA (2011)
4	Cropping systems	New intercropping and sequential cropping systems	>10	ICRISAT and ICARDA (2012)
5	Conservation agriculture	Mulching and crop residue-based management	50	Wall et al. (2013)

Note: The adoption cost for improved maize and groundnut cultivars are based on a seed rate of 25 kilograms per hectare for maize and 100 kilograms per hectare for groundnut (in shell). It is assumed that improved varieties are available for twice their output price and hybrids for four times their output price. Output prices are taken from FAOSTAT (FAO 2012b). The costs of CA are calculated by assuming the rental of a ripper and an increase in the use of labor with herbicide and some additional fertilizer. CA = Conservation agriculture; FAOSTAT = FAO Corporate Statistical Database.

Research and Technology Transfer Costs

This section discusses the size of research and extension investments needed to make the 20 technologies described in tables 8.1, 8.2, 8.3 and 8.4 a reality in reducing vulnerability and enhancing resilience. As mentioned in the introduction to this chapter, the adoption cost estimates were needed for use as inputs into the “umbrella modeling” exercise described in the main Africa Drylands study. As also mentioned in the introduction, the cost estimates are order-of-magnitude “guesstimates,” because in real life research and extension activities frequently have multiple overlapping objectives, so it is seldom possible to assign costs cleanly to individual, well-defined technologies. To further complicate matters, cost data are rarely reported in the literature, so they must be based on partial information and expert opinion. In spite of their subjective and somewhat fragmented nature, the back-of-the-envelope adoption cost estimates discussed below are believed to reflect reasonably accurately the size, both absolute and relative, of the investments that will be needed to fine-tune the 20 identified most promising technologies and promote their adoption in the four aridity zones.

Ten of the technologies listed in table 8.5 are already available for technology transfer. Although many would benefit from more systematic and comprehensive evaluation to allow fine-tuning of the recommendation domains in which they can be expected to be most effective, all of the technologies are far along in the development pipeline and do not need major additional research investment.

The other 10 technologies listed in table 8.5 are judged to be well advanced in terms of development but will often require additional research to adapt them to local circumstances. Many consist of improved germplasm, and while improved germplasm already exists that performs well in specific locations, additional research will be needed to develop additional varieties and hybrids showing good adaptation to local conditions. The improved germplasm technologies are divided into two groups: (1) improved varieties of pearl millet, sorghum, groundnut, and cowpea; and (2) pearl millet, sorghum, and maize hybrids in West Africa. The former will require relatively modest additional research investment, as reflected in the estimates appearing in table 8.5. The latter will require more significant investments, including from the public sector, which will need to kick-start the still-nascent industry for cereal hybrids in West Africa. Public investment in the development of hybrids will need to be complemented by policy reforms to increase the attractiveness of developing and selling commercial hybrids. As an example of these policy reforms, governments need to relinquish their monopoly in the production of breeders’ seed as one of their initial concessions to incentivize private sector participation in seed production.

Several crop management technologies are also singled out in table 8.5 as requiring additional research investment, including animal traction, herbicides, and conservation agriculture. The state of knowledge about animal traction in dryland regions of Sub-Saharan Africa remains fragmented and incomplete. Very

little research attention has been focused on empirical evaluation in farmers' fields of the performance of animal traction technologies, and even anecdotal evidence is sparse. Casual observation suggests that attempts by NGOs to introduce draft power in the drylands (usually from oxen) are often not sustainable, as the animals arrive at the butcher's shop when the project closes. Much more was known about animal traction in Sub-Saharan Africa in the 1980s than in the early 2000s.

Likewise, conservation agriculture technologies require fine-tuning to make them optimally attractive in dryland zones. Farmer participatory research could be extremely helpful in this respect, as has been conclusively demonstrated in other continents. The challenge for scientists and proponents of conservation agriculture is the same as in any other research area contributing to agricultural development in the drylands: to identify relevant utility-enhancing options that, given an enabling environment, are likely to spread autonomously from farmer to farmer (Erenstein 1999).

One can only hope that efforts to promote the uptake of conservation agriculture in dryland regions of Sub-Saharan Africa will avoid many of the mistakes and weaknesses that plagued watershed development schemes in India, which were the primary vehicle for promoting dryland agricultural development in the late twentieth century. In India's drylands, integrated watershed development became a mantra, mindset, or philosophy for agricultural development, but the performance of integrated watershed development initiatives only rarely lived up to expectations (Kerr 2002). Integrated watershed development initiatives did have some important and lasting impacts, such as planting across the slope, which today is one of the most popular and widely accepted practices used by Indian dryland farmers. But an integrated watershed development project is not a cost-effective mechanism for promoting a practice as simple as planting across the slope. Pragmatism has been and is still a scarce commodity in research on land and water management in dryland agriculture.

Extension cost estimates are highly sensitive to the assumptions made about fixed costs, especially the cost of extension agents. If every extension agent (or team of extension agents) is responsible for promoting a new technology in a very small area, the fixed cost per hectare of adoption will be high. But if every extension agent (or team of extension agents) is responsible for promoting a new technology in a very large area, the fixed cost per hectare of adoption will be low. The extension costs estimates presented in table 8.5 were derived by assuming that each technology is promoted on at least 100,000 hectares. Extension costs thus were estimated for a 100,000 hectare adoption area and then converted to cost per hectare to facilitate their use in the umbrella modeling exercise.

Generally speaking, the adoption cost estimates presented in tables 8.1, 8.2, 8.3 and 8.4 are correlated to the extension cost estimates appearing in table 8.5. Technologies that deliver larger benefits to farmers justify greater extension effort and greater investment in adoption costs. For some higher-cost, indivisible technologies, such as animal traction, it is difficult to structure a technology

Table 8.5 Perceived Research and Extension Costs by Technology Options

<i>Technology Option</i>	<i>Major Dryland Recommendation Domains</i>	<i>Available?</i>	<i>R&D Costs (US\$ million per Annum 2015–2019)</i>	<i>Extension Costs (US\$ million per 100,000 ha)</i>
Natural regenerative forestry in West Africa	Arid and Dry Semi-arid	Available		0.25 ^d
Improved short-duration, heat-tolerant pearl millet varieties	Arid	Partially available	3.5 ^a	0.125 ^e
Downy mildew-resistant pearl millet hybrids	Dry Semi-arid	Under development	3.5 ^a	2.0 ^f
Seed priming and treatment for pearl millet with TM Apron	Arid and Dry Semi-arid	Available		0.25 ^g
Improved drought- and low phosphorus-tolerant cowpea varieties	Arid and Dry Semi-arid	Partially available	1.25 ^a	0.50 ^e
Improved Striga-resistant sorghum varieties developed with MAS	Dry Semi-arid and Arid	Available		0.150 ^e
Microdosing fertilizer	Dry and Wet Semi-arid	Available		2.0–3.0 ^h
Drought-tolerant and insect-resistant cowpea varieties	Dry Semi-arid	Under development	1.25 ^a	
Land management and soil conservation practices: rock bunding and/or planting pits (<i>zai</i>)	Dry Semi-arid	Available		20.0 ⁱ
New short-duration groundnut varieties that escape drought	Dry Semi-arid	Under development	5.0 ^a	
Drought-tolerant and Striga-resistant maize varieties and hybrids	Wet Semi-arid	Available		0.155 ^e
Intensified use of inorganic fertilizer	Wet Semi-arid and Dry Sub-humid	Available		10.0 ^j
Animal traction for plowing and weeding	Wet Semi-arid and Dry Sub-humid	Available	5	
Sorghum hybrids from well-adapted Guinean landraces	Wet Semi-arid	Mostly available	5.0 ^{a,b}	2.0 ^f
Ridge tillage	Wet Semi-arid	Available		3.0 ^k
Input-responsive maize hybrids	Dry Sub-humid and Wet Semi-arid	Available	5.0 ^b	2.0 ^f
Disease-resistant groundnut varieties with some drought tolerance	Dry Sub-humid and Wet Semi-arid	Mostly available	2.0 ^a	1.75 ^e
Application of pre-/post-emergent herbicides	Dry Sub-humid	Under development	2.0 ^c	
New intercropping and sequential cropping systems	Dry Sub-humid and Wet Semi-arid	Available		0.55 ^l
Conservation agriculture with fertilizer and herbicide	Dry Sub-humid and Wet Semi-arid	Under development	10.0 ^c	

table continues next page

Table 8.5 Perceived Research and Extension Costs by Technology Options (*continued*)

Note: MAS = Marker-assisted selection; CA = Conservation agriculture.

- a. Additional expenditures on research are based on table 2.3 in Walker et al. (2014). The research cost per technology reflects the deficit in allocation between actual expenditure and a desirable allocation assuming that 1 percent of crop value of production should be committed to agricultural research. Pearl millet, groundnut, and sorghum are characterized by low research intensities and large deficits.
- b. Includes expenditures for the establishment of a hybrid seed industry in West Africa that features public and private sector partnerships.
- c. Derived from CIMMYT and IITA 2011; however, the assigned research amounts especially for CA is founded on slower than expected progress, the size of the task, the importance of research in soil fertility on dryland agriculture, and the need to invest in farmer participatory research.
- d. Farmer managed natural regeneration (FMNR) is a simple technology that has been called self-promoting. In Niger, funds for its dissemination came from food-for-work projects in response to the 1984 drought. Estimates of extension costs are not available in the literature; however, its rapid spread over the past three decades suggests that a heavy investment in extension is not needed to transfer the technology, which is predicated on having living stumps in farmers' fields. It is assumed that 40 extension agents would easily be capable of imparting knowledge on FMNR to 25,000 farmers in a three-year period during a seasonal four-month extension program.
- e. Assumes a seed bank model for extension of improved varieties. The project's time horizon is three years with a goal of realizing enough seed for farmers to plant an area of 100,000 ha at the end of the project. Beneficiaries are selected each year by extension agents and given small quantities of seed of improved varieties. In the next year, they have to repay twice what they were allocated in the previous year. It is assumed that 10–50 percent of production (depending on the subsistence orientation of the crop) is retained for seed for sowing in the next year. Extension agents can annually cover 120 farmers per cropping season, with work concentrated in the planting and harvesting periods. Costs include salaries of extension staff, per diems and transport, and training. Multiplication ratios for groundnut are assumed to be 15:1, for cowpea 30:1, for pearl millet 250:1, and for sorghum 225:1. Seed rates are 100 kilograms per hectare in shell for groundnut, 40 kilograms per hectare for cowpea, 25 kilograms per hectare for pearl millet, and 5 kilograms per hectare for sorghum.
- f. Extension costs are borne directly by the private sector and are not included. The amounts in table 8.5 refer to development costs for reestablishing a hybrid seed industry in three countries in West Africa. Expenditures focus on irrigation facilities for hybrid production, training of farmers' associations, and infrastructure for hybrid development and production.
- g. Extension costs are estimated to be twice the expenditure of a village seed bank for improved short-duration pearl millet varieties listed as the second technology in this table. Although seed priming and seed treatment are simple and very cost-effective technologies, their extension costs would be somewhat higher than technology transfer that focuses solely on varietal introduction. The increasing cost is attributed to heightened seasonality in the demand for extension information during the sowing period.
- h. Estimates are constructed from Tabo et al. (2007), who describe a large piloting program with an array of extension partners in Burkina Faso, Mali, and Niger in two cropping seasons using farmer-managed trials and demonstrations as the modalities for technology transfer. This effort resulted in 12,650 beneficiaries from over 2,000 trials and demonstrations. These results are extrapolated to 50,000 beneficiaries who on average cultivate 2.0 hectare of cereals. A total of about 8,000 trials and demonstrations are needed in about 1,500 villages over three cropping years. Diammonium phosphate (DAP) equivalent to 20 kilograms per hectare is the microdosing recommendation.
- i. Taken from an interim assessment of a large International Fund for Agricultural Development (IFAD) program on soil conservation and agroforestry in central Burkina Faso (IFAD 2004). Depending on how the calculation was carried out, the estimate for soil conservation works varied from slightly under US\$100 to slightly over US\$300 per hectare.
- j. Assumes a voucher program similar to the National Agricultural Input Voucher Scheme in Tanzania. Households without a history of commercial fertilizer use in higher production potential zones are subsidized up to 50 percent of the value of recommended fertilizer for 0.5 hectares for three years. Administrative costs are reckoned to be 25 percent of the total cost of the program. The fertilizer recommendation is listed in table 8.2 for the Wet Semi-arid Zone.
- k. Assumes a trained extension technician interacts with farmers and surveys fields to establish permanent ridges. All the field costs are borne by the farmer, who has access to animal traction on a field-size of 2–3 hectare. The farmer forms the ridges by five to six passes with a plow prior to planting. Thereafter, farmers are responsible for maintenance of the ridges. Each extension technician can interact with two farmers per day during a four-month period. Costs include salaries of extension staff, per diems and transport, and training. The above costs of ridge design-trained extension specialists are doubled to make farmers aware of the technology, to program implementation in an effective manner, and to cover indirect costs.
- l. Specified for maize/pigeonpea intercrops now emerging in East and Southern Africa. The format is the same as (e) above with additional costs allocated to training on alternate row planting versus planting maize and pigeonpea in the same row. New medium-duration pigeonpea varieties drive the adoption process. The seed rate is assumed to be 10 kilograms per hectare and the multiplication ratio is 75:1.

transfer program that will result in direct adoption; therefore, similar to the other technologies assigned research allocations in table 8.5, order-of-magnitude estimates are not made for animal traction.

Extension costs borne by the public sector increase when technologies are promoted with the help of subsidies. The extension schemes described in the notes to table 8.5 provide a modicum of subsidy in most cases. They respect the notion that subsidies should be kept to a minimum because subsidized institutional demand distorts private sector incentives for investment in seed development and production. Moreover, copayments by farmers are desirable because they reflect demand for the technology. Farmers are more likely to maintain unsubsidized soil conservation works than subsidized structures.

Extension costs were estimated differently for three groups of technologies: (1) improved varieties of cowpea, groundnut, maize, pearl millet, and sorghum; (2) cereal hybrids in West Africa; and (3) fertilizer and land management technologies. Many extension methods are available for the transfer of improved varieties. The generic scheme used here involves the use of a village seed bank featuring the repayment of “starter” seed. It is patterned after transfer of an improved groundnut variety, CG 7, in Malawi in 1999 (Subrahmanyam et al. 2000), and is one of the popular methods used to transfer improved germplasm in dryland agriculture in Sub-Saharan Africa (Moses Siambi, personal communication 2014).

Demand for seed is reflected in a higher sales price for starter seed of new materials than the output price of the same commodity prevailing in the market. Shortly after the pearl millet variety SOSAT C-88 was released in Nigeria in January 2000, the early seed multipliers sold their output at six times the farm gate price for millet (ICRISAT 2000). As discussed earlier in this assessment, SOSAT C-88 was the most extensively grown improved cereal variety in Sub-Saharan Africa by 2010, with an area approaching 1 million hectares. The community seed bank furnishes current and reliable information on the prospects for the variety over time so that the technology transfer effort can be restructured in response to emerging information on cultivar-specific market prices. Higher prices for introduced materials suggest positive gains for continuing technology transfer and greater scope for spontaneous adoption.

The estimated extension costs associated with the promotion of improved varieties range from US\$0.125 million in pearl millet to US\$1.75 million in groundnut. The difference stems from differences in seeding rates and seed multiplication ratios. The extension cost estimates are very reasonable, suggesting that with the exception of groundnut, promoting improved varieties should be eminently feasible in dryland zones. The lower end of the range of extension cost estimates presented in table 8.5 represents promotion of seed via emergency relief programs, which have frequently financed the distribution of seed of improved varieties in the drylands (Varma and Winslow 2004). In fact it is difficult to name a single country in the drylands of Sub-Saharan Africa that has not benefited from a varietal diffusion initiative funded via emergency relief. In such

initiatives, where the focus is usually on getting seed to vulnerable populations very quickly, it is important that attention be paid to ensuring not only the quantity but also the quality of seed (ICRISAT 2002). To the extent possible, modern varieties should figure prominently in such initiatives, which should be structured to strengthen and not bypass existing seed distribution systems.

The other costs listed in table 8.5 that are associated with the promotion of improved varieties represent expenses associated with development of infrastructure needed for the production of cereal hybrids in West Africa. The estimate of US\$2 million is only a guesstimate of the amount of funding needed to support the emergence of a private sector-led hybrid seed industry in West Africa. Institutionally, funds could be targeted to a regional seed production and distribution network of multiple partners for execution of small infrastructure projects in select West African countries where the enabling environment and demand for private sector seed production is perceived to be improving and growing.

The estimated extension costs of dryland crop and land management technologies range from about US\$0.25 million for seed treatment in pearl millet to about US\$20 million for stone bunding. Stone bunding is the only technology that is in the cost interval of several hundred dollars per hectare.

Given the imperative of responding to drought in the Sahel and the Horn of Africa, microdosing phosphorus and seed treatment of pearl millet are perceived to be the most bankable prospects. Although little or no effort has been made to date to promote these technologies on a large scale, a solid foundation of verified results suggests that such an initiative would have significant payoffs.

Note

1. See <http://dtma.cimmyt.org/index.php/varieties/dt-maize-varieties>

Summary and Conclusions

This book has presented the main findings and conclusions of an effort to assess opportunities for improving crop productivity in dryland regions of Sub-Saharan Africa, with an eye on improving the capacity of farming households to manage drought. Some technologies, such as earlier maturing crop varieties, may be less sensitive to moderate drought events, allowing households who grow those varieties to maintain production and safeguard household food security in the face of water deficits occurring near the end of the growing-season. Other technologies, such as judicious use of phosphorus fertilizer, may directly enhance production without significantly increasing income variability for the household. Technologies that both reduce risk and enhance profitability in smallholder production circumstances are prized and highly desirable in the drylands.

The fact that agricultural productivity in Sub-Saharan Africa was practically stagnant during the 1970s and has grown only modestly since the mid-1980s suggests that yield-enhancing, risk-reducing technologies have not been available to many African smallholder households. Even when new technologies have been introduced, often it has been difficult to determine their usefulness, because in an environment characterized by frequent droughts, generally poor soil, and widespread micro-variation, it is difficult to assess with accuracy the impacts of technological change. For that reason, any effort to forecast the diffusion and impacts of prospective technologies is fraught with uncertainty.

In spite of these difficulties, there are grounds for optimism that the pace of crop productivity growth in the drylands will be able to match or even exceed the trend in the recent past.

The diffusion of improved cultivars is more comprehensively documented than the diffusion of other technological innovations, and the impacts on productivity are better understood. By 2010, about 35 percent of the area planted to food crops throughout all of Sub-Saharan Africa was planted to modern varieties. Across the most important 20 food crops, about 3,600 improved varieties have been released in Africa since 1970; of these, over 1,000 were being grown in farmers' fields in 2010. With the exception of banana, yams, and rice, much if not most of the diffusion of improved varieties took place in the drylands. The

growth of modern variety adoption between 1998 and 2010 was equivalent to an annual linear increase of 1.45 percent. Adoption of modern varieties accounted for about 30 percent of productivity growth related to technological change in Sub-Saharan Africa since 1980.

Ten of the 20 technologies identified in this report as holding the most promise for the drylands are improved varieties and/or hybrids. In the Arid Zone, the most promising technologies include short-duration, heat-tolerant pearl millet varieties and hybrids, as well as drought-tolerant cowpea varieties that are able to tolerate the low phosphorus soils commonly found in that zone. In the Dry Semi-arid Zone, the most promising technologies include sorghum varieties with *Striga* resistance, cowpea varieties with drought tolerance and insect resistance, and short-duration groundnut varieties. In the Wet Semi-arid Zone, the most promising technologies include drought-tolerant and/or *Striga*-resistant maize varieties and hybrids, along with new sorghum hybrids developed from well-adapted Guinean landraces. In the Dry Sub-humid Zone, the most promising technologies include input-responsive maize hybrids and disease-resistant groundnut varieties.

Prospects for varietal change would be brighter if governments, especially those in West Africa, were investing more in crop improvement research targeting cowpea, groundnut, pearl millet, and sorghum. Proportional to the value of production, varietal output in these four important crops has lagged behind varietal output in maize, largely because of the extremely low level of research investment.

Another serious constraint that has limited the availability in West Africa of well-adapted improved cultivars of the leading staples is the extremely limited engagement of the private sector in adaptive research and seed multiplication. As experiences in the drylands of India and Southern Africa have shown, a thriving hybrid seed industry driven by public-private partnerships can offer farmers a range of cultivars adapted to more local agro-climatic conditions and market needs.

Political economy factors have also influenced the rate of technology diffusion in the drylands. Cowpea is widely cultivated in a number of African countries, including on several million hectares in Niger alone. Slow progress in the development of transgenic Bt cowpea has imposed a substantial cost on the many poor rural households that grow cowpeas. Globally, resistance to transgenically-mediated technological change continues in some circles, and that resistance has spilled over into Africa. Without the insect resistance conferred by the Bt technology, farmers who grow cowpea must rely on expensive, environmentally harmful insecticides in order to avoid losing a significant portion of their production, especially in years of adequate rainfall.

Improved crop management technologies, defined broadly in this book to include the introduction of trees into cropping systems and the use of mechanization, similarly have a mixed adoption record in the drylands. To be effective, many improved crop management technologies require local adaptation

combined with accurate targeting. The 20 technologies identified in this report as holding the most promise for the drylands include several crop management-related technologies, for example farmer-managed natural regeneration of trees, a technology that is now pervasive in the Arid Zone, where it continues to expand. Seed priming and low-cost seed treatments also have good prospects in the harsh production circumstances of the Arid Zone. In wetter zones, the most promising technologies include intensifying fertilizer use (especially through microdosing), applying herbicide, plowing with animal traction, intercropping cereals with grain legume, and investing in conservation agriculture (featuring mulching and residue-based management).

Among the promising crop-management technologies, conservation agriculture is undoubtedly the most controversial. The practices associated with conservation agriculture require considerable fine-tuning by participating farmers, who also need to have access to inorganic fertilizers and herbicides. Unless ways can be found of increasing production of biomass for residue management and decreasing seasonal labor use, conservation agriculture practices, if adopted, may be confined to a restricted area.

Several of the promising land and water management practices described in this report have had a checkered history in terms of their acceptance by farmers in dryland regions of Africa. Despite years of promotions, water harvesting, tied ridging, and contour bunding have not diffused widely. In contrast, rock bunding combined with the use of planting pits (*zai*) in the Dry Semi-arid Zone, and ridge tillage on soils susceptible to crusting in the Wet Semi-arid Zone are proven and widely accepted technologies that have tremendous potential for further expansion.

Prospects for crop insurance to contribute to improved crop productivity in the drylands are mixed. Participation in an efficient crop insurance scheme could be a boon to household risk management and could stimulate the adoption of more costly agricultural technologies, but the experience with pilot initiatives suggests that a viable, cost-effective yield or rainfall insurance program remains an unattainable goal. In particular, credit constraints, low financial literacy of farmers, and basis risk limit the demand for rainfall insurance.

The likely impacts of climate change on crop productivity in the drylands are difficult to predict with certainty, but recent modeling work suggests that the impacts, specifically of global warming, are likely to be relatively modest. Breeding for drought tolerance has always been a major component of international crop improvement programs, and breeding for heat tolerance, as well as agronomic research designed to identify practices to manage heat and drought stress, are viewed as relatively small departures from “business as usual.” As a result, the possibilities seem good that technical change will be able to keep pace with climate change, meaning that radical interventions to deal with the impacts of climate change will be needed only under highly specific circumstances.

Not surprisingly, prospects for achieving crop productivity gains are positively associated with agricultural potential, which in dryland regions of Sub-Saharan

Africa is determined mainly by growing-season rainfall. Prospects for improving productivity and increasing production are considerably brighter in the Wet Semi-arid and Dry Sub-humid Zones than in the Arid and Dry Semi-arid Zones. The higher payoffs generated by improved technologies in the more favorable zones justify higher levels of investment in research extension, and in adoption. Because it pays for farmers in the Wet Semi-arid and Dry Sub-humid Zones to invest more heavily in agriculture, they have a wider array of options to choose from than do farmers in the Arid and Dry Semi-arid Zones. Generally speaking, the emphasis in the two drier zones should be on managing risk and promoting resiliency, and the emphasis in the wetter zones should be on raising yields and increasing production.

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More than 200 million people living in dryland regions of Sub-Saharan Africa make their living from agriculture. Most are exposed to weather shocks, especially drought, that can decimate their incomes, destroy their assets, and plunge them into a poverty trap from which it is difficult to emerge. Their lack of resilience in the face of these shocks can be attributed in large part to the poor performance of agriculture on which their livelihood depends.

Opportunities exist to improve the fortunes of farming households in the drylands. Improved farming technologies that can increase and stabilize the production of millet, sorghum, maize, and other leading staples are available. Irrigation is technically and economically feasible in some areas and offers additional opportunities to increase and stabilize crop production, especially small-scale irrigation, which tends to be more affordable and easier to manage. Yet many of these opportunities have not been exploited on a large scale, for reasons that include lack of farmer knowledge, nonavailability of inputs, unfavorable price incentives, high levels of production risk, and high cost.

Future production growth in drylands agriculture is expected to come mainly from raising yields and increasing the number of crop rotations on land that is already being cultivated (intensification), rather than from bringing new land into cultivation (extensification). Controlling for rainfall, average yields in rainfed cropping systems in Sub-Saharan Africa are still much lower than yields in rainfed cropping systems in other regions, suggesting that there is considerable scope to intensify production in these systems. Furthermore, unlike in other regions, production of low-value cereals under irrigation is generally not economic in Sub-Saharan Africa unless the cereals can be grown in rotation with one or more high-value cash crops. The long-run strategy for drylands agriculture, therefore, must be to promote production of staples in rainfed systems and production of high-value cereals (for example, rice), horticultural crops, and industrial crops in irrigated systems.

Based on a detailed review of currently available technologies, *Improved Crop Productivity for Africa's Drylands* argues that improving the productivity and stability of agriculture in the drylands has the potential to make a significant contribution to reducing vulnerability and increasing resilience. At the same time, it is important to keep in mind that in an environment characterized by limited agro-climatic potential and subject to repeated shocks, farming on small land holdings may not generate sufficient income to bring people out of poverty.



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