Agricultural Systems

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Agroecology and Rural Innovation for Development

Second Edition

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Preface to the Second Edition

This book is intended for students of agricultural science, ecology, environmental sciences, and rural development, researchers and scientists in agricultural development agencies, and practitioners of agricultural development in government extension programs, development agencies, and NGOs. There is an emphasis on developing country situations, and on smallholder production systems.

This *second edition* has been significantly enhanced by the inclusion of two new chapters (on Sustainable Agricultural Intensification and Climate Change), and the updating of all chapters to reflect new evidence and new directions in agroecology and farming systems. Each chapter is written by experts in their topic, with both academic and field experience, providing a synthetic and holistic overview of agroecology applications to transforming farming systems and supporting rural innovation that include technical, social, economic, institutional, and political components.

The book is divided into four sections: the first section, *Reinventing Farming Systems*, introduces farming systems and the principles of agroecology, rural livelihoods, sustainable intensification, and sustainability. The second section, *Resources for Agricultural Development*, explores low-input technology, soil ecology, and nutrient flows, participatory plant breeding, and the role of livestock in farming systems. Section three, *Context for Sustainable Agricultural Development*, deepens understanding about inequalities in development (particularly gender inequality), the nature and spread of innovation in agriculture, supporting agriculture through outreach programs, and how agriculture is being, and will be, affected by climate change. The final section, *Tying It All Together*, takes a hard look at where we are now in terms of nutrition, wealth, and stability, and suggests a way forward. Rural innovation and building capacity to improve agricultural systems are themes interwoven throughout, which we hope that you enjoy learning about through this brand new edition of the book.

Chapter 1

Introduction

George Kanyama-Phiri, Kate Wellard, and Sieglinde Snapp

AGRICULTURAL SYSTEMS IN A CHANGING WORLD

Agriculture is the backbone of many developing economies. Despite rapid urbanization, agriculture continues to employ 65% of the work force in sub-Saharan Africa—70% of whom are female—and generates 32% of Africa's Gross Domestic Product (GDP) (AGRA, 2014; World Bank, n.d.). Agricultural systems are vital to tackling poverty and malnutrition. Over the past two decades, there has been marked progress in reducing global poverty, and yet, 900 million people struggle to live on less than US$1.90 per day, the majority living in sub-Saharan Africa and South Asia (World Bank, 2015). There were fewer undernourished people in 2015 compared to 25 years earlier: 795 million compared to 1.01 billion (FAO, 2015), but international hunger targets are far from being met. In sub-Saharan Africa almost one in four people are undernourished. Worldwide, 50 million children under 5 years are wasted, predominantly in South Asia, and 159 million are stunted, mainly in Africa and Asia (UNICEF, 2015).

Global agricultural performance has improved since 2000—one of the highest increases being in sub-Saharan Africa, where cereal production has grown annually by 3.3%. Cereal yields are increasing globally by an average of 2% per annum. This represents an increase of 70 kg/ha per year over the last decade in Latin America and Southeast Asia, to an average yield of 2800 kg/ha. In sub-Saharan Africa part of the increase is due to the increase in the area under cultivation so grain yields have increased more slowly, stagnating at around 1000 kg/ha for many years, with a modest increase in recent years (Fig. 1.1). These average figures mask large variations between and within countries, and across seasons.

In many countries, high population pressure with limited land holdings has resulted in continuous arable cultivation on the same piece of land, or extension of cultivation on fragile ecosystems such as steep slopes and river banks. These in turn can bring about biological, chemical, and physical land degradation. Food production has in many cases not kept pace with

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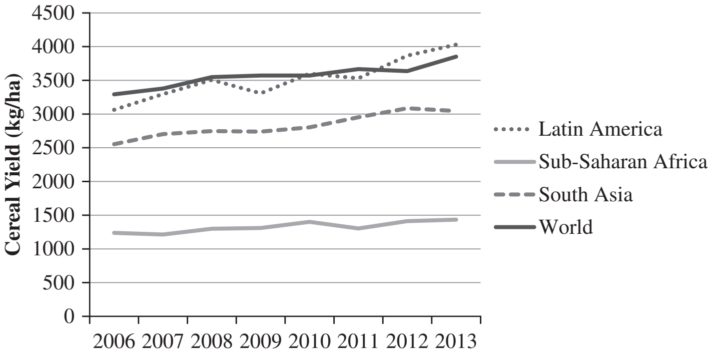

FIGURE 1.1 Cereal yield mean by region from 2006 to 14, World Bank Development Indicators accessed at http://databank.worldbank.org/data/ on April 1, 2016.

population growth in the face of shrinking land holdings. This is compounded by adverse weather conditions caused by climate change.

Evidence on global warming is unequivocal and shows an acceleration over the past 60 years. Climate projections show that heat waves are very likely to occur more often and last longer, and that extreme precipitation events—droughts and floods—will become more intense and frequent in many regions (IPCC, 2014). Climate change presents one of the most serious challenges to agricultural production in sub-Saharan Africa, and is the subject of an all new chapter of this book (see Chapter 13: Climate Change and Agricultural Systems). Boko et al. (2007) and Ringler et al. (2010) estimated that some countries are expected to experience up to a 50% decline in crop yields attributed to the negative impacts of climate change. The Malawi experience provides an illustration. In the 2014 − 15 season, the country experienced the late onset of rains, followed by devastating floods with losses of life and property, and then a dry spell and an abbreviated crop growing season. The result was a 35% decline in average crop yields. Associated with these global climatic changes are increasing risks of epidemics and invasive species such as weeds. Taken together, the need for rural innovation and adaptation to rapid change is more critical than ever.

Globalization and the liberalization of many developing economies of the world, especially in Africa, have not brought about commensurate agricultural economic growth and prosperity. Later chapters consider this essential context to development; however, the primary focus of the book is on working with smallholder farmers and rural stakeholders, where educators, researchers, and extension advisors can make a difference. We recognize the critical need to engage with policy makers and consider fully the context for equitable development. Trade barriers and tariffs, including subsidies, cause considerable disparities and tend to favor Northern hemisphere investors in agricultural trade and related intellectual property rights. The uneven

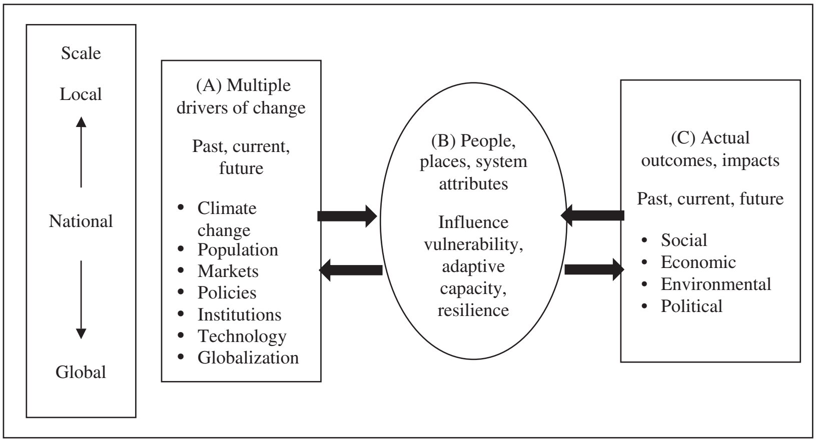

FIGURE 1.2 Agricultural systems in a changing world, shown at multiple scales with key drivers of change. *Adapted from Lamboll, R., Nelson, V., Nathaniels, N., 2011. Emerging approaches for responding to climate change in African agricultural advisory services: Challenges, opportunities and recommendations for an AFAAS climate change response strategy. AFAAS, Kampala, Uganda and FARA, Accra, Ghana.*

sequencing of liberalization is impoverishing and widening the gap between rich and poor countries, resulting in limited competitive capability among developing countries. Conflict and wars have further impacted negatively on food production, and led to loss of property and life, displacement, and misery throughout much of the developing world.

Agricultural development in sub-Saharan Africa is being undermined by the HIV/AIDS pandemic, and by other emerging epidemics such as the Ebola virus. The productive work force, rural families, and research, extension, and education staff have been badly affected. Gender inequality is another major social challenge. Despite contributing 70% of the agricultural labor in many developing economies, women rarely have access to requisite resources and technologies as compared to their male counterparts. The consequence of inequality is a vicious cycle of poverty and food insecurity, accentuated in households headed by women and children.

Agricultural systems are part of a complex, changing world (Fig. 1.2). Multiple drivers—including: climate change, population, technology, and markets (A); exert influences on people, places, or agricultural systems (e.g., an ecologically-based agricultural system) (B). These drivers work across different ranges, from local to global, and result in, for example, increasing land pressure, greenhouse gas emissions, and climate change. The attributes of the population, place, or system (e.g., their assets) affect their vulnerability, resilience, and capacity to adapt to change. The interaction between the drivers of change and the population, place, or system is the development process. Actual outcomes, impacts, and adaptations (C) can be seen as the results of the development process—for example, changed livelihoods, poverty, well-being, and environment (Lamboll et al., 2011) (see Chapter 3: Farming-Related Livelihoods, on Livelihoods, and Chapter 13: Climate Change and Agricultural Systems, on Climate Change).

Agricultural development depends to a great extent on investment in human capacity and education for successful generation and application of knowledge. It is a conundrum that increasing human population density can exhaust resources and impoverish an area, or through education and human capacity building, lead to innovation and prosperity. Investments in knowledge—especially science and technology—have featured prominently and consistently in most national agricultural strategies. In a number of countries, particularly in Asia, these strategies have been highly successful. Research on food crop technologies, especially genetic improvements, has resulted in average grain yields doubling over the past 40 years, and continued improvements have been shown over the last decade (Fig. 1.1). Average cereal yields remain notably low in sub-Saharan Africa, with modest but steady increases in recent years from 1250 kg/ha to almost 1500 kg/ha.

Gains in agricultural productivity and ingenuity in devising superior storage and postharvest processing have directly contributed to enhanced food security around the globe. Time and again the predictions that population growth will outstrip food supply have been disproved. New disease-resistant crop varieties and integrated crop management (ICM) have provided measurable gains for farmers, from the adoption of disease-resistant cassava varieties to high yielding, maize-based systems. Agricultural scientists in developing countries are innovators in genetic improvement, including partnering with farmers to develop new varieties of indigenous crop plants (Fig. 1.3). Complementary technological innovations have allowed farmers to protect gains in productivity, such as biological control practices to suppress pests, and postharvest storage improvements (Fig. 1.4).

The Green Revolution: On-going Lessons

The green revolution, launched in the 1960s, is an example of widespread and rapid transformation through new varieties and technologies that provided substantial, and often remarkable, increases in the productivity of rice and wheat cropping systems. Productivity gains, however, do not necessarily ensure equitable accrual of benefits. A review of over 300 studies of the green revolution found that over 80% produced unbalanced benefits and increased income inequity associated with the adoption of high yield potential varieties and production technologies (Freebairn, 1995).

The varieties produced by the green revolution provided a new architectural plant type that could respond to high rates of nutrient inputs with heavier yields in the presence of sufficient water and productive soils. These were widely adopted by farmers on irrigated lands, in some cases displacing

FIGURE 1.3 Improvement of the indigenous Bambara groundnut crop is underway in South Africa, where rapid gains in productivity and quality traits have been achieved.

FIGURE 1.4 Biological control is being practiced on a large scale in Thailand, where farmers are supported by innovative field stations and extension educators that demonstrate health-promoting composts and integrated pest management practices.

indigenous varieties and the biodiversity of land races. In other locales the new varieties were adopted judiciously, not replacing but supplementing the diversity of varieties grown to provide one more option among the many plant types managed by smallholders.

An example is the development of early-maturing rice varieties with a high harvest index. These plant types allocate to grain, with limited stover production, and do not necessarily produce tasty or storable grains, which were still valued by Sierra Leone farmers. Interestingly, the new high yield potential varieties were integrated into both “swamp” rice (informal irrigation) and upland, rain-fed rice production systems in Sierra Leone. These “green revolution” rice varieties supplemented but did not replace long- and medium-duration varieties which were moderate in yield potential, but had many other desirable properties. The new varieties allowed smallholder women and men to exploit specific soil types and land forms for rice production, and develop a wider range of intercrop systems of early and late duration rice varieties (Richards, 1986). This illustrates the adaptive and innovative nature of smallholder farming in the face of new technologies and genetic materials.

There are numerous critiques of the green revolution. Most emphasize the limited adoption of high yield potential varieties within agroecologies that have an unreliable water supply or inadequate market infrastructure. A lack of nuanced understanding of local conditions (which vary widely in time and space, and provide limited system buffering capacity), and misconceptions of farmer priorities, are key contributors to failures in some green revolution varieties and input management technologies developed for intensified production in the irrigated tropics that were inadvisably promoted in rain-fed and extensive agricultural systems.

The relevance of agricultural technologies that require substantial investment in labor and external inputs is particularly suspect for extensive agriculture where farmers often prioritize minimal investment. In a variable environment replanting is not uncommon, so low-cost seeds and minimal labor for seedbed preparation may be a goal, often not recognized by agricultural scientists. Optimizing return to small doses of inputs rather than optimizing return overall requires different types of technologies. Stable production that reduces risk is another common goal of farmers, particularly in sub-Saharan Africa, with different criteria for success than simply yield potential. The changeable and low resource environments experienced by smallholder farmers in much of the region require careful attention to technologies with high resilience.

Poor soil fertility, low and variable rainfall, underdeveloped institutions, markets, and infrastructure are realities facing the rain-fed tropics. Typically, farmer knowledge systems have been tested over many years and across a wide range of environments. The fine-tuned modifications that occur over a long period lead to resilient and relevant technologies. Agricultural researchers have only periodically been fully cognizant of this valuable resource: local knowledge systems. Recently, renewed importance has been given to valuing both indigenous and scientific understanding of the world. These

FIGURE 1.5 Participatory action research underway with Ugandan farmers interested in soil fertility improvement.

knowledge systems need to be integrated, rather than being seen as competing. The two world views can be complementary, as shown by the example of integrated nutrient management. Here, organic nutrient sources (such as residues and compost) can enhance returns from judicious use of nutrient inputs from purchased fertilizers and herbicides that reduce crop competition for nutrients (de Jager et al., 2004). Chapter 2, Agroecology: Principles and Practice, of this book explores such concepts of applied agroecology, and puts them on a solid scientific footing. A website that gives an opportunity to join a community of practice around these concepts, based on experiences of the book's authors in Malawi, can be checked out at: http://globalchangescience.org/eastafricanode. We welcome all to join the conversation.

The context for agriculture is changing rapidly, and the process of knowledge generation is undergoing transformation as well. Agricultural development is moving beyond a technology transfer model, to one that recognizes farmers and rural inhabitants as full partners, central to change efforts. Participatory approaches that are fully cognizant of the necessity for collaborative efforts are being tried around the globe: from participatory action research (PAR) on soil fertility in Uganda (Fig. 1.5) to community watershed improvement efforts in India. Other exciting examples include dairy farmers in the Netherlands participating in research circles, land care groups in Australia, and potato growers in Peru involved in participatory Integrated Pest Management (IPM) (see these examples and more in Pound et al., 2003).

The long-term aim of sustainable development is to enhance capacity and promote food security, livelihoods, and resource conservation for all: see Box 1.1

BOX 1.1 Sustainable Development Goals Relevant to Agricultural Systems

In 2015 the nations of the world adopted 17 Sustainable Development Goals (SDG) as a transformative approach to development. At least five SDGs are directly addressed in this book:

- Goal 1 to **end poverty in all its forms everywhere**.
- Goal 2 to **end hunger, achieve food security and improved nutrition, and promote sustainable agriculture**.
- Goal 5 to **achieve gender equality and empower all women and girls.**
- Goal 13 to **take urgent action to combat climate change and its impacts**.
- Goal 15 to **protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss**.

Source: *United Nations Sustainable Development.*

for key Sustainable Development Goals (SDGs) adopted by the United Nations. Tremendous adaptability and understanding is required to manage a biocomplex and rapidly changing world. This is a pressing reality for the more than three billion people living in rural areas with extremely limited resources. In these often risky, heterogeneous environments, access to food and income depends on a wealth of detailed knowledge evolved over generations, and the capacity to integrate new findings. This book presents a research and development approach that seeks to engage fully with local knowledge producers: primarily smallholder farmers and rural innovators.

Agricultural research has historically often suffered from an over-simplistic view of development and a top-down approach toward rural people. This was one of the major critiques that led to the rise of the farming systems movement in the 1970s. The technologies developed through a reductionist understanding of agricultural problems did not take into account farmers' holistic and systems-based management and livelihood goals (Norman, 1980).

Our goal is to bring farming systems research into the 21st century and provide a new synthesis incorporating advances in systems analysis, participatory methodologies, and the latest understanding of agroecology and biological processes. Table 1.1 presents a glossary of farming systems research and sustainable agriculture terminology as it has evolved over time. The next section of this chapter presents how farming system approaches to development have evolved and continue to change. Ultimately we recognize that access to food and increasing that access depends upon the broad shoulders and innovative capacity of men and women farmers that tend one or two hectares of land, or less. We seek to empower those hands, to support food security and equitable development starting at the local level.

TABLE 1.1 Definitions of Farming Systems Research and Sustainable Agriculture

Terminology	Definition	References
Farming system	A complex, interrelated matrix of soils, plants, animals, power, labor, capital, and other inputs, controlled—in part—by farming families and influenced to varying degrees by political, economic, institutional, and social factors that operate at many levels	Dixon et al. (2001)
Agricultural system	An *agricultural system* is an assemblage of components which are united by some form of interaction and interdependence, and which operate within a prescribed boundary to achieve a specified agricultural objective on behalf of the beneficiaries of the system. Farmers and rural stakeholders are at the foundation of agricultural systems, which includes consideration of equity and local control	FAO (n.d.)
Sustainable agriculture	An integrated system of plant and animal production practices having a site-specific application that will, over the long-term, satisfy human food and fiber needs; enhance environmental quality and the natural resource base upon which the agricultural economy depends; make the most efficient use of nonrenewable resources and on-farm ranch resources, and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole	US Congress (1990)
Ecological intensification	A knowledge-intensive process that requires optimal management of nature's ecological functions and biodiversity to improve agricultural system performance, efficiency, and farmers' livelihoods	FAO (2011)
Agroecological intensification (AEI)	Improving the performance of agriculture through integration of ecological principles into farm and system management	Coe and Nelson (2011)
Sustainable intensification	A form of production where yields are increased without adverse environmental impact, and without cultivation of more land	FAO (2011)
Low external input and sustainable agriculture (LEISA)	Agriculture which makes optimal use of locally available natural and human resources (such as soil, water, vegetation, local plants and animals, and human labor, knowledge, and skills), and which is economically feasible, ecologically sound, culturally adapted, and socially just	Reijntjes et al. (1992)

EVOLVING AGRICULTURAL SYSTEMS RESEARCH

Agricultural sciences are seen by some as naturally interdisciplinary: a “quasidiscipline” defined by real-life multidimensional phenomena. As such, a multidisciplinary approach is needed to address them adequately. Over the last 40 years different integrations have occurred. By the early 1970s, crop ecology had evolved, including disciplines such as physiology, pathology, entomology, genetics, and agronomy. From the mid-1970s to the 1980s, farming systems research was prominent, including biophysical and economic components. By 1985 a focus on sustainable production had become dominant. Now, worries about food production and global hunger have been modified by increased public concern about the rapid deterioration of the earth’s ecosystem, especially since the 1992 United Nations Conference on Environment and Development held in Rio de Janeiro, also known as the “Earth Summit.” Thus, sustainable agricultural management has been redefined as sustainable natural ecosystem management, including disciplines such as geography, meteorology, ecology, hydrology, and sociology (Janssen and Goldsworthy, 1996). These have been combined with new thinking on sustainability and poverty alleviation, so that international agricultural research centers have altered their focus on agricultural productivity and commodity research to a more integrated natural resource management (NRM) perspective (Probst et al., 2003). NRM aims to take into account issues beyond classical agronomy: spatial and temporal interdependency, on-site and off-site effects, trade-offs of different management options, and the need to involve a wider range of stakeholders in joint activities (Probst, 2000).

These evolving approaches are gradually being seen in the work of researchers on the ground, including international agricultural research centers, national agricultural research systems, extension services, nongovernmental organizations, development agencies, the private sector and, in particular, farmers’ groups. There is increasing recognition of farmers’ ability to adapt technologies to their own purposes. This was one of the instigating factors in developing farming systems research approaches in the 1980s. Another driving factor in developing farming systems and, more recently, participatory research methodologies, has been the perceived lack of relevance and relative failures associated with monocultural, green revolution technologies. Farming in semiarid and subhumid rain-fed production areas, and across the vast majority of sub-Saharan Africa, has remained at low levels of productivity, and has been left out of many agricultural development initiatives. A robust alternative has emerged, involving farmers through PAR to support local capacity building and adaptation of “best bet options” (Kanyama-Phiri et al., 2000; Kristjanson et al., 2005; Snapp and Heong, 2003).

Other approaches include support for value chains, which are closely related to market opportunities and educational and extension reforms: these

BOX 1.2 Testing "Best Bet" Options in Mixed Farming Systems in West Africa

The contributions of livestock to NRM take place within a complex of biophysical, environment, social, and economic interactions. To better understand and optimize the contribution of livestock, novel approaches have been developed that integrate these multiple aspects and consider the implications from household to regional levels. An example of such an approach is mixed farming systems in West Africa where international institutions—the International Institute of Tropical Agriculture (IITA), the International Livestock Research Centre (LRI), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)—have been working together with farmers to increase productivity whilst maintaining environmental stability through integrated NRM. The process began with prioritization of the most binding constraints that research can respond to (competition for nutrients and the need to increase productivity of crops and livestock without mining the soil). The introduced technologies—the best of everything that research has produced—were presented as "best bet" options which were tested by farmers against current practices. The implications and impacts of introducing best bet options were assessed, taking into account not only grain and fodder yields, but also nutrient cycling, economic/social benefits or disadvantages, and farmers perceptions. A further step would be to capture environmental implications such as methane emissions, construction of wells, and availability of fresh water.

Source: *Tarawali, S., Smith, J., Hiernaux, P., Singh, B., Gupta, S., Tabo, R., et al., 2000 August. Integrated natural resource management - putting livestock in the picture. In: Integrated Natural Resource Management Meeting, pp. 20–25. www.inrm.org/Workshop2000/abstract/Tarawali/Tarawali.htm.*

will be explored later in this book. In areas where agricultural research and extension (R&E) systems have remained stuck in a commodity-oriented mode, there have been failures to understand the complex interactions between social and biophysical processes, resulting in impractical agricultural technologies and policies that did not address farmers' priorities (Box 1.2).

Many international agricultural research centers and development projects are still primarily focused around improvements in monocultural, high input, and high return (to land) cropping systems. Although these often primarily meet the needs, resources, and aspirations of the well-endowed and linked-to-market groups of farmers, there are inspiring cases where genetic outputs and technologies have been used by farmers from diverse socioeconomic, gender, and age groups, if they provide adequate returns to their labor and investment, and support improvements in their livelihoods (livelihoods encompass the multiple strategies used to sustain self and family: see Chapter 2, Agroecology: Principles and Practice). Participatory breeding research and livestock innovation approaches help ensure relevance to diverse farmer requirements, and are addressed in detail in Chapter 8, Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers, and Chapter 9, Research on Livestock, Livelihoods, and Innovation, of this book.

Addressing and understanding the complexity of goals associated with a whole farming system was the main focus of the farming systems movement that attempted to improve client-orientation and to develop a more multidisciplinary approach to agricultural R&E. The farming systems approach shifted R&E from a commodity focus to a holistic approach that included crops, livestock, off-farm income generation, and cultural goals, as well as the economic returns of the entire farm.

Farmers continually make complex trade-offs of time and labor with multiple returns from diverse farm and off-farm enterprises that address the whole farming system and livelihoods within a rapidly changing environment. Diagnostics of system complexity and understanding farmer priorities in order to develop relevant technologies and interventions led to farming systems teams that bridged social science and biological science inquiries. Collaborative endeavors among social scientists, biologists, educators, and rural community members have been growing over many years; this has led to and strengthened recognition of the whole farming system and livelihood strategies within which varieties and other technologies are assessed and adopted, discarded, or temporarily adopted (Box 1.3).

The value of interdisciplinary inquiry has been heralded by many, but the challenges are tremendous and many whole systems approaches have devolved into a single focus or dispersed efforts over time. Communication across disciplines is a huge challenge, requiring long time frames and commitment to working together. Institutional reward structures that focus on individual achievements and changing donor priorities appear to have marginalized farming systems teams in some organizations and projects. The potential returns from a committed, enduring farming systems approach is seen in the steady enhancement of farmer livelihoods in regions of Brazil, where farming systems teams have labored for two decades. Here, a range of germplasm and technologies have been introduced: a long-season legume (pigeon pea) providing nutrition for poultry while enhancing soil productivity and linked to new maize varieties; and integrated use of poultry manure and fertilizer, are components of more sustainable farming systems (Fig. 1.6).

Over time, an ecologically based understanding has informed a farming systems approach to enhance the diagnostic and descriptive aspects of R&E. A rigorous understanding of the biological and physical landscape and processes in the ecosystem can greatly improve the technical insights and knowledge that scientists bring to agricultural development. Rather than empirical trial and error, the crop types and management practices suited to a given agroecology can be more accurately predicted. This will lead to identification of the most promising options that farmers and local extension advisors can then test for performance within a given locale and social context.

BOX 1.3 Cowpea Variety Development and Farmer Adoption in West Africa

An illuminating example of multiple collaborative endeavors is the IITA's intercountry African Cowpea Project (PRONAF) in West Africa. The initial focus of cowpea breeders on determinant, short-statured varieties was not successful, as cowpea is used by many farmers not only for grain and leaf production (e.g., as a vegetable), but also for livestock fodder, products which require some indeterminate, viney traits in cowpea. This adoption story (documented by Inaizumi et al., 1999; Kristjanson et al., 2005) shows how livestock researchers worked with plant breeders and social scientists over a number years, whilst extensionists, geographers, and agricultural economists were also involved in the dissemination and evaluation.

Losses due to pests were evidently a major constraint, so IITA established the Ecologically Sustainable Cowpea Protection (PEDUNE) project to find alternatives to the use of toxic pesticides, and promote Integrated Pest Management (IPM) as the standard approach to cowpea pest management in the dry savannah zone. The project identified botanical pesticides such as extract of neem leaf (*Azadirachta indica*), papaya, and Hyptis, and introduced new aphid- and striga-tolerant cowpea varieties, and encouraged the use of solar drying. The program has worked with the West and Central Africa Cowpea Research Network and the Bean/Cowpea Collaborative Research Programme (CRSP). It uses Farmer Field Schools (FFS), a learner-centered approach where farmers' groups conduct field experiments to test and learn about technology options under realistic conditions, improving their crop management decision-making skills in the process. The FFS represent an exciting extension – farmer partnership for catalyzing the evaluation of new agricultural technologies (Nathaniels, 2005).

Agroecology is the science of applying ecological concepts and principles to the design, development, and management of sustainable agricultural systems.

The key principle is to manage biological processes, including reestablishing ecological relationships that can occur naturally on the farm, instead of managing through reliance on high doses of external inputs (see Chapter 2: Agroecology: Principles and Practice).

Improved understanding of plant interactions with soil microbial and insect communities is contributing to systems-oriented management practices (see Chapter 5: Designing for the Long-term: Sustainable Agriculture). Through carefully chosen plant combinations and integration of plants with livestock, an agroecologically informed design can improve the inherent resilience of a farming system. Indigenous practices often rely on agroecological principles such as diversity of plant types and strategic planting

FIGURE 1.6 Pigeon pea has been introduced on smallholder farms in Brazil. Note soil fertility enhancing residues accumulating in front.

of accessory, or helper plants, to reduce pest problems and protect soils. This is shown in the remarkably similar plant combinations used by farmers around the world. For example, in hillside vegetable production systems, from Korea to the Upper Midwest in North America and the Andes in South America, farmers plant strips of winter cereals (rye in Korea and the United States, barley in Peru) along the contour across slopes where onions, potatoes, and other tubers are grown, to confuse pests and prevent erosion while building soil organic matter. In more tropical zones, vetiver grass strips can play a similar role (Fig. 1.7).

DIFFERENT PATHS TAKEN

Farming system characterization and understanding livelihood strategies lie at the foundation of agricultural development. It is a challenging process, one that will be addressed from different perspectives in the following chapters. Factors to consider include environmental aspects, such as the agroecology and resource base, and socioeconomic aspects including population density and community goals, levels of technological complexity, and market-orientation.

Take the crops and animals present on a farming system as an example of the complexity involved. A mixture of crops is grown, including intercropped cereals and edible legumes, where there is competition for the available land, labor, and capital resources. Where land is a limiting factor,

FIGURE 1.7 Vetiver grass planted along bunds for soil conservation in Malawi.

farmers can maximize usage of land through intercropping of legumes and cereals or doubling up of legumes, to both increase yields and improve soil fertility. However, to identify the best-bet cereal/legume combinations, researchers must partner with farmers to ensure that their preferences are embedded in the development process. Research in West and Southern Africa (Snapp and Silim, 2002; Kitch et al., 1998) has demonstrated that food legumes are preferred over nonfood legumes and that most small-scale farmers choose new varieties of legumes primarily for food and cash income security rather than for soil fertility enhancement.

There are exceptions, where plant species are adopted primarily for sustaining a farming system. Nonfood legumes play a major role in the Central American humid tropics, as weed-suppressing crops in maize-based and plantation systems. Maize is planted into the dense foliage of recently slashed *Mucuna pruriens*, a green manure “slash and mulch” system. This and other promising options for sustainable agriculture are discussed in Chapter 5, Designing for the Long-term: Sustainable Agriculture.

The importance of livestock varies from region to region, and indeed from family to family. Often in dry areas and where rainfall is highly variable, livestock are highly prized, and are essential to culture and livelihood. Livestock provide a means to concentrate energy and biomass over a large area through grazing, and are flexible in the face of periodic or occasional drought. The system of transhumance relies on moving livestock annually to utilize grazing effectively. Chapter 9, Research on Livestock, Livelihoods, and Innovation, discusses in-depth livestock innovations and agricultural development. It is illuminating to consider briefly the role of small ruminants, in particular for poverty alleviation. Families that have small

BOX 1.4 Intensive and Extensive Cropping Systems

Intensification of cropping systems occurs in time and space, and includes:

1. Intercropping with complementary crop species;
2. Double cropping over time, with two crops a year. One crop may be a soil building plant species, such as a green manure from herbaceous or tree legume species, and the other a nutrient exploitive species that often has high cash value, extracting benefit from the soil building phase of the speeded up rotation sequence;
3. Intensified plant populations of a monocultural species, often a plant type that has vertically disposed (erect) leaves that can minimize shading, while at the same time maximizing the interception of Photosynthetically Active Radiation (PAR) when a very high density of plants are grown in a given space. Although substantial nutrient sources will be required, weed control requirements may be minimized as plant cover is achieved quickly in an ideal situation.

Extensive systems are another pathway, and may be pursued if the climate is highly variable, e.g., with severely limited rainfall or other critical resources. Livestock are often very important in these environments, and stover may be a primary use, greater than human food value, for many cereal crops.

The tools being used by farmers are not necessarily good indicators of how intensive the management practices are, as, e.g., plowing, which may be used in extensive or intensive land use. Plowing can facilitate planting and weeding of an improved fallow, or allow a large area to be planted to meet food security requirements, thus reducing pressure to intensify through use of inputs or related investments.

ruminants in West Africa were the first to adopt the new dual purpose cowpea. The introduction of a rotational crop of pigeon pea combined with improved, early duration maize varieties and intensified poultry production in Brazil also highlights the role of integrated crop and livestock technologies, where research followed farmer interest in intensified versus extensive production, for different aspects of the farming system.

Researchers have at times prioritized intensification, whether through introducing new crop or livestock varieties that produce more per unit grown, or through agricultural input use. We contend here that agricultural system performance and resilience can be enhanced both through extensive and intensive cropping systems, but this must be done in consultation with the ultimate end users, the smallholder farmers (see Box 1.4).

Another pressing problem is organic matter depletion under continuous arable cultivation in heavily populated and land constrained agricultural systems which have invariably led to decreased land productivity. To circumvent this problem a great deal of research has been conducted. Some of the agricultural systems options qualify as “best bet” natural resource improving

FIGURE 1.8 The crop legume "cowpea" (*Vigna unguiculata* L.) is a productive source of high quality organic matter and multiuse products, widely adapted to the semiarid and arid tropics.

technologies, through their potential for adaptability and adoption by end users (Box 1.2).

It is important for agricultural scientists and change agents not to underestimate the substantial biologically based challenges, and economic challenges, that act as barriers to farmer adoption of integrated, low input, and organic matter-based technologies. This is nowhere more evident than in the marginal and risky environments that many smallholder farmers inhabit. The lack of easy answers has been well documented. Often the areas that are most degraded, such as steep slopes, are those that allow limited plant growth, requiring intensive labor and other investments to overcome a degraded state (Kanyama-Phiri et al., 2000). There are emerging technologies, such as drought-tolerant cowpea which combines farmer utility as a grain, vegetable, and fodder source, with moderate but consistent soil-improving properties (Fig. 1.8; Box 1.3).

Strategic intervention is the key to successful agricultural development programs, and will be discussed in more depth in relation to different smallholder farming systems throughout this book. Chapter 4, Farming Systems for Sustainable Intensification, gives a detailed discussion of African farming systems trajectories of change, and intensive versus extensive strategies (Box 1.5).

Impact at Local and Regional Levels

Participatory approaches are being experimented with widely, as a means of supporting the generation of local adaptive knowledge and innovation. PAR can have an impact at broader levels as well, through improving research relevance. This has not been the explicit goal of many PAR projects, but if

BOX 1.5 Best Bet Agricultural Systems Options for Improved Soil Fertility

1. Inorganic fertilizers

Use of nutrients from inorganic sources has the advantage of quick nutrient release and uptake by plants, for a consistent yield response. However, the cost of inorganic fertilizers and associated transportation costs has proven to be prohibitive for many limited resource farmers. It been has reported elsewhere (Conway, pers. comm.) that in Europe a nitrogen fertilizer such as urea costs US$70 per metric ton. By the time the fertilizer reaches the coast of Africa the price will have doubled, to include transport, storage, and handling, and may be much higher if many middlemen are involved in the process of importing the fertilizer and packing it for resale. Eightfold increases in fertilizer costs are not uncommon by the time the fertilizer reaches a farmer located in a Central African country, pushing the commodity beyond the reach of most end users. Thus, the use of inorganic fertilizers on staple food crops by smallholder farmers requires subsidies, at least in the short-term.

2. Incorporation of crop residues and weeds

Residues from weeds and crop residues have been overlooked at times, as the wide C/N ratio, high lignin content, and low nutrient content generally found in crop residues and weeds limits soil fertility contributions from these organic sources. However, cereal and weed residues build organic matter and improve soil structure for root growth and development. Legume crop residues have higher quality residues and are one of the most economically feasible and consistent sources of nutrients on smallholder farms. Grain legumes such as soybean (*Glycine max* L.), cowpea (*Vigna unguiculata* L.), common bean (*Phaseolus vulgaris L.*), and peanut (*Arachis hypogea* L.) are best bet options for soil fertility improvement under rotational agricultural systems in sub-Saharan Africa. Countrywide trials in Malawi have documented over a decade that peanuts, soybeans, and pigeon pea consistently and sustainably improve maize yields by 1 t/ha, from 1.3 t/ha (unfertilized continuous maize) to 2.3 t/ha (unfertilized maize rotated with a grain legume) (MacColl, 1989; Gilbert et al., 2002).

3. Green manures from herbaceous and shrubby legumes

A green manure legume is one which is grown specifically for use as an organic manure source. It often maximizes the amount of biologically fixed nitrogen from the *Rhizobium* symbiosis that forms nodules in the roots. This fixed nitrogen is available for use by subsequent crops in rotational, relay, or intercropped systems. Green manures also have an added advantage of a narrow C/N ratio, which facilitates residue decomposition and release of N to subsequent crops. In southern and eastern Africa, best bet herbaceous and shrubby legume options for incorporation as green manures have been widely tested. These include *M. pruriens*, sun hemp (*Crotalaria juncea*), Lab lab (*Lab lab purpreus*), pigeon pea intercropped with groundnut, and relay systems with *Tephrosia vogelii* (see Chapter 5: Designing for the Long-term: Sustainable Agriculture). Residue management and plant intercrop arrangement are important to consider, along with the species used for a green manure system. Sakala et al. (2004) reported

(*Continued*)

BOX 1.5 (Continued)

higher maize grain yields from early compared to late incorporated green manure from *M. pruriens*. Similarly, for smallholder farmers on the Island of Java in Indonesia, threefold increases in maize yields have been reported following incorporation of a 3-month-old stand of mucuna or sun hemp.

causal analysis and iterative learning are explicitly included, then research findings can have wider applications. For example, participatory, on-farm research on nutrient budgeting has been shown to be an effective means to improve farmer knowledge of nutrient cycling; however, it has the potential to provide valuable research insights as well. This was shown in Mali, West Africa, where participatory nutrient mapping was undertaken to support villagers learning about nutrient loss pathways and integrated nutrient management practices (Defoer et al., 1998). At the same time, Defoer and colleagues gained knowledge about farm and village-level nutrient flows. Some of the information generated will be locally specific, as nutrient losses are conditioned largely by site-specific environmental factors, yet we contend that knowledge generated locally can often be used to improve research priorities, and to inform policy.

One of the goals of this book is to support broader learning from the PAR process. Agricultural researchers are charged with a dual mandate: to provide local technical assistance that supports farmer innovation at specific sites, while simultaneously generating knowledge of broader relevance. To work at different levels and meet these dual objectives, careful attention must be paid to choosing sites that are as representative as possible of larger regions. Thus, local lessons learned can be synthesized, and disseminated, over time.

Examples are developed in this book of how to support outreach and “take to scale” participatory NRM, crop and livestock improvement (see chapters: The Innovation Systems Approach to Agricultural Research and Development; Outreach to Support Rural Innovation). Promising strategies for large-scale impact will vary, depending on objectives. Successful extension examples include Farmer Field Schools and education/communication campaigns that address an information gap, and engage rather than preach. Education requires documentation of current knowledge and farmer practice, to identify missing information and promote farmers testing for themselves science-based recommendations. This focus on knowledge generation contrasts with promoting proscribed recommendations, and is illustrated by a radio IPM campaign in Vietnam that challenged farmers to test for themselves targeted pesticide use. The campaign resulted in large-scale experimentation among rice farmers, and province-wide reductions in pesticide use

(Snapp and Heong, 2003). Another innovative example is from Indonesia, where participatory research on sweet potato Integrated Crop Management (ICM) was scaled-up through FFS. A unique aspect of this project was that FFS education materials were developed through joint farmer – researcher learning about sweet potato ICM over a number of years. Only after this participatory development of training materials were FFS initiated to communicate with farmers on a range of ICM principles and practice (Van de Fliert, 1998).

Participatory and adaptive research approaches have evolved out of a desire for the most effective, informed, farming systems approaches possible. Participation helps bridge gaps and enhances communication among researchers, extension advisors, and rural stakeholders. It recognizes the importance of scientific input from both biophysical and socioeconomic enquiry, while at the same time valuing indigenous local knowledge. By so doing it provides a basis for increased understanding and iterative technology development in partnership with stakeholders, especially smallholder farmers.

Agricultural systems science requires attention to synthesis, reflection, and learning cycles (Table 1.1). These are key ingredients in maintaining quality and rigor in an applied science which must engage with the complexity of real-world agriculture. Synthesis techniques are emerging that help address these challenges, including statistical multivariate techniques, meta-analysis, and geo-spatial analysis. These are important methods that can help researchers and educators derive knowledge from local experience, and understand underlying principles of change. Elucidating drivers or regulators of change and building in iterative reflective steps are important components of agricultural systems research. Chapter 4, Farming Systems for Sustainable Intensification, discusses in more depth agricultural systems evolution over time, and approaches to catalyzing change in sustainable directions.

Institutional reform and engagement with policy is an area that agricultural systems science is beginning to move toward, as discussed in Chapter 14, Tying It All Together: Global, Regional, and Local Integrations. Farming systems may not have sufficiently addressed institutional change, and this newly reborn farming systems movement—called here "agricultural systems"—is working not only with farmers and R&E, but is now taking on and transforming institutions and policy in every part of society.

LOCAL INSTITUTIONS FOR AGRICULTURAL INNOVATION

Linkages between researchers and local users can vary greatly depending on how "ownership" of the research process is distributed between the two. In recent years most research projects have sought local people's participation, but objectives of such participation are diverse, ranging from legitimizing outsiders' work and making use of local knowledge, to building local

BOX 1.6 Types of Participation in the Agricultural Innovation Process

- *Contractual participation*: the researcher has control over most of the decisions in the research process, the farmer is "contracted" to provide services and support.
- *Consultative participation*: most decisions are made by the researcher, with emphasis on consultation and gathering information from local users.
- *Collaborative participation*: researchers and local users collaborate on an equal footing, though exchange of knowledge, different contributions, and sharing of decision-making power throughout the agricultural innovation process.
- *Collegiate participation*: researchers and farmers work together as colleagues or partners. "Ownership" and responsibility are equally distributed among the partners, and decisions are made by agreement or consensus among all parties.

Source: *Based on Biggs, S., 1989. Resource-poor farmer participation in research: a synthesis of experiences from nine National Agricultural Research Systems. OFCOR Comparative Study Paper. ISNAR, The Hague (Biggs, 1989).*

capacity for innovation development and transformation. This last objective is essential to increase the capacity of marginal groups to articulate and negotiate for their own interests, and to improve their status and self-esteem (Probst et al., 2003). The type of participation which evolves will define the research process and roles of researchers and farmers in all areas, including planning, monitoring, and evaluation of the learning (Box 1.6).

Innovation development may be based on formal research or informal farmer experimentation, or a combination of the two. "Hard" and "soft" systems approaches can be identified (Bawden, 1995). Hard systems approaches attempt to understand entire systems (e.g., farms, groups of farms, or communities) by looking at them from the outside, and assuming that system variables are measurable and relationships between cause and effect are consistent and discoverable by empirical, analytical, and experimental methods. This is the approach taken by farming systems research. Soft systems proponents argue that systems are creations of the mind, or theoretical constructs to understand and make sense of the world. Thus, soft systems methods aim at generating knowledge about processes within systems by stimulating self-reflection, discourse, and learning (Hamilton, 1995).

We argue that both research methods are needed: "soft" PAR on processes of NRM (e.g., organization, collective management of natural resources, competence development, conflict management), and conventional "hard" research that focuses on technological and social issues (e.g., soil conservation, nutrient cycling, agronomic practices, socioeconomic aspects). Successful attainment of goals of increased production and environmental sustainability depends on the meaningful integration of the two (Probst et al., 2003).

Researchers have adopted a range of approaches to agricultural innovation to date, including:

1. *Transfer of technology* (TOT) model: with technology being developed by researchers at the "center," adapted by local researchers, and transferred by extensionists to farmers;
2. *Farmer First* model: where farmers participate in the generation, testing, and evaluation of sustainable agricultural technologies, often based on their own local practices, with researchers documenting rural people's knowledge, providing technology options and managing the research;
3. *Participatory Learning and Action Research* (PLA): developed through critical reflection and experiential learning through the process of addressing local development challenges. Researchers help different groups develop their knowledge and capacities for self-development, as facilitator, catalyst, and provider of methodological support and opportunities (Roling, 1996).

Each approach has its strengths and weaknesses, and may be used in combination to complement each other in different situations. Currently, most research falls under the "transfer of technology" and "farmer first" approaches. The longer-term PLA approach requires a reorientation of skills, management, and financing modes (without predefined quantifiable targets), and is only just beginning to be considered by researchers. One example of researchers attempting to put PLA research into practice is the Center for International Forest Research (CIFOR) project on Adaptive Collaborative Management (Box 1.7).

BOX 1.7 CIFORs Project on Adaptive Collaborative Management (ACM)

Improving the ability of forest stakeholders to adapt their systems of management and organization to respond more effectively to dynamic complexity is an urgent task in many forest areas. The ACM project addresses a number of research questions:

1. Can collaboration among stakeholders in forest management, enhanced by social learning, lead to both improved human well-being and to the maintenance of forest cover and diversity?
2. What approaches, centered on social learning and collective action, can be used to encourage sustainable use and management of forest resources?
3. In what ways do ACM processes and outcomes impact on social, economic, political, and ecological functioning?

The project collaborates with many institutions involved in research, implementation, and facilitation of change across a number of countries. Researchers see themselves as part of the system rather than neutral. Since there is no single "objective" static viewpoint from which forest management dynamics can be observed, forest managers and users are all actively and meaningfully involved

(*Continued*)

BOX 1.7 (Continued)

in the research. Research outputs are targeted toward different users at local, national, and global levels, including: manuals on methods and approaches, toolbox for development practitioners, policy briefs, research papers, and software such as simulation models.

Source: *www.cifor.cgiar.org.*

Exciting recent developments show the potential for decentralized and client-driven R&E to be highly relevant to smallholders. Experiments in realigning R&E are currently underway in a number of developing countries, such as Bolivia and Uganda. The political context is promoting rapid change in agricultural R&E, with almost universal disinvestment in government agricultural services providing incentives for more client-driven extension and private sector partnerships. In some countries, such as Bolivia, the public sector investment in agricultural R&E has shrunk to almost nil. Although there are concerns about meeting the needs of the poorest clients under these circumstances, promising shifts toward more responsive and integrated extension have arisen in Bolivia and Uganda. These countries show that it is possible for extension and agricultural advice services to reduce the level of commodity focus, and focus more attention on science in the service of client partnerships, catalyzing rural innovation while giving consideration to the whole farming system.

CATALYZING DIRECTIONS OF CHANGE

The rural environment is undergoing rapid change. Globalization, climate change, and epidemics are some of the forces impinging on farming systems. Farmers are developing innovative responses, and can be supported to intensify—or in some cases extend—in directions that are sustainable, resilient, and equitable.

The case for working with smallholder farmers as a key engine of development and production is widely known. Not in all cases, but in many situations, the ability of smallholders to be highly productive on a per acre basis is outstanding. Farmers will produce given access to resources and incentives, even if their land holding size is small. Examples include China and Russia (and numerous others) who have fed their billions not from the collective farmer movement that built up large farms, but from individual smallholder efforts, where many farmers built very productive small plots (intensive gardens) that fed most of the population. The indigenous knowledge (IK) of smallholders is unsurpassed—they know their resources, such as soils and priorities, better than anyone!

Researchers have become interested in linking with what they see as a vast untapped resource, and many have initiated participatory research projects to try to extract and replicate this knowledge. This can increase the efficiency and effectiveness of development programs, since IK is owned and managed by local people, including the poor. However, the danger is that in joining researcher-driven activities farmers abandon some of the very practices which have built up and continually extend and modify their local knowledge base. A few researchers have taken an alternative "empowering" approach to participatory research, seeking to enhance farmers' capacities to experiment and extend their knowledge. This requires scientists to strive to understand the process of local knowledge generation and then to support and complement it (see Box 1.8).

BOX 1.8 Research Approaches to Indigenous Knowledge

Indigenous knowledge is the basis for local level decision-making in food security, human and animal health, education, NRM, and other vital economic and social activities. Agricultural and social scientists have been aware of the existence of IK since colonial times, but from the early 1980s understanding of farmers' practices as rational and valid has rapidly gained ground. Two contrasting interpretations of IK are:

1. Local knowledge is a huge, largely untapped, resource that can be removed from its context and applied and replicated in different places (like formal science). Proponents of this perspective have scientifically validated IK or sought similarities and complementarities between their knowledge and farmers' knowledge. Farming Systems Approaches and Participatory Research and Development largely follow this thinking.
2. IK is based on empirical experience and is embedded in both biophysical and social contexts, and cannot easily be removed from them. It follows that the process by which IK is created is as important as the products of this research.

Many participatory research projects have superimposed a western scientific method of inquiry over local innovators' procedures without first assessing local knowledge and understanding the processes that generate it. This can result in innovative farmers: "playing along" or participating, but not internalizing or adopting research/extension messages; abandoning their practices and following those brought by outside agents who they see as more knowledgeable (and powerful) than they are; or adopting and adapting elements of western scientific research modes.

Some participatory research projects, particularly those which aim to empower local people, attempt to support indigenous research as a parallel and complementary system to formal agricultural research. The approach is to enhance the farmers capacities to experiment through training in basic scientific and organizational principles. Skills include problem-solving, and analytical and

(*Continued*)

BOX 1.8 (Continued)

communication capacity building, particularly in adaptive experimentation and technology dissemination.

Tangible results and impacts on the lives of the poor have been achieved under each approach. However, achieving a lasting impact requires stimulating processes for innovation that are already present in rural communities. Case studies of participatory research empowering IK can be found in the accompanying DVD.

Source: *Saad, N., 2002. Farmer processes of experimentation and innovation: a review of the literature. Particip. Res. Gender Anal. Program. CGIAR (Saad, 2002).*

The goals and interests of smallholders vary widely, but a starting point is identifying where change is occurring, and where interest in intensification is high. The challenge is to bring researchers and smallholder farmers together in a productive partnership, based on respect for each others' knowledge, skills, experience, and situation.

Major developments have occurred over the past decades in systems thinking and the adaptation of the Innovation Systems Approach from industry to agriculture. The Agricultural Innovation Systems approach is based on dynamic multistakeholder partnerships. These can comprise farmers, input suppliers, traders, and service providers (researchers and extension staff) who are facilitated to work *together* toward a common objective, such as producing cut flowers for export, or increasing the efficiency of cassava production, processing, and distribution for the domestic market. The concept has gained ground due to sponsorship from the World Bank (2012) and other major donors and is further discussed in Chapter 11, The Innovation Systems Approach to Agricultural Research and Development.

ROAD MAP

This book synthesizes theory and practice to support innovation in agricultural systems. Over three decades ago, farming systems research emerged out of a deep commitment to meet the needs of farmers and the rural poor. Commodity-focused, green revolution technologies were critiqued as not being relevant to the resources or priorities of many smallholder farmers, evidenced in low levels of adoption. This was particularly evident for rainfed agriculture in Africa and South Asia. Farming systems approaches of the 1970s and 1980s turned out to be inadequate to the tremendous task at hand, and disappointed many advocates. However, lessons were learned and experience accumulated in support of holistic approaches to development. The commitment to a systems perspective grew through the 1990s and into the first decade of the 21st century, strengthened by the development of more interdisciplinary methodologies and participatory approaches. The goal of this book is to support this revival of farming systems, through summarizing lessons from applied agroecology and outreach in support of innovation. We hope it will be of value to you the reader.

A road map of the book topics follows. The first section of the book lays out the principles and practices involved in reinventing farming systems. In this, the introductory chapter, we present some of the serious challenges faced by farmers and rural communities, and the dynamic, complex nature of equitable and sustainable development. This is followed by an overview of emerging opportunities and successful examples of rural innovation and agricultural development. The underlying biophysical gradients that guide the formation of farming systems and principles of applied agroecology for improved design are the focus of Chapter 2, Agroecology: Principles and Practice. Agroecology theory and practical implications are presented. Chapter 3, Farming-Related Livelihoods, presents ways to address the complexity of farmer livelihoods, building on farming systems research, livelihoods, and analyzing experience. Approaches and tools are presented that educators, extension staff, researchers, and change agents can use to work with smallholder farmers around the globe. Chapter 4, Farming Systems for Sustainable Intensification, is an all new chapter for this second edition, and considers drivers of agricultural intensification. That is, the how and why of farming system trajectories, and what can help bring about sustainable intensification.

Chapter 5, Designing for the Long-term: Sustainable Agriculture, presents the next steps in reinventing farming systems. This includes an overview of design principles for long-term sustainability, and applications within a developing country context.

The next four chapters explore the resources that support rural livelihoods, namely: soil productivity, and plant and animal genotypes. Chapter 6, Low-Input Technology: An Integrative View, explores lessons from research on the environment and conditions that support adoption of low input agriculture technology, in a developing country context. Chapter 7, Ecologically Based Nutrient Management, presents agroecological approaches to nutrient management, including theoretical and practical considerations to improve nutrient efficiency, and enhance productivity. Chapter 8, Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers, and Chapter 9, Research on Livestock, Livelihoods, and Innovation, focus on participatory plant breeding efforts and livestock improvement, including exciting examples of innovation, and genotype improvement that follows when farmer priorities are fully taken into account. Theory and practice is presented for this more client-oriented and co-learning approach to development of technologies, that are suited to the complexity of farming systems.

Section three considers the context for sustainable agriculture and development. Gender and equity in development is the focus of Chapter 10, Gender and Agrarian Inequities, where the complexity of social relations and access to resources is addressed through a historical review of agricultural systems and inequities, with in-depth examples from Malawi at the household and community level. The theory of innovation and approaches to catalyze rural innovation are addressed in Chapter 11, The Innovation Systems Approach to Agricultural Research and Development. Chapter 12, Outreach to Support Rural Innovation, presents new models in agricultural outreach, highlighting extension that is client-oriented, and demand-driven knowledge generation and dissemination. Climate change and agriculture, including challenges and adaptation, are the topics of Chapter 13, Climate Change and Agricultural Systems. This is an all new and comprehensive look at the manyfold and dynamic changes underway with climate change, and both incremental and visionary responses possible within agricultural development. The book ends with Chapter 14, Tying It All Together: Global, Regional and Local Integrations, which addresses head on the challenges of the 21st century for rural innovation and development. Promising pathways and integration across local and global efforts in agricultural systems development are explored in this, the penultimate chapter of the book.

Our intention in this book is to provide powerful examples of R&E programs that have achieved impact in a developing country context, to inspire and improve understanding of agricultural change.

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INTERNET RESOURCES

The International Association of Agricultural Information Specialists has a website that provides support for searching different databases on agricultural knowledge, and a blog on recent agricultural information related topics http://www.iaald.org/index.php?page=infofinder.php

Agricultural knowledge links are available at the Food and Agriculture Organization FAO "Best Practices" website, see http://www.fao.org/bestpractices/index_en.htm

Knowledge management for development e-journal often has articles of interest to agricultural information specialists: http://www.km4dev.org/journal/index.php/km4dj/issue/view/4

A website exploring agricultural systems research, applied agroecology, and rural innovation is maintained by the authors of this book http://globalchangescience.org/eastafricanode

Chapter 2

Agroecology: Principles and Practice

Sieglinde Snapp

INTRODUCTION

Agriculture is an example of a managed ecosystem. The principles that are useful in understanding natural ecosystems apply to agriculture. In this chapter, an introduction will be made to ecosystem concepts and how these can be applied to improve the management of agricultural systems, with particular reference to tropical agroecologies. Ecology is concerned with different scales over time and space, from the individual to the community, from populations to ecosystems (Fig. 2.1A−C). The socioeconomic context is particularly important to the purposes, functions, and organization of agroecosystems, and is the focus of other chapters in this book, including Chapter 3, Farming-Related Livelihoods, on livelihoods and Chapter 10, Gender and Agrarian Inequities, on equity and social dynamics.

Agroecology is an approach that relies on ecological understanding and the use of ecological principles to design semiclosed and resilient farming systems with high environmental services. The principles of agroecology must also meet "relevance criteria," such as reasonable yield for use by humans. The offtake from agricultural systems must meet farmers' goals, and have feasible requirements for labor, land, capital, and other investments. The principles for sustainable, long-term agricultural practices are developed in depth in Chapter 5, Designing for the Long-term: Sustainable Agriculture. Here we provide an introduction to ecological concepts, including drivers of ecosystem change, agroecozones, community composition and evolution, the organism niche, and applications in farming system design. Then we turn to what have been termed the ecological pillars of tropical agroecology: complementarity, redundancy, and mosiacs (Ewel, 1986). The concepts of complementarity and mosaics, in relationship to diversity, successional patchiness, and landscape ecology are describe in depth by Wojtkowski in his 2003 book on Landscape Agroecology.

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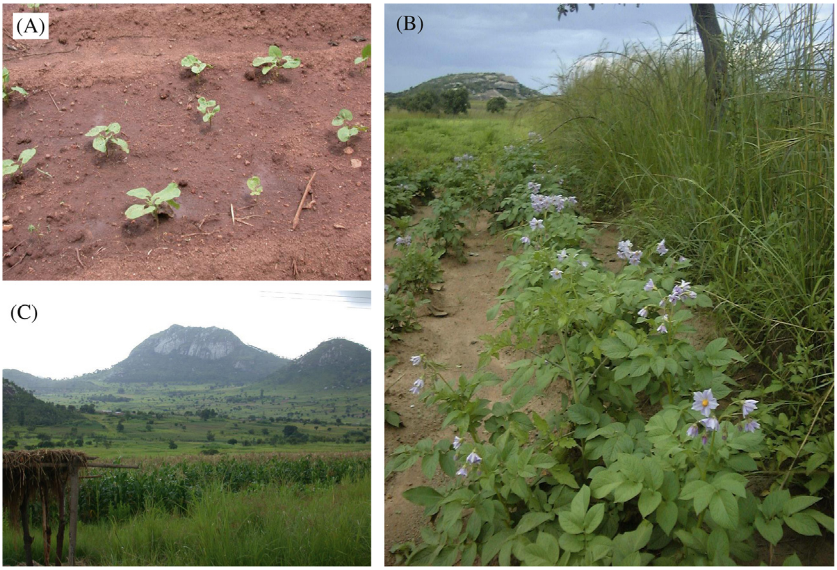

FIGURE 2.1 Photographs illustrate levels of ecosystem organization with agroecology examples of the individual organism, community, and watershed. (A) Individual organism: a bean plant. (B) A community: potato plants in the foreground are growing in a field with an erosion prevention strip planting of vetiver grass intercropped with a Mango tree. (C) A highland watershed in southern Africa. Note the shelter for field watchers (protecting crops from foragers such as monkeys and stray livestock), a maturing maize crop, vegetable gardens near water sources, and a mosaic of woodlots, grain fields, and pasture land throughout the watershed, reaching to the forest edge on steep mountain slopes.

Gradients of resources define the environmental context within which plants, animals, and soil biota interact, and profoundly influence the complex communities of macro, meso, and microorganisms that evolve. Temperature and moisture are the primary gradients that delineate ecological zones. Soil properties are another important resource gradient, one that influences ecosystem development, and that is in turn influenced by ecosystem biota. Soil parental materials interact with moisture and temperature gradients, and living organisms, over long time periods as soils evolve.

ECOSYSTEM DRIVERS

In addition to resource gradients, major disturbances and fluctuations in resource availability are fundamental regulators of productivity in ecosystems. Fire, flooding, soil disturbance, and herbivore damage from insects or livestock are the most common irregular disturbances in agroecosystems. Planned disturbances as farmers perform soil tillage, weeding, and harvest operations are also important regulators of system performance in agroecosystems. Turning over the soil, and burning residues just before crops are planted are important means of enhancing nutrient availability in synchrony with crop demand, as well as providing weed suppression (Fig. 2.2).

Fire is an effective disturbance to break pest and disease cycles. As well, fire has been used for thousands of years to address constraints to residue decomposition in agroecosystems with large amounts of low quality residues or a long dry season (Fig. 2.3). It may be one of the only practical means of reducing weed presence in subhumid to humid farming, replacing large inputs of labor for weeding. However, frequent fires will alter species succession and soil resource quality. It can have unfortunate side effects, such as favoring the invasion of aggressive grass species, and reducing nitrogen (N) inputs into a system. Upon burning, the majority of the N in the residues will be lost through volatilization; how much is left to support crop growth will depend on the heat of the fire, as N losses increase at high temperatures.

Farmers have developed methods of smoldering organic materials, which may serve to minimize N losses. This involves slow burning of trash heaps, and can serve as an informal method of compost preparation (Fig. 2.4). More research is needed to compare controlled, slow burning of waste materials to more traditional composting processes. This has particular relevance where rainfall is unreliable and water limits decomposition in compost heaps. Recently, interest has grown in oxygen-limited burning to produce biochar, a product that has shown promise as a soil amendment in

FIGURE 2.2 Oxen tillage prepares the land to plant cotton in southern Mali.

FIGURE 2.3 Burning residues in Zambia, a common field preparation practice.

FIGURE 2.4 Smoldering compost heap on a smallholder farm in Northern Malawi.

some environments, although its role in enhancing soil function is variable, and not well understood. There are indigenous farmer practices in South Asia and South America that utilize various types of biochar, and this is an area of active research (http://www.biochar-international.org/sites/default/files/CARE_Vietnam_1.31.2012.pdf).

Flooding is another type of disturbance that can greatly alter weed populations and change soil conditions. Farmers use strategic flooding as an important management tool for crops tolerant of water saturated conditions. The world's most important grain crop, rice, is well adapted to growth in a flooded environment. This has contributed to the popularity of rice, as timed flooding can be used to suppress the vast majority of weeds.

Tillage is the most important tool farmers have to prepare the seed bed for crop plants, at the same time burying weed seed and enhancing nutrient availability. On smallholder farms, "tillage" may vary from a planting stick, used to disturb a localized area around the seed, to the greater disturbance possible with hand hoes, and oxen pulled implements such as moldboard plows. A central challenge to the long-term sustainability of farming systems is that disturbance to enhance nutrient mineralization also enhances mineralization of soil organic carbon (C). Productivity is mediated in almost all soil types by C status, as this largely determines soil water holding capacity, nutrient buffering and supply, as well as soil structure and aeration. Thus, agroecological management requires attention to replenishing organic materials through manure and residue additions (Fig. 2.5), and

FIGURE 2.5 Crop residues are an important source of organic matter and can be managed to protect soil from erosion.

mitigating loss pathways to enhance soil C assimilation. Tillage depletes soil C through oxidation, and breaking up aggregates that protect soil C. Soil aggregation is supported preferentially by root biomass, and thus growing long duration plants that enhance the presence of active roots over the year and reduce soil disturbance is an effective means to build soil C (see chapter: Designing for the Long-term: Sustainable Agriculture, for more information).

Reduced tillage systems have been the subject of farmer experimentation in many locations around the world, from Brazil to Zambia. To develop a practical and successful reduced tillage system requires a major shift in not only the planting method, but also in weed and nutrient management strategies. Where it has been successfully adapted to local environments, reduced tillage systems have been shown—in some but not all cases—to improve soil organic matter and water holding capacity through enhanced residue retention on the soil surface, and reduced oxidation of soil C. Weed management can be a tremendous challenge, particularly in humid environments, and the majority of reduced tillage systems rely on herbicide inputs. The feasibility of conservation tillage in Africa is contested, but there is general agreement that the economics, multiple demands on crop residues, widespread reliance on free grazing, fire and hand hoe cultivation all pose challenges to conservation agriculture adoption (Giller et al., 2009). A surface mulch is instrumental to building soil function in a reduced tillage conservation system, and the diversity of crops grown is sometimes an overlooked central principle of conservation agriculture. Growing a living cover to supplement residues, and innovations such as layered mulch are being experimented with as means to suppress weeds (Fig. 2.6).

FIGURE 2.6 A living cover intercrop system of sweet potato grown between maize plants.

AGROECOZONES

Agroecologies vary from the subarctic to temperate, with pronounced warm and cold seasons, to subtropical and tropical. Tropical regions are defined by warm temperatures with no frost and varying intensity of precipitation from dry to wet. These include the arid to semiarid tropics, the subhumid tropics, and the humid tropics. The constant warmth and moisture availability in the humid tropics can support high levels of productivity; however, soil resources are often depleted and limit growth in the humid tropics. Deeply weathered soils predominate in this agroecozone, where nutrients have been leached by the excess of moisture in relationship to evapotranspiration demand, and chemical weathering has reduced nutrient supplies. Pests, as well as agriculturally desirable plants and livestock, thrive in the subhumid and humid tropics. This often limits production of food and other agricultural products. In temperate and drier zones, by contrast, there are cold periods or aridity that can provide a break in the growth of pests. Of considerable importance in tropical agriculture are the highland ecologies of hill and mountain agriculture that are relatively cool in temperature. These agroecologies are characterized by precipitation patterns that vary markedly over short distances, depending on topography, producing heterogeneous microclimates.

An agroecology is defined by more than the long-term average temperature or moisture pattern. The distribution and variability of resource distribution is critically important. Detailed zonation of agroecosystems often takes into account information on temperature and precipitation variation, particularly in relationship to plant growth requirements. Where information is available about large-scale climatic patterns, this can be of considerable value in understanding and predicting agricultural performance (Patt et al., 2005). In Zimbabwe a concerted effort to evaluate rainfall patterns in the unimodal agricultural zone was successful in documenting a pattern for the timing of cessation in the rainy season; in 8 out of 10 years the rains stopped within a 2-week time period. This was regardless of the timing of the start of the rains, and resulted in a high probability of a dry year when the rains started late. Shifts to lower fertilization rates and drought-tolerant species and varieties are thus recommended upon late rains in Zimbabwe (Piha, 1993). Recent changes in global climate and increased variability in climatic patterns need to be carefully considered. Long-term precipitation averages or timing of rainy season onset are not reliable guides (see “Climate Change,” chapter: Climate Change and Agricultural Systems, for further information).

Careful consideration of agroecologies, based around gradients of moisture and temperature, along with soil resources, can provide a guide regarding which farming systems or crop combinations will be present. This approach also can provide insights into which types of interventions or technologies might be expected to perform well. An important example of zonation occurs across the region of West Africa (http://www.fao.org/docrep/004/x6543e/x6543e01.htm), where aridity dominates in the north, and moisture increases in a southerly direction. Three zones are delineated across West Africa, the arid Sahelian zone of agro-pastoral parklands (*Faidherbia albida*, Baobob, mangos, and other fruit trees), and drought-tolerant crops such as millet; the semiarid zone of the sahelo-sudan with many livestock (Zebu, sheep, and goat), along with the cereals sorghum and millet, and pulses such as cowpea and groundnut; and the subhumid zone which is crop dominated (notably, maize, sorghum, millet, rice, yam, cotton, cowpea, groundnut, and intensive production of mango and cashew), with mixed livestock (cow, goat, sheep, donkey, and pig). Agroecology zones can be quite large, as illustrated by the West African example, or, finely delineated in cases such as dissected topography, or along bodies of water. As discussed later in this chapter, for highland agroecologies it is possible to use biophysical zonation to help target testing of technologies and identify potential options.

COMMUNITY STRUCTURE

Communities of species have coevolved within ecological zones. The presence and diversity of plant communities and associated animals, soil organisms, and symbionts can be categorized in relationship to gradients of moisture and temperature. Isolation enhances speciation. Diverse ecologies often evolve in the presence of barriers to species movement, such as oceans that surround islands and the effective “island” ecology of an inaccessible mountainous area. A tremendous diversity of species has been documented for island nations and highland ecologies around the world. This diversity may account in part for the large number of crops that originated from mountainous areas, including some of the most important food crops, such as maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), barley (*Hordeum vulgare* L.), mustard (*Brassica juncea* L.), common bean (*Phaseolus vulgaris* L.), and many fruit trees.

The crops grown within three relatively isolated regions are shown in Table 2.1. These crops of smallholder farms in the Andes, Ethiopia, and Madagascar illustrate two counter trends that are widely observed. On the one hand, a handful of ubiquitous crop species that have penetrated farms around the globe, and on the other hand, examples of diverse, local species that are unique to particular regions. The adaptation of a crop genotype to a specific ecozone has been used by some scientists as part of the criteria for choosing genotypes—species or varieties—to test, as they are likely to succeed in an area with similar environmental traits. A successful example of this targeted deployment approach is the adoption of new potato varieties in Rwanda, East Africa, where genetic materials were chosen for testing from a similar climatic zone in South America (Sperling and King, 1990). Highland initiatives have

TABLE 2.1 Crops Grown in Isolated Ecologies, From the Mountain Highlands of Ethiopia and the Andes, to the Island Nation of Madagascar

Ethiopia	The Andes	Madagascar
Staples – Tef (*Eragrostis tef*) – Ensete Plus wheat, maize, sorghum, millet, barley	Staples – Quinoa (*Chenopodium quinoa*) – Kiwicha (*Amaranthus caudatus*) – Oca (*Oxalis tuberosa*) – Ulluco (*Ullucus tuberosus*) – Maca (*Lepidium meyenii*) – Mashua (*Tropaeolum tuberosum*) Plus potato, maize, rice, barley	Staples – Rice – Plus cassava, maize, yams, indigenous fruits
Oilseeds – Niger seed – Flax – Rapeseed – Castor bean Plus peanut, sunflower, safflower, sesame, soybean	Oilseeds – Quito palm (*Parajubaea cocoides*)	Oilseeds – Peanut
Pulses – Fava bean (*Vicia faba*) – Chickpea – Vetch (*Vicia dasycarpa*) Plus common bean, lentils, peas, pigeon pea	Pulses – Lupin (*Lupin mutabilis*) – Lima bean – Fava bean (*Vicia faba*) – Dry pea – Nunas or popping bean (*Phaseolus vulgaris*) – Basul (*Erythrina edulis*)	Pulses – Rice beans (*Vigna umbellate*) – Bean (*Phaseolus lunatus*) – Cowpea (*Vigna unguiculata*) Pigeon pea

recently begun to catalyze discussions through the internet, providing an opportunity to exchange knowledge and genetic materials among those who work in similar mountainous zones, from around the globe (Tapia, 2000).

A key criterion for adoption is meeting local quality trait requirements, as well as adaptation of varieties or species to climatic conditions. Success in meeting local demands has been achieved recently through participatory plant breeding methods—as discussed in Chapter 8, Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers. Although some genotypes are particularly well adapted to microclimates, there are also examples of species that show tremendous adaptability. Many of these species have spread around the globe. Genotypes that are rapidly adopted by smallholder farmers often have traits in common, such as the vigorous growth, weed suppressive plant architecture, and robust, pest-resistance traits of such successful crops as maize and soybean (*Glycine max* L. Merr.).

Species diversity is an important characteristic of a community, and is defined—at the simplest level—as the number of species present. The organisms that are straightforward to count are often used to describe community diversity, which leads to an emphasis on macro organisms in soil ecology, whereas it is challenging to enumerate or even define the concept of species for microorganisms. The organisms that have the greatest impact on the ecosystem, and in many cases the most visible organisms, are sometimes referred to as the dominant species. Ecosystems vary markedly in diversity over time and space, and in the presence of dominant species. The scale at which measurement is undertaken will influence which organisms are perceived as dominant, and the diversity characteristics of the ecosystem.

Species diversity in agroecosystems is determined in large part by human intervention. Management practices favor specific species by planting propagules, such as seeds, clonal materials, and seedlings, and by removing or suppressing unwanted species. The disturbance regime imposed by management also greatly influences the species present in agroecosystems. Crop species and common weed species tend to be adapted to the highly disturbed environment of conventional agriculture, with frequent tillage to release nutrients and provide a bare soil environment. In developing lower-disturbance systems, such as reduced tillage row crop production, it may be necessary to select new crop genotypes with the appropriate traits for this specific environment. This is underway in no-till systems. Plant breeders are selecting for wheat cultivars that are tolerant of environmental conditions present in no-till, that require rapid elongation and other traits associated with vigorous seedling growth in cool-temperature soils with multilayered residues (see CIMMYT website). There is evidence that weed species community composition is also adapting to a no-disturbance regime, with shifts toward perennial weed types.

ORGANISM NICHE

An organism can best be understood in relationship to its environment; the multidimensional habitat or niche that it exists within. Organisms take up resources through space and time, often minimizing competition through exploiting a specific niche.

The fundamental resources being competed for include light, water, and nutrients. As shown in Fig. 2.7, crop species are adapted to niches across the farmscape. Consider a moisture gradient: from the flooded paddy where rice

(*Oryza sativa* L.) thrives, using the unique morphological traits that allow rice to grow in a water saturated environment, to the highly fluctuating environment at the paddy edge which requires stress tolerant crops such as sorghum (*Sorghum bicolor* L. Moenche). A bank next to the paddy provides a niche for a deeply tap-rooted species such as pigeon pea (*Cajanus cajan* L. Millsp.) that requires a well-drained environment. Maize is planted on fertile sites where moisture is sufficient, but not in excess. Variable maturity genotypes of maize can be planted at different times in the growing season, to take advantage of shifting temporal niches.

A classic combination of plant species that illustrates the concept of sharing a niche is the maize – bean – squash (*Curcurbita pepo* L.) triculture grown by farmers from the semiarid southern US to the subhumid tropics of Eastern Africa. Maize is a fast growing grass, which photosynthesizes through the C4 pathway which allows it to thrive in hot weather, and to photosynthesize at times of the day and season when the C3-pathway plants such as bean and squash are not growing fast. The bean plant through its symbiosis fixes N, and thus minimizes competition for N with the other two species, while the sprawling growth habit of the squash tends to suppress invasive weed species and use a different portion of the canopy than the upright maize and bean complex (as the viney bean grows on the maize stalk).

Temporal separation of niches is common, as shown in Fig. 2.8A, where pumpkin flourish after maize is harvested. A spatial niche is illustrated in Fig. 2.8B, where soybeans are growing on the tops of ridges while a pigeon pea crop is growing in the furrow between ridges. This is expected to reduce competition, as root systems have minimal interaction when spatially separated in this

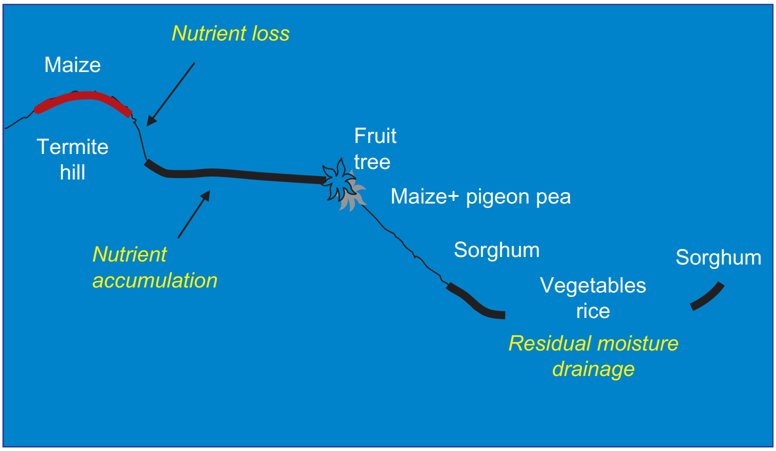

FIGURE 2.7 Crop placement across a farmscape. Farmers often locate high value and nutrient demanding crops at low spots in the topography, where moisture and soil fertility are least limiting.


(A) (B)

FIGURE 2.8 (A) Pumpkins grown as a relay intercrop in maize, producing a crop after maize is harvested. (B) Soybean growing on ridges and pigeon pea growing in the furrows between the ridges.

way, which facilitates sharing a habitat. This mixed cropping system maximizes yield per unit area, conserves soil through extended cover, and minimizes the risk of complete crop failure through the presence of diverse crop phenology.

COMMUNITY EVOLUTION

Community composition is influenced by the resources available and in turn, may influence resource quality, and the trajectory of the evolving community. That is, plants, associated symbiotic organisms, and animals that enrich soil nutrient status alter the habitat, and change species composition over time. One of the most ecologically important examples of plant species interaction with the soil resource is the interaction of N-fixing associations, such as the legume symbiosis with *Rhizobium* bacteria, which enhances soil N status through biological N fixation. The presence of N-fixing symbiosis also alters soil pH through associated acidification. Soil that is N-enriched may favor the dominance of grass species adapted to N acquisition early in the growing season, at the expense of legume species. Slowly, species composition will shift from legume-dominated communities to grass-dominated communities.

Management practices—planting desired species and suppressing others—speed up the process of succession observed in natural communities. Consider the following successional systems:

1. A crop rotation, where a sequence is followed, such as a 3-year rotation of maize – soybean – cotton;
2. A pasture, where a mixture of grasses and legumes are planted and the pasture community evolves over time, species being suppressed or augmented through intensity of management;
3. A tree plantation, where trees are intercropped initially with an annual crop such as common bean, then as the trees mature they are intercropped with a living cover crop such as mucuna, to suppress weeds and renew fertility.

Farm managers should take into consideration, and manipulate, the ecological processes that govern succession in each of these agricultural systems. A central question that is under active investigation is the ideal ratio of the legume component to the other components in the agricultural systems, and how this ratio is expected to change over time (Drinkwater and Snapp, 2007). Initially, the intensity of legume presence is expected to be a substantial component, particularly for a nonfertilized system. As the soil N status increases, and managers become concerned about the cost of expensive legume seed in a cropping system, or the bloat potential of legume tissues in a pasture system, a decreased legume presence will be appropriate. A pertinent example is pasture mixture recommendations, which often involve a shift from about 40% to 25% legume component, after a pasture is well established. Farm priorities, animal requirements, and environmental conditions will all influence the ideal proportion of legume presence.

Intensified production and removal of harvestable products in agricultural systems often exacerbates the N limited status of soil type, as grain and leaf products used for human consumption are N-enriched. However, N status is dynamic and at many points in time, or at specific locations in the rural landscape, P limitation may be a greater determinant of productivity than N (Fig. 2.9). In slash and burn forms of agriculture, P may be initially limiting as a flush of N is released from the ash of accumulated organic materials,

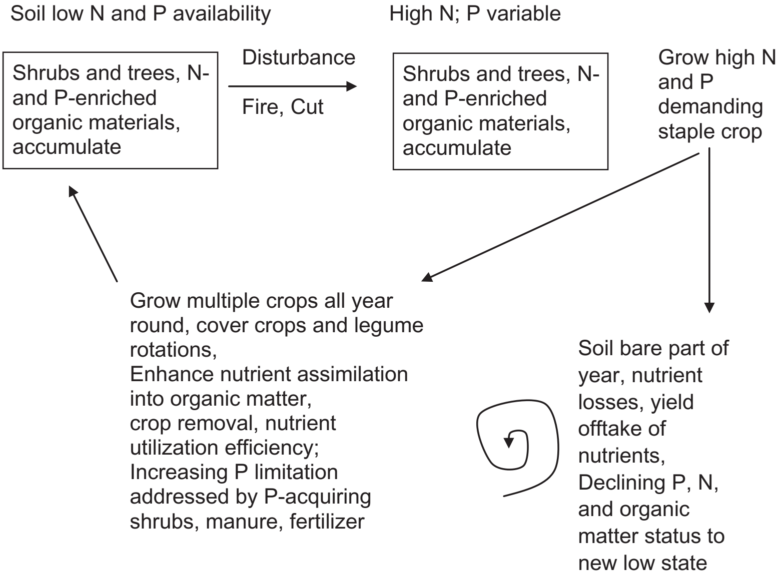

FIGURE 2.9 Nutrient dynamics over time in natural regeneration cropping systems such as slash and burn agriculture.

and from the disturbed soil of a newly cleared field. Phosphorus status will depend greatly on soil type, as well as on management in the recent past, and on the species grown at the site. Research has shown the P availability varies markedly from field to field in smallholder agriculture (Tittonell et al., 2005). Future investigations are required to determine the effect of plant species on plant-available P, and the efficiency of P fertilizer. Preliminary evidence is consistent with legumes playing a significant role in enhancing P availability, as shown by long-term studies of tropical pastures (Oberson et al., 1999) and crop rotations (Gallaher and Snapp, 2013).

Promoting the growth of deep-rooted, mycorrhizal and semiperennial species as intercrops or improved fallows will imitate a natural system, such as the rapid succession that occurs on stream beds or other disturbed environments (Jackson, 2002; Manlay et al., 2002). The principle of integrating plants with extensive rooting structures has been promoted as a means to enhance nutrient status. Nutrients are recycled from deep in the profile, and soil quality is built up through maintenance of continuous soil cover. Paradoxically, perennial-dominated cropping systems are highly competitive with, and will often suppress, annuals. During the early growing season, which is critical for the establishment and growth of annual crops, the presence of actively growing perennials will be highly competitive for water and light. Notable exceptions include a traditional cereal – tree intercrop system that relies on the reverse vegetation phenology of *F. albida*. This tree leafs out in the dry season, with minimal competition for water or light during the main growing season. In agroforestry, farmers generally manage to promote preferred species by frequent cutting of perennial branches, or limiting competition by growing species in different locations and separating plants in time.

Another commonly observed specialization of species that allows cohabitation in nature is through the different photosynthetic pathways and morphological traits that favor C3 grasses to grow most actively and photosynthesize during cooler times of the year, whereas C4 grasses tend to dominate during hotter times of the year. This complementarity has not been utilized to a great extent in designed agricultural “community assemblies.” One example is the buffered production of forage through mixtures of species to take advantage of the complementarity in growth of cool (C3) and warm (C4) season adaptation.

PLANT GROWTH TYPES

The ability of plants to cohabit in an ecosystem relates to many factors. Plant life strategies include growth types, resource acquisition mechanisms, and other key competitive and survival traits. Plant traits often vary in a coordinated manner, forming plant functional types. In agroecology, an emerging principle is to design combinations of functional types with complementary traits that form a productive community with resilient properties.

A useful typology for describing functional types is to use life strategies, where species are grouped into stress tolerators, ruderals, and competitors. Survival of organisms is divided into three strategies, adapted to ecosystems that vary in stress and disturbance. A survival type adapted for each habitat is described, except for the combination of high disturbance and high stress which induces mortality (Table 2.2; Grime, 2001). There is an extensive plant ecology literature based on three strategy groups, and this will be drawn upon in this chapter, although classification into two functional strategies—r and K selected species—is also common (r-strategists are opportunists with a high intrinsic growth rate and preferential allocation to reproduction, usually producing many offspring; K-strategists tolerate or avoid interference, allocate to vegetative and other non-reproductive activities, and produce a few large seeds, or care for their young among animals). Disturbance from fire or herbivory (insect or livestock damage), and stress from limiting resources (insufficient water, nutrients, or light) combine to describe three environments where organisms can survive. These are low disturbance, high stress (e.g., stress tolerators, such as perennials adapted to arid zones), low disturbance, low stress (competitors, including many rapid growing species with high plasticity), and high disturbance, low stress (ruderals, such as rapid maturing annuals, often pioneering species).

Annual crops and successful weed species are often ruderal plants. They are adapted to highly disturbed and high nutrient environments, with rapid growth that maximizes the ability to acquire resources, and utilize nutrients and fixed carbon for reproductive purposes. The leaf area index of ruderal crop plants is generally high, which is consistent with what might be termed a competitive-ruderal, and is important to the ability of crop plants to compete with weeds, as discussed below. Ruderal plant traits include minimal investment in stress toleration traits, such as tissue defense compounds against herbivores. The consequence is that insects and mammals prefer to consume plant tissues from ruderals that have few of the recalcitrant plant chemical compounds (e.g., phenols and lignins) that make tissues unpalatable and indigestible. There are trade-

TABLE 2.2 Strategies for Survival of Organisms

	Low Disturbance	High Disturbance
Low Stress	Competitors	Ruderals
High Stress	Stress tolerators	Mortality (no viable strategy)

offs for farmers between growing crops that are highly insect resistant—that grow slowly and produce defensive compounds—and growing crops that rapidly produce desirable food products, which are susceptible to herbivore damage.

Among crop plants all three growth types are represented, e.g., common bean is classified as a ruderal given its rapid growth habit, early reproductive phase, edible, and highly pest-susceptible tissues. In contrast, soybean is also a grain legume yet has many traits that are more often associated with the stress-tolerator group. This includes a range of plant growth types, and defense traits such as pubescence that discourages insect herbivory, and biochemical compounds that require processing for humans to obtain nutritional value from soybean grain. Maize has competitor traits, including highly effective nutrition acquisition mechanisms such as N mineralization-inducing root exudates, high N uptake activity, and a large nutrient demand (sink capacity). The design of cropping systems should take into consideration what are complementary combinations of functional traits, such as a highly competitive crop mixed with a resource-sparing ruderal type.

Weed species have life cycle characteristics that mimic or are closely aligned with the life strategy of the infested crop species. Diversification with different life forms in rotational and intercrop systems will reduce the success of a mimic strategy. That is, weed species with similar life cycles to crop species will be disturbed and suppressed to the extent that an agricultural system incorporates different life cycles. Examples include the use of a pasture or forage rotated with crops to suppress persistent weeds, or relay planting of a long-growth duration, viney legume crop into a short season grass crop to suppress annual grass weeds. *Mucuna puriens* is one of the most widely grown green manure species, in part due to its ability to suppress aggressive grass weed species such as *Imperata cylindrica* (Tarawali et al., 1999).

Identifying organisms that contribute to sustainability, while simultaneously producing harvestable products, is central to the design of ecologically based farming. However, the coordinated evolution of plant traits and biological constraints has led to close linkages, in many cases with traits that are not compatible with high yields. For example, it has been the goal of researchers for decades to develop stress tolerant plants that can grow in saline soil, or with minimal water. Yet stress tolerant traits include a slow growth rate, a perennial habit, and production of defense compounds. To adapt farming to a highly stressed environment, a shift may be required from the focus of current research, which emphasizes annual production and a large "harvest index" (yield as a percentage of aboveground biomass), to instead consider perennial plants with indeterminant growth habits. There are perennial food crops to be used as models, including oil crops—e.g., avocado (*Persea Americana* Mill.) and the West African shea nut (*Vitellaria paradoxa* L.), and carbohydrate crops, e.g., banana (*Musa acuminata* Colla), and the Ethiopian enset (*Ensete ventricosum* Welw. Cheesman).

Developing perennial crops from annual grains is a far-reaching goal, yet this is being pursued by scientists both through domestication of perennial relatives of annual crops, and through breeding perennial traits into annuals. There has been progress in selecting for perennial grain sources among wheat breeders, where perennial wheat selections produce about 40% of the yield of annual varieties, see recent findings at: http://pwheat.anr.msu.edu/. As expected, initially trade-offs are severe between perenniality and annual grain yield, as photosynthate investments in cold tolerance mechanisms and deep root systems are expected to reduce the amount of photosynthate available for reproductive grain. In general, perennials are associated with much lower human "offtake," around 10% of aboveground plant productivity compared to 50% or so for annuals (Cox et al., 2006). However, efforts to improve productivity of perennial cereals are under way (Box 2.1), and recent research has highlighted the high photosynthetic rates achievable with perennial analogs relative to annual wheat and rye (Jaikumar et al., 2014).

Rural inhabitants in many environments use indigenous knowledge of plant products, and have found slow growing stress tolerator perennials to be important food and medicine sources, particularly in drought years (Fig. 2.11). The use of Basul (*Erythrina edulis*) or "tree bean" of the Andes is an example of this system. Basul is a shrub that is grown often along property lines or in gardens, where it provides important risk mitigation in drought years as its dried seeds are an important nutritional safety net. It is a relatively rapid growing pioneer species so a ruderal among shrubs, but a stress tolerator compared to short duration annual grain legumes.

Ecologists widely debate which traits to consider, and which categorization systems to use to evaluate species and predict performance. Grouping of species into functional groups can be conducted using many different traits, from life forms to growth habit. Useful criteria for agroecology applications include grouping species by length of growing season, determinancy and indeterminacy, and ability to grow in a compensatory manner. These traits influence which species are adapted to different locales and timing sequences within a farming system. Photosynthetic pathways, and thus growth response to hot and dry environments, are also useful characteristics to consider as functional categories. For example, C3-pathway species such as wheat are adapted to cool conditions, and C4-pathway species such as maize thrive in warm seasons and locations. Combinations of C3 and C4 grasses are the basis for many successful pasture systems.

An approach that has begun to be explored for designing cropping systems is to consider combining plants from a continuum of symbioses. Trisymbioses are represented by the vast majority of legumes, which are

BOX 2.1 Perennial Crops

In Kansas, USA, the Land Institute has pioneered efforts to develop perennial grain crops, including genotypes related to sorghum, sunflower (*Helianthus annuus* L.), and wheat (*Triticum aestivum* L.). At Washington State University, plant breeders have worked for over a decade to produce a variety of perennial wheat that could be planted about once in 3 years, and grain harvested each year (Fig. 2.10). This would conserve soil, reduce input costs, and generally diversify farmer options for environmentally friendly farming. The winter hardiness, yield potential, and quality traits of perennial wheat varieties are highly variable, and genotypes will require further development. Farmers are interested in perennial grains, particularly those who grow crops on steep slopes or are looking for a means to radically alter weed population dynamics, while reducing tillage. A much longer development process is required to develop a perennial grain legume crop for temperate or subtropical regions. There is a semiperennial tropical grain legume available, if one considers that pigeon pea is often "ratooned" or cut back after harvest, and a second or third harvest is obtained. A recent meeting convened by the Food and Agriculture Organization in Rome, Italy, found promising opportunities to be pursued, see http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/fao-expert-workshop-on-perennial-crops-for-food-security/en/.

FIGURE 2.10 Perennial wheat varieties undergoing testing at Kellogg Biological Station, Michigan State University, USA. *Photo taken and used by permission of Brook Wilke.*

associated with both rhizobia and mycorrhizal symbioses. Most crop plants have mycorrhizal symbionts, only. Some crops are highly mycorrhizal-dependent, such as cassava (*Manihot esculaenta* Crantz) and onions (*Allium* species). Brassica species and a few other crops are interesting exceptions

FIGURE 2.11 A wide range of products are produced by perennial legumes.

as they are not mycorrhizal, and are often associated with the suppression of soil fungi. This is consistent with the use of brassica species as a "break crop," to include in a rotation sequence to suppress disease organisms or at any rate, alter soil biota considerably (see chapter: Designing for the Long-term: Sustainable Agriculture, for more on the sustainability implications of agro-diversity).

ECOLOGICAL PRINCIPLES APPLIED TO AGRICULTURE

Natural plant communities illustrate principles that can be used to improve the resilience of cropping systems, and to enhance efficiency (Knops et al., 1999). Agricultural systems that cycle energy and nutrients in an efficient manner can be termed semiclosed, and will have low requirements for external inputs. There is a continuum from natural ecosystems where no products are removed, which can be termed closed systems, to semiclosed systems with foraging (e.g., natural ecosystems with limited removal of products, such as reproductive parts of trees and fungal organisms), to semiclosed systems such as those discussed in this book (e.g., those that rely on biology to reduce farming systems losses and replenish resources), to an open, and highly productive, conventional agricultural system. Open systems have high resource-requirements, and the potential for significant leakiness, particularly if they are productive.

The discussion that follows presents ecological pillars in tropical agroecology that can be applied to tighten nutrient and energy flows, for more stable and efficient function. These principles have been called complementarity, redundancy, and mosiacs by Ewel in his seminal paper (1986). This work has been extended, with in-depth consideration given to complementarity and mosaics, diversity, successional patchiness, and landscape ecology for sustainable agriculture by, among others, Wojtkowski in his 2003 book on Landscape Agroecology.

COMPLEMENTARITY

The theory of niche differentiation is a useful concept to optimize the design of plant combinations for complementarity of species across time and space. To maximize productivity in agroecology requires careful consideration of Gause's (1934) theory that two species cannot occupy the same ecological niche at the same time. This is the origin of our understanding of "competitive exclusion"; if two organisms have similar niches, over time one will generally exclude the other. Overlapping patterns of land use, such as relay cropping and taungya, semisequential tree and crop systems, must minimize competitive exclusion while maximizing resource capture through complementarity. Resources such as light and nutrients may be underutilized in cropping systems that are based on monocultures of annuals, particularly during the period at the end and beginning of the planting cycle when resources tend to be in excess of plant demand. For a detailed discussion of the theory and practice, see the book "Agroecology: The Ecology of Sustainable Food Systems" (Gliessman, 2007).

Species used in mixed cropping systems ideally have complementary traits, such as short and long-duration growth habits, which, when combined will ensure the capture of sunlight and recycling of water and nutrients throughout the growing season (Snapp et al., 2010). Characterizing species based on such traits as growth habit, pest tolerance, maturity date, and nutrient acquisition strategies are useful first steps in considering which crops combine well. These factors are the basis of complementary intercrops that are widely grown, such as mixtures of cereal and legume species, e.g., maize – bean and sorghum – cowpea (*Vigna unguiculata* L. Walp.). Not only is resource utilization enhanced through the complementarity of these species combinations, but fostering a diversity of species in a farming system will enhance pest resistance through promoting beneficial insects and suppressing pest outbreaks (Knops et al., 1999).

There is a diversity of traits present, even in closely related organisms. This can be illustrated for domesticated legume species (Fig. 2.12). Many have contrasting growth habits, which has consequences for the harvest index and the nutrient status of residues. If a plant has a short maturation period and determinant growth habit, then it will usually have a high harvest index. There has been considerable plant breeding effort over decades to select for greater

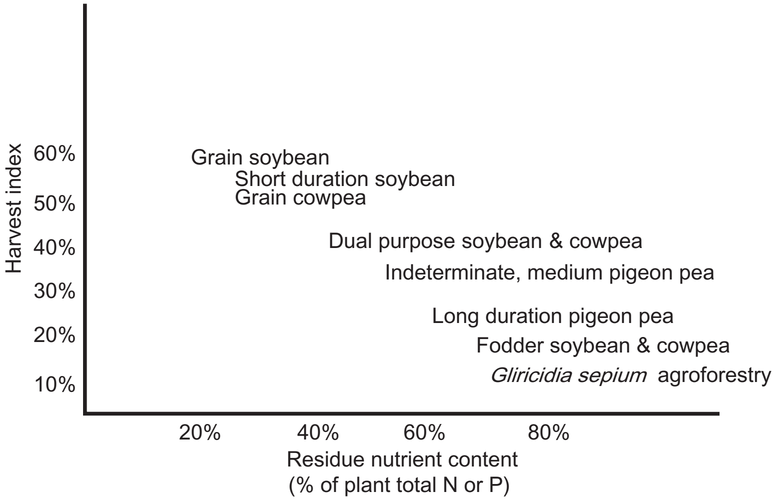

FIGURE 2.12 Legumes domesticated for agricultural use vary in harvest index, and this trait is inversely related to the nutrient content of plant residues as nutrient offtake is high as harvest index increases in high yield potential crops.

determinacy, resulting in a wide range of yield potential and plant growth types. An example of the range possible is provided by pigeon pea, a species that is a short-lived perennial managed as an annual or biannual, whereas indigenous varieties may take more than 300 days to mature. Plant breeding efforts have developed very early maturing pigeon pea growth types that can mature in less than 80 days. This provides a tremendous diversity of plant growth types for farmers to experiment with, and to integrate into a farmscape.

There is generally a trade-off between residue nutrient content in determinant and indeterminant growth habits (Fig. 2.12). That is, determinant plants have limited amounts of low nutrient content residues, as nutrients have been remobilized to reproductive tissues and removed as harvestable products. In contrast, plants with a long maturation period and indeterminant growth habit often have nutrient-enriched residues. Although yield potential may be limited, there are multiple benefits associated with plant types that combine a modest amount of food production with nutrient-enriched vegetation that can be used as a vegetable, as livestock fodder, or to build up soils. An example is provided by long season, climbing bean genotypes which fix more N, and acquire more P, than determinant bean types.

Indeterminant, long-duration plants are generally successful candidates to be grown as multipurpose crops on field margins and around field perimeters. It is important to take into account the range and type of products that indeterminant plants produce. Multiple harvests of leaves for vegetable use may occur along with grain yield at the end of the growing season, and yield potential may be substantial from indeterminant plants. Farmers often value these secondary products highly, but they are difficult to measure as they require labor-intensive, multiple harvests and attention to complex quality traits associated with high moisture vegetables or medicinal products. For all of these reasons, secondary products may be undervalued by researchers.

Farmers are often aware of and value multifunctional traits (Mhango et al., 2012). Participatory action research has become a particularly valuable tool for highlighting secondary plant products, and the varietal preferences of marginalized groups such as female heads of households (see chapter: Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers). Many legumes produce, in addition to grain, vegetable products such as pods and leaves. Small amounts of fuel, construction materials, and leaves are produced by indeterminant crops such as sorghum (Fig. 2.13). Stover from dryland crops are essential livestock fodder sources. Perennial agroforestry species such as *Gliricidia sepium* are shown on the lower right corner of Fig. 2.12, as these plants have few or no immediate food products (harvest index approaching zero), but have many secondary products, including soil fertility enhancement, forage, fuel wood, and construction materials.

Design of complementary species mixtures must take competitive interactions into full account. Ideally plants with complementary root and shoot systems can be grown together. As shown in Fig. 2.14, pigeon pea has a deep tap root compared to an intercrop determinant species, thus minimizing competition with shallow-rooted crops such as peanut (also termed groundnut; *Arachis hypogaea* L.). Pigeon pea has a very slow growth rate initially, which facilitates temporal compatibility with most crops. However, it is important to consider the tremendous plasticity of root systems. If the topsoil has substantially higher nutrient and water content than the subsoil, then the

FIGURE 2.13 Mali farmers value sorghum and millet tover for many uses, including livestock fodder and as construction materials.

vast majority of perennials will explore the topsoil, as well as foraging deep, and thus will directly compete with shallowly rooted annual crops. Physical barriers that preclude deep rooting exist in many tropical soils as well, such as laterite layers.

Active management in agroforestry systems is critical to successfully suppress tree root activity in favor of crop roots. Management practices include frequent shoot pruning, which enhances root die off, and partial burning of tree branches or aboveground portions of a tree on an occasional basis. Careful choice of species and placement of trees are some of the more effective means to separate tree and crop roots, as shown in a *Gliricidia* – maize intercrop system in Malawi (Makumba et al., 2006). To this end, the *Glyricidia* shrubs are often grown along terrace bunds, in furrows between ridges, along perimeter mounds, or separated in time, as illustrated by improved fallow systems (see chapter: Farming Systems for Sustainable Intensification).

In the subhumid tropics, N is the nutrient that limits productivity by a substantial margin (phosphorus and micronutrients rarely limit growth, except in the more extreme environments of specific soil types, and in very arid or humid climates). Thus, minimizing competition for N is important, which is often addressed by using legume intercrop species. However, the presence of a legume does not guarantee an effective symbiosis. The consequences of intercropping maize with the nonfixing legume *Senna spectabilis* are presented as a cautionary tale (Box 2.2). There are inherent time demands associated with managing multiple species, and inherent biological variability, which can be significant barriers to the adoption of agroforestry systems (Sirrine et al., 2010).

Sequential rotation systems are one of the most successful means of integrating complementary species over time, where sufficient land is

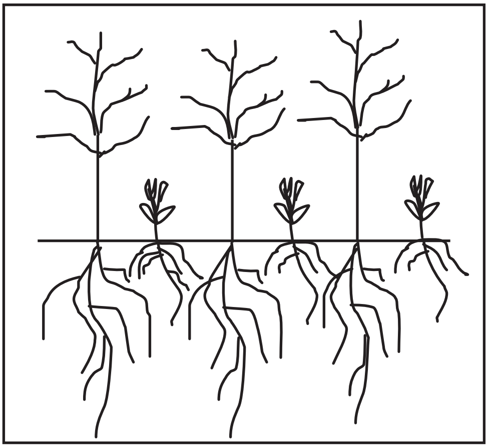

FIGURE 2.14 Spatially and temporally compatible legume intensification system: long-duration pigeon pea and maize, or medium-duration soybean or peanut.

BOX 2.2 Competition and Hedgerow Intercrops

Senna spectabilis is a tropical legume that has been promoted as a hedgerow intercrop species for agroforestry systems. It has N-enriched leaves (~3.2% N) and is an easy to establish species, one that produces large amounts of N-enriched biomass faster than many N-fixing species (Table 2.3). However, the discovery that *S. spectabilis* did not symbiotically fix N raised an urgent question, where was the N-enriched status derived from? The plant traits that support high leaf N content *S. spectabilis* were shown to include a highly extensive, plastic root system that could branch rapidly in the presence of inorganic soil N and rapid N uptake and assimilation capacity. This agroforestry species acts as a highly effective weed species, and has traits that maximize its ability to compete with cash crops. Promotion of *S. spectabilis* based on tremendous biomass production potential was an insufficient criteria, and may have been based on performance on research station trials, where soils of high organic matter may not have been representative of smallholder farm environments. Biological review of *S. spectabilis*, and testing on-farm, revealed the highly competitive nature of this species, and its unsuitability as an intercrop species.

TABLE 2.3 This Information on Tropical Legume Biochemical Composition Is Based Upon the Tropical Residue Quality Data Base Developed by Cheryl Palm and colleagues (2001)

Species (Latin name)	Leaf Biochemical Composition	Growth Duration	Uses
Mucuna	3.8% N 4.0% sPP 6.6% Lignin	Annual indeterminant viney bush (long duration annual)	Soil fertility enhancement, grain (requires processing)
Pigeon pea (*Cajanus cajan*)	3.5% N 3.0% sPoly 10% Lignin	Short-lived perennial bush; annual varieties (termites and nematodes reduce life expectancy)	Grain, vegetable pods, fuel wood, forage, soil fertility enhancement, medicinal
Crotelaria species	4.1% N 2.6% sPoly 4.0% Lignin	Short-lived perennial bush; annual varieties	soil fertility enhancement, forage
Tephrosia vogelli	3.0%N 5.9% sPoly 8.0 Lignin	Short-lived perennial bush (termites reduce life expectancy)	Soil fertility enhancement, fuel wood, improved fallow
Sesbania sesban	3.4% N 3.8% sPoly 6.7% Lignin	Short-lived perennial tree	Soil fertility, poles, improved fallow
Senna spectabilis	3.1% N 3.4% sPoly 15% Lignin	Perennial nonfixing legume tree	Soil fertility enhancement as a hedgerow
Gliricidia sepium	3.5% N 3.8% sPoly 15.5 % Lignin	Perennial, managed as a bush	Soil fertility enhancement as a hedgerow, fuel wood
Leucaena	3.0% N 8.8% sPoly 16.7% Lignin	Perennial, managed as a bush	Soil fertility enhancement as a hedgerow, fuel wood

N, Nitrogen; sPoly, total soluble polyphenols as a percentage of leaf weight; Lignin, complex polymer that acts as a binder in cell walls.

FIGURE 2.15 An Andean 7-year rotation cropping system involves partitioned fields and planned sequences of crops to suppress pest populations.

available to follow this practice. In the Andes a traditional system is the 7-year potato crop rotation that incorporates: (1) a nutrient accumulating phase (several years of grazed pasture with manure additions, 1 year of grain lupin (*Lupin mutabilis* L.) which is a N-fixing and P solubilizing legume followed by a small grain such as barley which builds soil aggregation and organic matter); (2) a high nutrient demanding tuber crop, grown every seventh year, such as potato (or at higher altitudes indigenous tubers such as oca, *Oxalis tuberosa*), provides cash income and a staple food product. The 7-year cycle may seem long, but it disrupts and suppresses a major nematode pest with a 6-year life cycle. The diversity of crops (six crop species) over time and space provides pest cycle disruption, habitat for beneficial insects, and a wide range of food species that buffer against weather risk. Traditionally, these complex rotation systems were systematized by dividing fields into seven or more parcels, and rotating crops through the designated areas (Fig. 2.15).

An interesting multiple species system that is used in the subtropical and subhumid tropics of Australia, and in the Americas, revolves around rotational pasture grazing. A mixture of grasses and forage legumes is rotationally grazed by cattle. This system optimizes plant growth and quality by carefully controlled and intermittent grazing. Controlled grazing stimulates forage regrowth, maximizing production of highly palatable vegetative tissues. In a multispecies version of this system, poultry are either included with cattle, or are sequenced immediately after cattle graze using movable poultry pens. This is a labor-intensive, but ecologically sensible design. Poultry are one of the most energy-efficient forms of livestock, and are highly effective at consuming grubs, including cattle pests that thrive in manure. Thus, system performance and resilience to pests are both enhanced by including organisms that fit different components of a complex food web (Fig. 2.16).

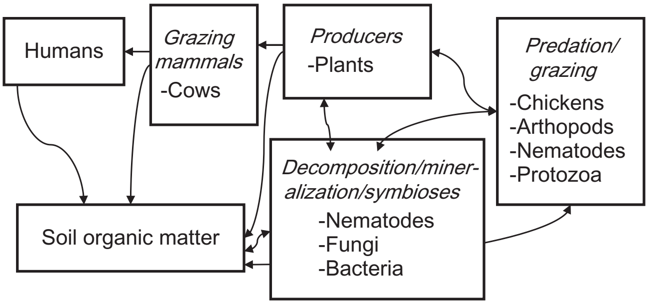

FIGURE 2.16 Soil food web associated with a pasture farming system.

Animal – crop interactions involve careful consideration of species composition, weather, and timing. Climate variability can be addressed through attention to complementarity in species choice, and utilizing the mobility inherent in livestock that can be used to reduce, or intensify, grazing, as required. Combinations of species can reduce risk, and improve resource utilization. If one plant or animal species does not thrive at a specific locale in a given year, due to the precipitation or temperature regime that year, then another species has the potential to compensate. To optimize the productivity of farming systems, attention to plant associations is essential, as plants are the primary producers on the farm, supporting livestock, the soil food web and, ultimately, the human consumers (Fig. 2.16). Agroecological principles of complementarity provide a base for the design of plant associations over time and space, where animal interactions are beginning to be elucidated as well.

REDUNDANCY

Redundancy is another key design principle, one that acts as a buffer to ensure that organisms representing different functional groups are present. By redundancy we refer to the deliberate inclusion of several organisms with similar features. This can be thought of as an insurance policy (Naeem and Li, 1997). A high degree of redundancy is often found in natural ecosystems, in addition to complementarity. A clear example is provided by soil biota. Functional redundancy is often present. This means that many soil organisms perform very similar functions, such as decomposers, thus soil communities appear to be quite robust (Susilo et al., 2004). This holds up across many trophic levels. Tremendous functional redundancy throughout the soil food web is shown in Table 2.4 for ecosystem services (e.g., nutrient cycling, carbon sequestration, and disease suppression). Characterization of soil microbial communities along agricultural intensification gradients have documented that a long shadow can be cast by historical land use. Decades on, soil biota reflect historical legacies and often have disparate communities; yet, they

TABLE 2.4 A Summary of How Agricultural Management Practices Influence Soil Biological Organisms, Grouped by Function

Management Practice	Biological Groups	Function
1. Macro disturbance (burning, tillage, and pesticide use) 2. Shift in nutrient management (legume species, manure use)	1. Meso/macro fauna: shredders and engineers 2. Residue microorganisms	Residue decomposition
1. Macro disturbance (burning, tillage, and pesticide use) 2. Shift in plant species (perennial to annual, deep-rooted to shallow, change in residue quality)	1. Roots 2. Microorganisms	Soil C sequestration
1. Shift in plant species (cereal to legume) 2. Nutrient management (fertilizer, manure use)	1. Free and symbiotic N-fixing organisms Example: *Rhizobium*	Nitrogen fixation
1. Shift in plant species (cereal to legume) 2. Nutrient management (fertilizer, manure use)	1. Microorganisms (particularly bacteria with phosphatase activity and AM fungi)	Phosphorus solubilization
1. Macro disturbance (burning, tillage, and pesticide use) 2. Irrigation	1. Roots 2. Microorganisms 3. Macro and meso fauna Example: fungal hyphae	Soil aggregation
1. Compost application to sealed soil crust	1. Macro and meso fauna Example: Termites	Soil porosity
1. Crop species diversity 2. Compost	1. Diverse soil food web Example: AMF competition and exclusion suppression of *Rhizoctonia* root rot	Disease suppression
1. Crop species diversity 2. Input use (fertilizer, pesticide) 3. Disturbance	1. Predators, grazers, parasites, pathogens Example: entomopathogenic bacteria and fungi control of white grub	Pest population control

maintain similar soil functions. Redundancy may play a key role in resilience, but also makes it challenging to alter the soil biology of agricultural systems (Schmidt and Waldron, 2015). This was documented in Kenya, using soil sampled along a gradient from forests to agroforestry, to intensive cropland. Strong legacy effects were shown in terms of soil microorganisms present, simultaneous with redundancy in functional capacity to degrade diverse substances (Lagerlöf et al., 2014). This indicates that historical management of soils casts a long shadow. In a practical sense, it means that it may be necessary to add large amounts of organic amendments, or alter tillage dramatically, in order to shift soil biology to improve agricultural function.

One challenge to designing productive agricultural systems using this principle is that redundancy has the potential to suppress productivity. Indeed, competitive interactions are high when similar organisms are grown together. There are concerted efforts to minimize this problem in crop production, as generations of breeders have selected for ideotypes that have a high tolerance to dense populations. Examples include wheat and maize; these crops illustrate how an upright plant type and erect leaves can minimize intraspecies competition for light. Advantages of managing for a high density of plants with redundant features can include reduced pest problems, and enhanced ability to exhibit compensatory growth (Ewel, 1986). At the same time, agricultural intensification for high production through input use has often been closely associated with reduced redundancy (Laliberté et al., 2010). Deliberate consideration in design may be needed to counteract a tendency toward genetic simplification and loss of redundancy in modern, high input agriculture.

Environment plays a large part in the relevance of redundancy features to agroecosystem design. If water is not scarce, this strategy has great potential for success in tropical environments, as light is rarely limiting in the tropics, and competition for water is the major factor that reduces productivity in close plant associations. Conversely, there are many advantages to "built in" redundancy under high moisture environments, as multiple layers of leaves will reduce rainfall impact and protect the soil resource from erosion. In addition, phosphorus nutrition and availability to crops depends on the organic fraction of soils in many humid tropical soils. Highly leached soil chemistry has a high P-fixation capacity that can be circumvented through maximizing P uptake in plant residues and cycling P through the organic pool—which requires large amounts of vegetative growth. This topic is further explored in Chapter 7, Ecologically-Based Nutrient Management.

Redundancy is a feature of cropping systems based on genotypes that exhibit diversity within, as well as between, species. It is often possible to find species that have overlapping sets of traits, with stress responses that are related, but distinct. Enhanced pathogen resistance can be achieved, e.g., through combining isogenic or closely related varieties that have slight differences in plant resistance genes. This has been termed a "multiline" approach, and has been adopted to control disease outbreaks in Chinese rice production, among other cereals (Mundt, 2002). The deliberate combination of varieties is a useful strategy, as complementarity between specific genes is united with the redundancy inherent in combining closely related genotypes.

An intercrop system that has both complementary and redundancy features is a legume – legume intercrop that combines early and late maturing species (Fig. 2.14). An example is a pigeon pea – peanut intercrop, which is grown by smallholder farmers in India. A variation of this system is the "doubled-up legume" system, a pigeon pea – soybean intercrop which is being experimented with in Northern Malawi (Snapp et al., 2002; and see Fig. 2.8B). The functionally identical system of pigeon pea – peanut (also called groundnut) was released by the Malawi Government in 2016 as a novel technology that produced two food crops while improving soil fertility (Snapp et al., 2010). Note that both species are seeded at the same time, the peanut grows as an understory, and the longer duration pigeon pea shrub grows slowly initially, until after the peanut harvest. This complementarity in growth pattern minimizes competition for resources. This intercrop has the redundancy of including two legumes. The N-fixation pattern of the two species mixture is expected to be of longer duration than N-fixation of either crop grown alone. Further, species vary in tolerance to various stresses, and the combination provides a buffered response to a stressful environment. If we consider the earlier example, pigeon pea is sensitive to flooding events, but relatively tolerant of soil acidity. Thus, the combination of pigeon pea and soybean (or peanut) will be able to respond to either stress through the redundant presence of two N-fixing symbioses.

The intermediate growth habit of a short-lived, N-fixing shrub has many redundant features. The moderate stature and indeterminant growth habitat are generally adapted to browsing by mammals and insect herbivory, with rapid regrowth capacity and unique suites of plant biochemical compounds. The tissues of shrubby species often have defense compounds such as polyphenols that provide intermediate effectiveness against herbivores; but not the highly lignified or waxey tissues of long-lived trees, nor the high palatability of vegetative tissues of annuals (Table 2.3). Investment in relatively "low cost" defense compounds such as polyphenolics is evolutionarily sensible for tissues of intermediate lifespan. Examples of common tropical legumes, including leaf composition and plant growth type, are shown in Table 2.3. Tissue biochemistry varies markedly in these species, and is influenced by soil nutrient status, tissue type, and age of the plant organ. The consequences of plant biochemistry are only beginning to be understood, including the impact of residues on soil organic matter, on N mineralization, and on the diet of insects and mammals. Legumes play unique, multipurpose roles in farming systems, but require careful testing to determine the long-term influence of above and below-ground residues.

Designing for genetic diversity at both the species and cultivar level can help ensure redundancy, as well as functional complementarity.

Examples of species redundancy include growing similar cereals such as two C4 cereals that thrive in hot environments: e.g., maize and sorghum. To further enhance redundancy farmers can grow diverse germplasms of both species. Redundancy through growing similar crop species, and multiple cultivars of each species, can help ensure farm resilience to shocks, whether imposed by weather extremes, shifting markets, or pest outbreaks. There is a very large body of research on the regulation of pests through managing genetics. Pest life cycles often require management at the landscape level, and attention to genetic diversity across farms and communities (Hajjar et al., 2008). The next section of this chapter shifts to this landscape ecology perspective.

MOSAICS

Landscape ecology provides many insights into the impact of land use structure and the function of agricultural systems (Wojtkowski, 2003). For example, a mosaic pattern of growth has been shown to be common in natural ecosystems. Localized disturbances tend to bring about a mosaic of diverse age structure in a community, as long-lived plants are blown over or uprooted by storms, and young plants colonize the location where light and nutrients are suddenly available. In a similar manner, perennial and annual plantings of different age structures in an agricultural landscape can be planned, as strategies to both reduce risk and enhance returns. A mosaic pattern is often associated with more stable productivity over time than more uniform land management. This is in part due to climatic variability, as extremes in weather will often be tolerated by some at least of the diverse species present in mixtures spread across a landscape, while a monoculture of any given species could be devastated.

High productivity is common at the boundaries of different land uses, such as the interface of perennial trees and annual fields. An edge effect is often observed on the perimeters of experimental plots as well, which is why yield measurements are conducted toward the center of plots, away from a potentially distorting edge. This has led to the contention by some that mosaic land use is inherently more productive than monoculture agriculture. Indeed, light availability and altered wind patterns are some of the processes at work that influence yield potential at edges and interfaces between land uses. However, productivity will vary greatly over a mosaic of widely varying plant types and mixtures. The presence of perennials displaces some annuals, and this can lead to reduced production potential for staple foods across the entire land area, despite local improvements in yield potential. This aspect of trade-offs and risk needs to be carefully assessed. Farmer participatory research on agroforestry in Southern Malawi has highlighted the sometimes unexpected food security risks associated with integration of new perennial species into farming systems (Sirrine et al., 2010). If land access is limited, then the success of a mosaic may depend on the presence of perennials that produce relatively high value crops, such as staple food or horticultural products. For example, if perennials of different age and size categories produce marketable products such as coffee or nuts, then mixtures of perennials may be economically feasible, as well as environmentally sensible.

A mosaic land use pattern may be particularly valued by managers facing diverse landscapes, and changeable weather. Farmers contending with a highly variable climate will find a diversity of plant types and age classes important, as a means to buffer weather extremes and erosive forces. Mosaics are highly suited to farmers engaged in marketing a range of products, in high rainfall areas, with access to sufficient land. By contrast, high population density areas with small farm sizes and relatively uniform conditions will tend to prioritize productive cereals such as maize or rice.

Microclimate variation is high in mountainous regions, and small differences in elevation can be utilized in areas that have variable topography. The Andes has been an ideal location to develop highly complex cropping systems that utilize diverse altitude niches (Fig. 2.17). This spreading of crops across the landscape and at different elevations prevents catastrophic crop failure from localized weather, or insect pests. Producing seed crops is often

FIGURE 2.17 Mountainous terrain and alluvial valleys provide a wide range of niches for growing crops at different altitudes and in a range of environments, a common risk avoidance strategy in the Andes.

carried out at higher altitudes to take advantage of low insect and virus loads in colder zones. Instead of controlling through expensive insecticides, the use of high altitude ecozones is a prevention strategy that takes advantage of the isolation and minimal insect pressure at high altitude locations, ideal conditions for producing high-quality seed. This strategy is particularly important for clonal propagation materials, such as potato tubers, for seed.

The interplay of socioeconomic and biophysical complexity is nowhere more dramatic that at the interface of land and water. This is often the most contentious of land use areas, with very high production potential, and a mosaic of diverse and often conflicting management objectives. Farmer management is often informal but intensive, as is beginning to be appreciated for drainage zones, wetlands, and riverine environments throughout the developing world. The Amazon flood plain, e.g., was once thought to be a natural area exploited by farmers through recessional planting after flood waters recede. Yet recent findings illustrate that human interventions along the Amazon include centuries of channel building, mound erection, and soil dredging, to replenish soil fertility and intensify crop production. In China, the recycling of nutrients through dredging and hauling soil from water ways to fields was historically a primary nutrient cycling pathway, one that required considerable labor but was highly effective.

Land use is a dynamic process. Extensive use such as livestock grazing is replacing crop production along many Latin America waterways, while the opposite trend of intensification is occurring along drainage zones in southern Africa. Promoting farmer experimentation and diversification of land management requires close attention to indigenous knowledge and current land use patterns, as highly valued crops and nutrient responsive crops are often located very precisely within intricately managed landscapes (Fig. 2.7). Alterations in land use have long-term ramifications that are difficult to predict. In sum, management of mosaics is a complex undertaking that requires attention to climate, topography, and stakeholder objectives, as well as long-term planning horizons.

A paradigm that is often evoked in discussions of landscape mosaics is that of “land sharing” versus “land sparing” (Perfecto and Vandermeer, 2010). The evidence is still out regarding whether management for high yield on one portion of land is associated with reduced pressure on other land, and subsequently, on enhanced opportunities for wildlife conservation and environmental service generation. A strong counterargument values the land sparing approach, and the role of mosaics in agricultural land use, along with corridors. These facilitate colonization and related mechanisms that help prevent species becoming extinct (Perfecto and Vandermeer, 2010). These are a few of the emerging issues, but the socioecological complexity of land use decision-making should not be underestimated (Fischer et al., 2008). Further research is urgently needed into the role of mosaics and land sparing approaches in resilient rural landscapes.

FARMING SYSTEMS BY AGROECOLOGY

Cropping system challenges are specific to climatic zones. Agroecology design requires comprehensive understanding of the variability in moisture and temperature gradients, and in soil resources. For example, the length of the growing season will determine the intensification options that can be pursued. If cold or dry conditions limit the growing season to a few months, there will be few viable plant-based technologies that restore soil fertility, which increases the requirement for external inputs. Extensive options, such as silvopastoral systems, are also well suited to short season climates. An agroecological perspective is presented below on the specific challenges faced in dry versus humid environments.

Arid environments are marginal for many farming system endeavors, as plant productivity is limited by insufficient and erratic rainfall. Return to inputs is often limited and highly variable, increasing risk markedly. It is difficult to predict when or where to apply external inputs and labor. Livestock play a unique role in dryland farming, being able to move in response to climatic variability, and concentrate nutrients in a low productivity environment. Grazing animals convert low quality plant residues into valuable products, such as meat, milk, and manure. Livestock integration with crop production helps reduce risk through transfers between the two systems. Application of manure builds soil organic matter and water holding capacity, for improved crop production, while crop residues are crucial components of livestock feed. Box 2.3 illustrates how climate, and farmer investment in

BOX 2.3 Livestock and Crop Integration

The ratio of livestock to crops varies depending on aridity, the extent of grazing area and cropland, and socioeconomic context. An animal unit of one cow, or two small ruminants, can produce 1–2 tons of manure annually, and requires about 1 ha of grazing land. However, the quality of plants grown will markedly alter the area of required grazing, from 15 ha of dry savannah per cow in southern Zimbabwe, to 0.2 ha of planted legume – grass fodder per animal in Kenyan stall-fed dairy systems. The amount of manure required to support cropland will also vary, depending on feed quality and animal species. Approximately 5 t/ha of manure will appreciably improve cereal grain yields, based on recent findings from subhumid and semiarid on-farm trials carried out in East and Southern Africa (Ncube et al., 2007). Recommended rates of manure application tend to be higher, as much as 10–40 t/ha for maize production in Zimbabwe. Overall, crop – livestock system ratios of about 5:1 appear to be sustainable, five animals on 5 ha of grazing land for every hectare of crop land. Access to land is often insufficient to support this ratio, and innovations in fodder and livestock systems are required—as is discussed in depth in Chapter 7, Ecologically-Based Nutrient Management.

fodder and animals, interacts to determine resource use efficiency in crop – livestock systems.

Extensive versus intensive use of land and labor are challenging questions in dry environments. Many traditional systems rely on reducing risk by minimizing investment in seeds. Planting seeds may be required several times over if the start of the growing season involves sporadic rains, as is common in West Africa. Seed priming or soaking are related technologies that can help condition seeds to rapidly grow and take advantage of sporadic rains in dry environments. Weed management is often not a major investment in this dry environment, as only a few plants can survive and weeds are removed by farmers for use as fodder or food. If they are supported by access to market opportunities, many farmers are genuinely interested in making larger investments in crop production. A successful example of a productivity-enhancing investment that utilizes soil biota is the Zai hole, a technology developed in Northern Burkina Faso and being experimented with widely in West Africa (Kaboré and Reij, 2004). Small basins are dug in land to be rehabilitated and handfuls of manure added, which attracts termites that dig channels and improve water infiltration. The basins capture wind-blown residues, and the site-specific concentration of nutrients and water supports plant growth in the Zai hole.

Targeted input use can markedly enhance crop tolerance to environmental stress. Irrigation is one of the most widely used technologies to enhance return to other investments, such as fertilizer and high quality seed. However, irrigation is an expensive technology that is only applicable where water is available, and economic returns are sufficient. A novel technology for dry areas is the use of "microdosing," where small doses of fertilizer (5–10 kg of nutrients per ha) are point-applied, directly to the base of a plant. This supports the growth of healthy plants, with large root systems, and has been shown to markedly improve drought tolerance. Microdosing of sorghum with phosphorus fertilizer in West Africa has been shown to markedly improve water use efficiency, and yield potential for environments ranging from arid to semiarid (Buerkert et al., 2001). The economic risk of fertilizer use is considerable in a dry environment, and technologies must be thoroughly tested over long time horizons to fully assess climatic risk. A successful agricultural development strategy in West Africa has been the combination of biological risk mitigation through microdosing, and inventory credit systems to reduce economic risk.

To summarize, the dry environment strategies discussed here involve either: (1) flexible and extensive approaches, such as concentrating nutrients and energy through grazing and manure transfers to cropland; or (2) intensification, targeted to specific locations. Examples include watered niches in dry environments, and targeted microdoses of fertilizers or organic amendments. Understanding trajectories of intensification in marginal environments is challenging and requires multidisciplinary teamwork between social and biological scientists.

Humid environments face quite different challenges than arid ones. Biological productivity is high, and growth limiting factors tend to be competition from weeds and herbivory by insects. Disease is another growth limiting factor, for both plants and animals. Understanding the processes and timing of interventions is critical in this rapid growth environment. Biologically sensitive management in the humid tropics, e.g., requires knowledge of pest and predator growth dynamics. Not only is this essential to integrated pest management, but also to below-ground pest management and organic matter decomposition (Table 2.4). Interestingly, recent research indicates that timing is critical to the health of crops planted into soil amended with organic residues (e.g., manure and leaf litter). Widespread seedling damage from grubs, termites, and soil-borne root rot organisms will result if crops are planted and insufficient time is allowed for decomposition, as facultative organisms on decaying residues transfer to young, vulnerable seedlings. Yet, if sufficient time between organic amendment and planting is allowed, then a diverse soil community asserts itself and there are many examples of specific suppression of soil diseases and parasitic organisms.

A key challenge in the humid and subhumid tropics is competition from weeds. Weed management efforts take up the majority of labor inputs in many cropping systems, as farmers are caught in a cycle of weeding, and generation of weeds. Commonly, weed management relies on shallow tillage with an oxen plow or hand hoe, and this leads to soil disturbance which enhances weed germination. Managing these weeds requires further disturbance, which promotes yet more weeds. This is a difficult cycle to break, but there are novel technologies to alter the seedbed environment, such as dust mulchers that cut rather than turn over weeds, and thus reduce surface disturbance and the exposure of weed seed to germination conditions (Renner et al., 2006). The use of a "stale seed bed" relies on a regime of high initial disturbance to kill several generations of weeds, before planting a crop with minimum disturbance into this prepared bed.

Ecologically based weed management relies on principles such as asymmetry competition, where early crop growth is enhanced relative to weed growth. If a high density planted crop, or augmented crop (e.g., transplants), can out-compete weeds initially, this will allow canopy closure and weed suffocation through denying sunlight, water, and nutrients. Cereals are ideal candidates for this approach, as they have an erect shoot growth habit that facilitates a high density of plants within a row, and rapid achievement of height, shading weeds. Limiting resource availability between rows, through point applied water and nutrients, will support an asymmetrical cropping system design. An intercrop system can also be designed to maximize rapid canopy closure and expansion of the leaf area index, as shown for the triculture discussed earlier of maize, bean, and squash. In this widely grown intercrop, maize provides a fast growing element that initially shades weeds, the bean climbs the vertical maize and increases the leaf area index, while squash forms a ground layer that shades weeds attempting to germinate.

Overall, management of moist environments requires understanding of processes that control trade-offs in investments. Enhancing fertility will have little or no effect on productivity without augmenting control of weeds and other pests. Smallholder farmers have limited resources and need advice about less than ideal systems, such as combinations of modest investments versus large investments in either nutrient augmentation or weed control (Snapp et al., 2003).

APPLICATION OF ECOLOGICAL PRINCIPLES TO A CHANGING WORLD

The ecological literature has developed the useful concept of a dynamic equilibrium (Botkin, 1990), replacing historical views of ecosystem evolution moving toward a climax system. The theory is that ecosystems evolve with feedback between the environment and organisms, each influencing the other so that a permanent steady state does not occur, but rather equilibrium states are achieved that offer temporary optimum balance. For example, infertile soils on a sand dune condition the type of plants that will thrive at that site. Over time the pioneering plants and their symbionts enrich the dune soil through N-fixation and mineralization, and this sets up a new state whereby a different set of plants are favored. Eventually—as longer lived plants such as trees become established and residues shift toward acidifying and recalcitrant tissues—the soil environment is slowly altered again, and the dynamic equilibrium continues. Plant and symbiont evolution within agricultural systems may be following similar dynamic equilibrium patterns, although more research is required. For example, mycorrhizal fungi may be parasitic within fertilized systems, compared to low-input systems (Kiers et al., 2002). Agroecological management may involve selecting plants and associated organisms to perform well within a changing, and minimally resourced, environment.

A cropping system rotation can be viewed as a rapid form of plant succession. Many cropping systems involve deliberate alternation of complementary plant types, including following nutrient enriching plant sequences with nutrient demanding plants. For example, a rotation might start with a legume forage that builds soil fertility (e.g., alfalfa, *Medicago sativa* L.), followed by a nutrient demanding and vigorous C4 grass (e.g., maize), then a moderately nutrient enriching crop such as a legume grain crop (e.g., soybean), and finally a C3 grass (e.g., wheat) that provides effective soil cover and high surface rooting density to regenerate compacted soil. In some Mediterranean systems wheat is intercropped or rotated with a very deep tap-rooted brassica (e.g., rapeseed), which enhances nutrient recycling and provides “break crop” properties by drastically altering soil biology.

The above are planned successional systems. In addition, opportunistic evolutionary systems have been explored as management options. One of these is an opportunistic fallow in Malawi, a unimodal tropical environment where grasses and shrubs will often invade after an annual crop is grown during the long dry season. Promotion of desirable types of shrubs and trees, such as *Tephrosia* and *F. albida* species, has been explored as a low-labor means of establishing agroforestry fallow systems to rehabilitate soil. This system is called "Farmer managed natural regeneration," and is spreading rapidly in some areas of Malawi (R. Winterbottom, World Resources Institute (WRI) & World Agroforesty Center (ICRAF) (2014). "Inception Report" for Taking to Scale Tree-based Ecosystem Approaches that Enhance Food Security, Improve Resilience to Climate Change and Sequester Carbon in Malawi (unpublished). Washington, DC: World Resources Institute). Generally, an annual crop cycle must be sacrificed in this opportunistic fallow, precluding adoption by farmers with small land holdings. A related system is that of judicious weeding to remove weeds with negative traits and allow survival of desired weeds, to support a successional weed community with desired traits.

In summary, agroecology relies on understanding of the biophysical and socioeconomic context. Agroecological zones can help in planning and designing of options to test. It also requires flexibility: design for a dynamic rather than a steady state system. It requires understanding of spatial heterogeneity over time and space, and a planning horizon of many years. Out-dated concepts in sustainable agriculture are based on the transfer of technologies and set recommendations. In contrast, agroecology is based on knowledge, participatory action research, and education. Farmers and other rural stakeholders have local knowledge, and access to the raw ingredients of plants, animals, and natural resources; agroecology has the mandate to broaden the range of organisms and technologies available, and to provide support for the development of knowledge and adaptive responses to rapid change.

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INTERNET RESOURCES

http://www.icimod.org/?q=16904
Website of the International Centre for Integrated Mountain Development, Kathmandu, Nepal, with links to mountain agroecological efforts around the globe.

http://ipmnet.org The Database of IPM Resources: A compendium of customized directories of worldwide IPM information resources accessible through the Internet.

http://www.iwmi.cgiar.org/africa/west/pdf/AdoptionConstraints
This website describes a wide range of resource conservation technologies, and the extent of adoption in sub-Saharan Africa.

http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/fao-expert-workshop-on-perennial-crops-for-food-security/en/ This website documents recent efforts by the Food and Agriculture Organization (FAO) and partners to to convene community engagement and scientific involvement in the development of perennial grain crops.

www.nwaeg.org New World Agriculture and Ecology Group (NWAEG) is an international organization which analyzes the problems of contemporary agriculture and ecology in order to support the development of alternatives.

Chapter 3

Farming-Related Livelihoods

Barry Pound

THE COMPLEXITY OF FARMER DECISION-MAKING

Farmers are systems thinkers. They have to decide which crops (if any) to grow, and where and how. They have to decide which livestock to keep (if any), and where and how. They have to decide what to sell (when and where), and what to keep for the household. They must balance investment in protecting local natural resources for future generations with immediate requirements to feed and shelter their family. They must also consider investments in education, nonfarm employment, and social interaction with their neighbors, friends, and relatives. They have to predict the outcome of playing higher levels of productivity against higher levels of risk. Their lives may depend on getting the balance right (see Fig. 3.1).

Farmer decisions are based on experience, natural indicators, the information they obtain from other farmers, the radio, the shopkeeper, government extension staff, and other service delivery agencies such as nongovernmental organizations (NGOs), private sector vets, and input suppliers. They then make their best guess with the limited information available to them. In particular, it is difficult to predict the future—the climate, market prices, consumer preferences, policy changes, and the security situation. The majority of smallholder farmers live in marginal environments with minimal infrastructure, giving them limited margin for error, and vulnerability to climatic, financial, and biotic shocks, and conflict (see Fig. 3.2).

The farmer's life and the way in which he responds to his situation also depends on factors outside agricultural science, such as his health and that of his family, his education, and the linkages he has with others in and beyond his community. And, of course, our farmer may not be "he" at all, but "she," with the different roles, responsibilities, rights, resources, and aspirations that this implies (see Figs. 3.3 and 3.4).

Fig. 3.5 was developed during a consultancy looking at the climate resilience of African smallholder farmers. It lists the strategic aims of the farmer in striving for an overall strategic goal of managing future risk and

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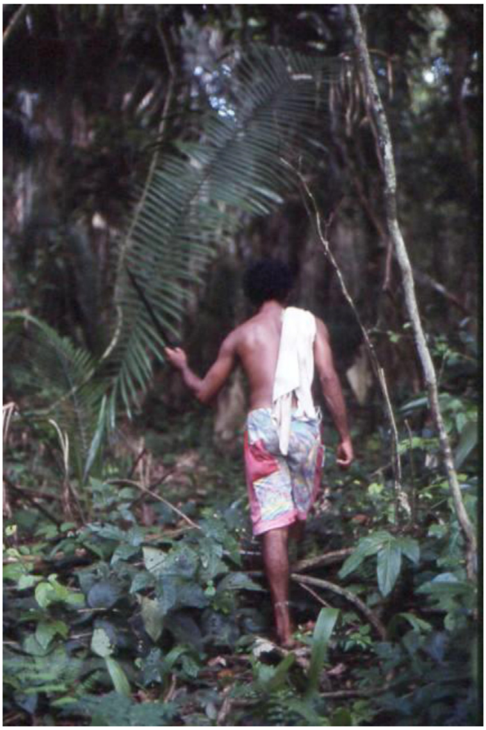


FIGURE 3.1 Put yourself in his shoes. As an immigrant from the food-deficit high plains of Bolivia, you have traveled to the very different environment of the tropical lowland rainforests, and along logging tracks to the end of the road. You now have to make a living from the unfamiliar forest using a machete, a box of matches, and your wits.

FIGURE 3.2 Erosion gulleys and compaction caused by livestock grazing and passage, Nargas valley, Afghanistan. What are the alternatives, apart from growing opium poppy?

FIGURE 3.3 Women farmers in Uganda sharing written information. Literate members may share information with less literate friends and family.

FIGURE 3.4 A woman farmer in Nepal explains her success in cauliflower production and marketing. Extension services are still predominantly male, and few take the trouble to find out the specific priorities and concerns of women.

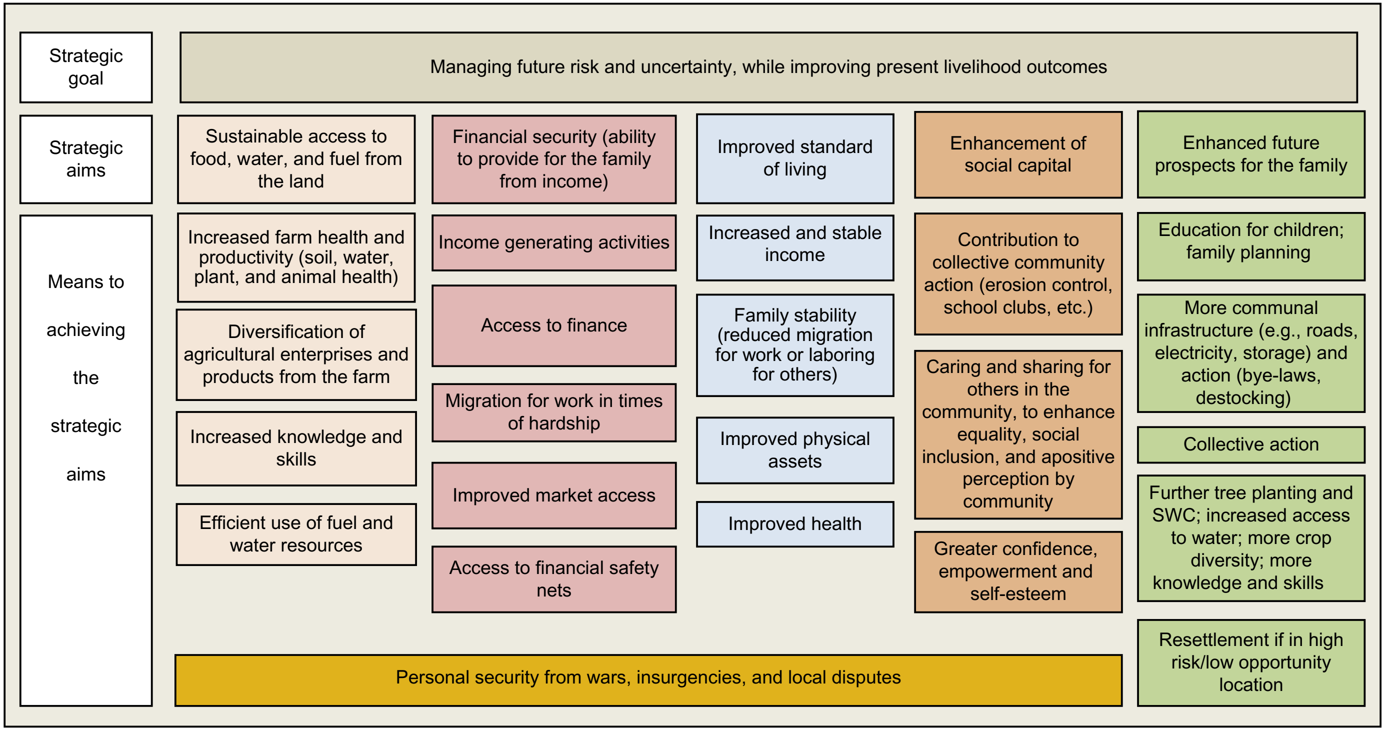


FIGURE 3.5 Farmers' generic livelihood strategies.

uncertainty, while improving present livelihood outcomes. Some of the means of reaching those aims are given in the figure, but these will be specific to the individual circumstances of the farming family (e.g., they would be very different for pastoralists in northern Tanzania to cash-cropping vegetable growers in India's Punjab). However, we suggest that most farmers have similar aims that go beyond short-term agricultural production and include social, economic, and cultural aspirations within and beyond farming.

THE SUSTAINABLE LIVELIHOODS FRAMEWORK

As researchers and agricultural advisors, we have to admire farmers for being able to think their way through this complexity. We also need a framework that will help *us* think in a logical way about the different factors that influence the decisions that farmers, and those that support the farmer, have to make.

One framework that has been extensively used at the household and community level is the Sustainable Livelihoods framework (Carney, 1998, 1999; DFID, 1999), which is presented in Fig. 3.6.

Carney (1998) suggested that: "A livelihood comprises the capabilities, assets and activities required for a means of living." She merged this with sustainability to state that: "A livelihood is sustainable when it can cope with

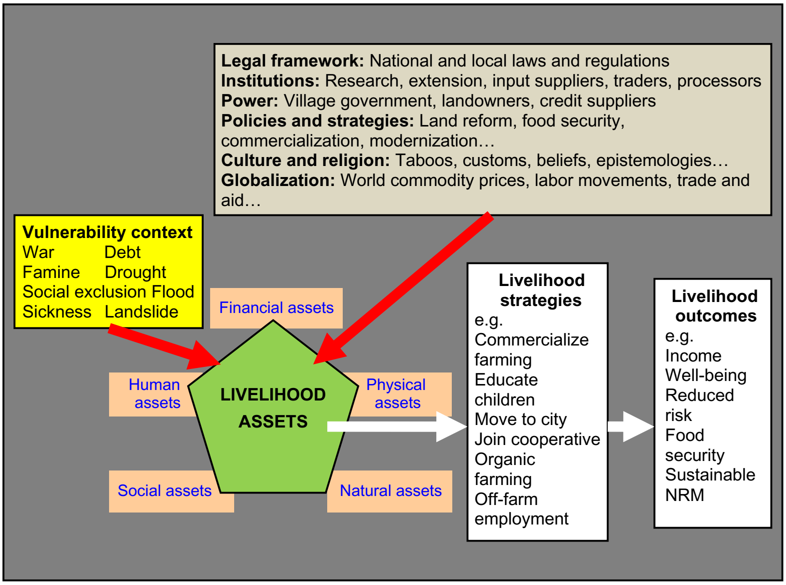


FIGURE 3.6 Farming-related livelihoods. *After Carney, D. (Ed.), 1998. Sustainable rural livelihoods. What contribution can we make? Department of International Development. Russell Press Ltd, Nottingham.*

and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base."

This people-centered framework starts with the premise that all farmers have some assets, and that these can be divided between their natural assets, physical assets, social assets, human assets, and financial assets (see Table 3.1).

Some assets might be relatively high and others relatively low at any point in time. The level of assets is dynamic, and a rise in one can mean a fall in another. For instance, one could buy land, thereby trading financial assets for natural assets. In slash and burn agriculture, one might sacrifice trees and shrubs (a natural asset) through burning to provide short-term fertility (a different type of natural asset) to grow a cash crop to provide finance (a financial asset) for school fees (education being a human asset). The assets are thus interwoven and, to some degree, interchangeable.

TABLE 3.1 Examples of Livelihood Assets

Natural	Physical	Social	Human	Financial
Plants (crops, trees, shrubs, and their genetic resources)	Houses and household goods	Family (immediate family, clan, tribe, ethnic group)	Education (including literacy)	Cash
Livestock, wildlife and their genetic resources	Roads, paths, and bridges	Friends and neighbors	Information, skills, and knowledge	Savings and their security
Land and its soil, rock, aggregate, and minerals	Machinery and equipment	Groups, societies, associations, cooperatives	Health	Salary/ wages/ remittances/ pensions
Water resources, above and below ground	Telephones and mobile communications	Neighboring villages and wider links	Labor/ employment	Credit and its conditions
The quality of, and access to, natural resources	Storage, processing, and marketing facilities	Trust and cooperation between social groups	Empowerment/ voice/legal entitlements	Debt and its conditions

The farming world is one of risk. Assets can be severely and quickly affected by war, famine, drought, disease, or falling into debt. Being in a remote place can add to the vulnerability of families and communities through poor access to services, aid, inputs, or markets. Vaitla et al. (2012) explore the links between livelihoods, resilience, and change, using the harsh, remote environment of Tigray in Ethiopia as a case study.

The ways in which assets are used can be affected by a number of external influences, such as the legal framework (which can include local bye-laws), government, NGOs and private institutions, the balance of power within the community, national policies (and how these are interpreted and implemented locally), and the culture and values of the community. All of us, even in remote parts of the world, are also touched by globalization. For instance, increases in the cultivation of crops for biofuels have significantly strengthened world-market grain prices, which have had a ripple effect on food prices and behavior right across the globe.

The farmer has to process all of this data and come up with a livelihood strategy for himself and his family that will lead to livelihood outcomes that he hopes will be beneficial in the short, medium, and longer terms.

It is our responsibility as researchers, advisors, and policy makers to understand the complexity facing farming families. The holistic livelihoods framework helps us to do so, by providing a check list of issues. Do we understand the vulnerabilities and shocks facing a community? Do we know which assets are limiting performance? Do we know how external institutions affect farming decisions and the capacity of farmers to take up the options available to them? Do we know what livelihood strategies rural communities are following or aspire to?

If the answer to all of these is “Yes,” then we have a good chance of being able to develop relevant technologies, interventions, and policies based on up-to-date evidence—always mindful of the fact that situations can change overnight.

PARTICIPATORY RURAL APPRAISAL AS A PART OF SUSTAINABLE LIVELIHOODS ANALYSIS

Sometimes there is sufficient up-to-date information available to be able to analyze local livelihood situations without the need for fieldwork, but that is rare. More commonly there is little recent, comprehensive, information available. Since the mid-1990s, the author has been involved in livelihood analyses using participatory rural appraisal (PRA) in east African countries, eastern Europe, Afghanistan, and Yemen. All of these have involved the use of a mixture of PRA-type tools, carefully selected for each individual case. In Afghanistan (Pound, 2004), the objective was to understand the present livelihood situation in villages in Bamyan Province (which had been severely affected by war with the Soviet Union, by conflict with the Taliban, and by drought) so that a large FAO project could develop relevant farming-related development interventions. Box 3.1 describes the sequence followed and the methods used. A further example of use of PRA in SLA can be found in Morse et al. (2009), which critically appraises the use of Sustainable Livelihoods Analysis as a tool to understand the situation of contrasting villages in the middle belt of Nigeria, with the intention of developing or modifying development interventions for and with the villages. In this respect they maintain (p. 65) that "SLA is an example of an approach founded on good theory driven by an understandable desire to link intervention to evidence."

In Moldova (Eastern Europe) a similar method for livelihood analysis was used (Pound, 2001), but instead of three wealth rank groups of men and women, thirteen social groups were interviewed as these represented the different social constituencies in the communities. It is important to be flexible and inventive in the use of methods, so that they achieve the objectives set, and conform to the cultural and logistical situation of the study.

Some of the tools described (e.g., the farming systems diagram; see Fig. 3.7) take several hours of careful questioning to complete. However, they are worth it as they provide very specific information that can tell a more precise story than a lot of aggregated data. They can pinpoint vulnerabilities, and gaps in knowledge, services, or resources that can usefully be addressed by development agencies. Many of the tools described are very visual, and are developed with the community members so that they can see exactly what is being produced, even if they are illiterate. It is then easy to "question the diagram" and probe for further in-depth information or suggestions about specific issues.

COMPLEMENTING QUALITATIVE INFORMATION WITH QUANTITATIVE DATA

Such mainly qualitative data can be complemented by quantitative information, such as that obtained through the use of focused questionnaires. The use of electronic tablets greatly increases the accuracy and speed of questionnaire surveys as the answers can be uploaded directly to a central computer, where the analysis can be done immediately using appropriate software (see Fig. 3.8). If the survey is being run over several days, the analysis can be done on a daily basis, enabling adjustments to be made during the survey to ensure a balanced representation of gender, ethnic, and social categories in the study.

Some tablets have a Ground Positioning System facility, so that when the survey is started the tablet records the location. Fig. 3.9 shows the distribution of interviews done for a household survey in northern Uganda.

Once the field information is available, it is important to work with government officials, research organizations, private sector suppliers, and farmer groups to see what interventions are supported politically, and which are appropriate technically, viable economically, and practical logistically.

BOX 3.1 Methods for Sustainable Livelihoods Analysis Applied to the Project "The Development of Sustainable Agricultural Livelihoods in the Eastern Hazarajat, Afghanistan"

Objectives

1. Characterize current livelihood systems, including vulnerabilities and constraints;
2. Identify development drivers and intervention opportunities;
3. Establish a baseline for monitoring the responses to these interventions.

Approach

Sustainable Livelihoods analysis, using PRA tools involving men and women from different wealth groups to gain both qualitative and quantitative information.

Methods Used for the Field Survey

1. *Introductions*: It is always important that village leaders are clear who you are and what you want to do.
2. *Village profile*: This is a PRA technique that is not in the literature. Starting with a clean sheet of flip chart, a circle is drawn to represent the village. A group of villagers describe the buildings, services, trades, and social institutions in the village. A second circle is then drawn, and villagers are asked to describe the external influences on their lives (government, links other villages, market linkages, NGO interventions, etc.), and the vulnerabilities they face.

The picture shows the development of a village profile with fishermen in southern Yemen. Such exercises can be the start of local dialogue, not just a tool to extract information. It is important that those communities that contribute to surveys are also involved in subsequent development initiatives.

(*Continued*)

BOX 3.1 (Continued)

3. *Quantitative information on resource distribution and the labor situation*: Village members provide information on the number of households in the village owning large livestock within set numerical ranges (avoiding the need to identify who has how many livestock). Similar resource profiles are obtained for land ownership, migration, and labor use. The information helps to understand the way in which natural resources are distributed between families in the village.
4. *Wealth ranking*: At this point, wealth ranking is carried out to differentiate between the poor, medium, and better-off families in the village. Two or three respected members of the village are selected to write the names of all household heads on separate cards, and are then asked to allocate these to three piles, corresponding to poor, medium, and better-off categories.

Conducting wealth ranking with villagers is a serious business. After separating households into wealth groups, the participants are asked what criteria they used for allocation. What does well-off mean? What makes a family poor?

5. *Activity profiles with women*: Semistructured interviews are then carried out (by women team members) with groups of women from each of the three wealth rank categories to determine the daily and annual activities of women

(*Continued*)

BOX 3.1 (Continued)

(domestic, farming, nonfarming), to identify the main constraints that women face, and to identify their suggestions for improving their livelihoods.

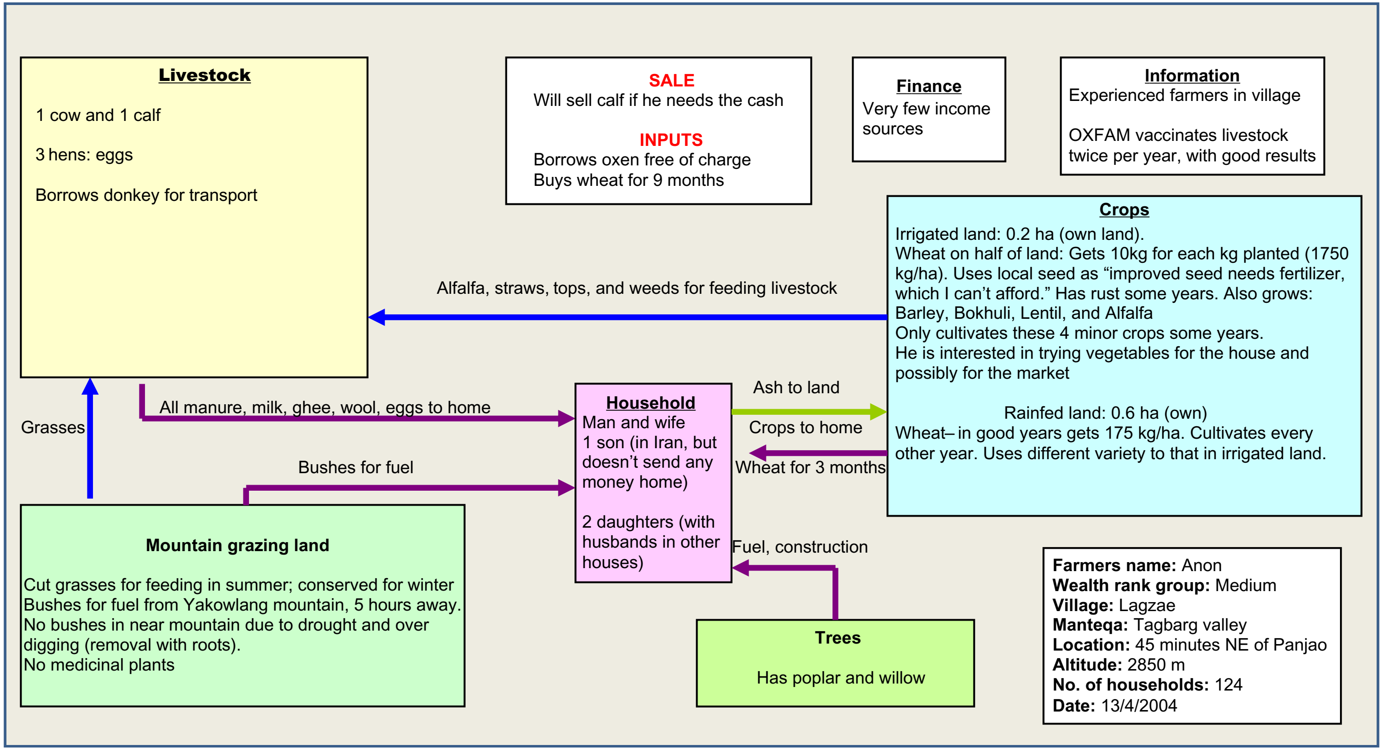
6. *Semistructured interviews with men*: Groups of men from the three wealth categories are also interviewed (separately) to determine household income sources and the debt situation for each wealth category, to identify the main constraints faced by men, and to identify their suggestions for ways to improve their livelihoods.
7. *Farming system diagrams* are developed with a few representative farmers selected by the village (see Fig. 3.2). These look at their labor situation, their land (including common property and share cropping), crops and livestock produced, interactions between crops, livestock and common land, sale and household use of farming products, off-farm and nonfarm employment, farming constraints and opportunities, and the sources of farmer knowledge and services.

Constructing a farming systems diagram with village members in Afghanistan. Using a vantage point like this helps, as one can point to the mountains and ask: Is there seasonal transhumance to the mountains? What about medicinal herbs from the high valleys?

Use of the Information

The results were analyzed and development drivers (including nonfarming drivers such as the need for literacy training, nonfarm employment, and microcredit) identified. These were used to develop a set of practical interventions that were then successfully applied.

Source: *FAO Project: GCP/AFG/029/UK.*



Livestock

1 cow and 1 calf

3 hens: eggs

Borrows donkey for transport

SALE
Will sell calf if he needs the cash

INPUTS
Borrows oxen free of charge
Buys wheat for 9 months

Finance
Very few income sources

Information
Experienced farmers in village

OXFAM vaccinates livestock twice per year, with good results

Crops

Irrigated land: 0.2 ha (own land).
Wheat on half of land: Gets 10kg for each kg planted (1750 kg/ha). Uses local seed as "improved seed needs fertilizer, which I can't afford." Has rust some years. Also grows: Barley, Bokhuli, Lentil, and Alfalfa
Only cultivates these 4 minor crops some years.
He is interested in trying vegetables for the house and possibly for the market

Rainfed land: 0.6 ha (own)
Wheat– in good years gets 175 kg/ha. Cultivates every other year. Uses different variety to that in irrigated land.

Household
Man and wife
1 son (in Iran, but doesn't send any money home)

2 daughters (with husbands in other houses)

Mountain grazing land

Cut grasses for feeding in summer; conserved for winter
Bushes for fuel from Yakowlang mountain, 5 hours away.
No bushes in near mountain due to drought and over digging (removal with roots).
No medicinal plants

Trees

Has poplar and willow

Farmers name: Anon
Wealth rank group: Medium
Village: Lagzae
Manteqa: Tagbarg valley
Location: 45 minutes NE of Panjao
Altitude: 2850 m
No. of households: 124
Date: 13/4/2004

FIGURE 3.7 Farming system diagram. Farming family in Panjao District, Afghanistan, at 2850 m altitude.

FIGURE 3.8 Conducting a questionnaire survey using an electronic tablet in Karamoja, Uganda.

FIGURE 3.9 Location of household survey interviews in a village in Karamoja, Uganda.

In a minority of cases, there may be a very good technical case for an intervention, but the policy environment needs to be challenged. This was the case in Tanzania, where the privatization of government veterinary services left most rural livestock keepers without animal health support. The NGO FARM-Africa piloted the use of "Community-Based Animal Health Workers" to fill the gap in service delivery. These proved very successful in reducing animal mortality and disease, but were initially rejected by the Tanzanian Veterinary Association. It took several years of advocacy and lobbying to change government policy, but community-based animal health workers are now an accepted component of animal health care in the country (see Fig. 3.10).

FIGURE 3.10 Training community-based animal health workers in Tanzania. The trainees are selected by their communities, and are accountable to them.

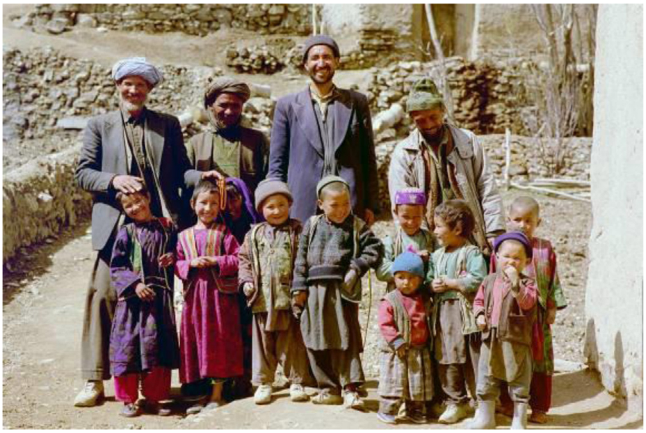


FIGURE 3.11 Afghan village men look after the children while their wives are at adult literacy classes. It is important that the men are in favor of the lessons, as these seem to be.

Sometimes, it is difficult to know if an intervention will work without trying it on a pilot basis. One of the findings from the livelihoods analysis in Afghanistan described in Box 3.1 was the very low levels of literacy among rural women. This severely restricted their involvement in any nonfarm employment, and their self-esteem. Literacy classes, using agricultural themes such as vegetable growing as the subject matter for the lessons, were tried on a pilot basis and have proved a tremendous success (see Fig. 3.11).

THE INFLUENCE OF INSECURITY ON LIVELIHOODS

While countries like Afghanistan and Yemen are infamous for their conflicts, many countries in Africa are also affected. The Karamoja region of northern Uganda is an example, where the incessant violence between tribes within Karamoja, and with their neighbors in South Sudan and Kenya, has constrained development and left the area far behind other parts of Uganda. The drivers of conflict in Karamoja are categorized in Table 3.2 against political, economic, social, cultural, legal, and environmental headings, again reinforcing the need to look at situations from a broad, multidisciplinary perspective.

Insecurity inhibits livelihood development in many ways, but it is not necessarily the case that removing the insecurity will lead to immediate benefits (the so-called peace dividend). Often trust has to be rebuilt between people and state, and between different factions within the population. Goods and services have to be (re-)instated, and investments made by state, civil society, communities, and the private sector. Often, external agencies have limited resources so they work with communities to see what they can do for themselves with a minimum of outside assistance.

CREDIT INITIATIVES TO KICK-START LIVELIHOOD CHANGES

It is common for livelihood analyses to identify that poor families (who usually have minimal physical collateral) have little access to credit. This severely limits their enterprise options. Recently there has been an expansion in the use of group schemes aimed at poor (but economically active) families. These usually require the family to join a group and save into a scheme that then lends from the accumulated capital to its members. Two examples are Self-Help Groups which are very successful in southern India (Reddy and Manak, 2005) and now in Afghanistan (Pound, 2006; see Fig. 3.12), and the Savings and Credit Cooperative Societies which are becoming a feature of NGO projects in eastern Africa (Bwana and Mwakujonga, 2013).

In northern Karamoja (Uganda), Mercy Corps conducted a study of over 300 Voluntary Savings and Loan Associations (local, self-administered savings, and credit groups supported mainly by NGOs). They estimated that the 1100 groups in three districts had a combined capital of 7.3 billion Ugandan Shillings (around US$2.5million). Interest rates on loans (set by the groups themselves) were mostly 10% per month. The major uses for the credit are shown in Fig. 3.13. While the majority of lower value groups used credit for brewing local beer for sale, high value groups used their credit almost exclusively for farming, brick-making, and retail businesses, showing how important it is to disaggregate data by wealth or social group.

A different approach is taken in Ghana by the Livelihood Empowerment Against Poverty (LEAP) Program (FAO, 2014), which provides cash transfers to extremely poor households with the goal of alleviating short-term

TABLE 3.2 Drivers of Conflict in Karamoja

Political	Economic	Social	Cultural	Legal	Environmental
Unequal treatment of tribes by political process	Poverty	Discrimination in the community	Bride price—BUT changing attitude and lowering of expectations	Open borders—enable access to weapons	Famine due to poor harvests due to climate variability
Uneven disarmament of tribes (within Uganda and in neighboring countries)	Increasing demand for cash for buying household items, school fees, medicines, etc.	Illiteracy	Cattle theft and raids, with revenge raids and killings		Natural resources scarcity leading to disputes about pasture, water, and land
			Recognition/status is partly in terms of ownership of cattle		
Fear and mistrust of state security providers—especially in the past	Unemployment	Lack of employment opportunities, especially for youth	Polygamy—also an aspect of male status in society		
Political competition for power and privilege	Famine due to drought, lack of resources, and lack of information		Influence of witch doctors, cultural leaders, and opinion leaders		

FIGURE 3.12 Afghan farmer in a self-help group in Badakhshan, Afghanistan, hands over his monthly savings to the group treasurer. Note the careful, peer-witnessed registration of this transaction. The saver will have the chance to borrow capital from the group to invest in an agricultural or nonagricultural enterprise.

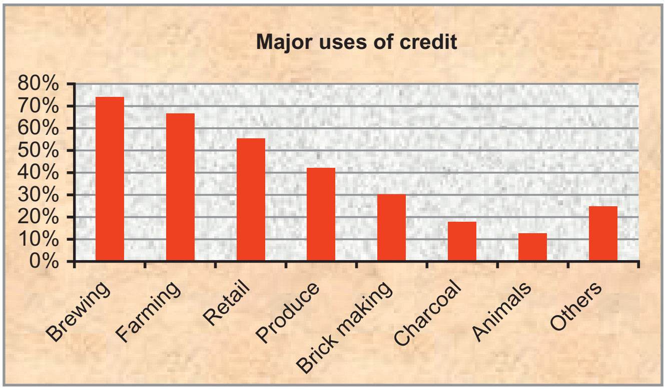


FIGURE 3.13 Use of credit from VSLAs in Karamoja, Uganda. *From Mercy Corps, 2014. VSLAs in northern Karamoja: Brief. Northern Karamoja Growth, Health and Governance Program, Mercy Corps (Mercy Corps, 2014).*

poverty and encouraging long-term human capital development. A unique feature of LEAP is that beneficiaries are also provided with free health insurance through the National Health Insurance Scheme (NHIS). However, the program has shown that the cash transfer has to be set at a level high enough to make a significant difference to livelihoods, and that the implementation of the program needs to be well organized so that beneficiaries receive regular cash transfers that they can trust and plan by.

CONCLUSIONS

This chapter champions the use of the Sustainable Livelihoods framework for identifying relevant interventions with rural communities in developing countries. To be sure that our technologies, policies, and advice are relevant, we need to understand the social, human, physical, natural, and financial assets of those communities, and the vulnerabilities and shocks faced by them. We need to know how external institutions and influences affect farming decisions, the capacity of farmers to take up the options available to them, and what livelihood strategies they are following or aspiring to. Sensitive use of PRA tools within a Sustainable Livelihoods framework can be a learning experience for communities, as well as for external agencies.

We have seen that farmers face complex situations and make decisions based on technical, social, economic, and cultural considerations. It is unlikely therefore that one technical discipline (e.g., agriculture) is going to be sufficient to support farming families. Instead, dynamic, multistakeholder partnerships are now seen as an effective way to bring different interests and perspectives together to serve groups or communities. These partnerships can support commodity development across the value chain from producer to consumer, and can also support the family in its nonfarming aspirations, such as education or nonfarm employment, social interaction, or improving the local environment. This *innovation systems approach* is evolving, and is explored further in Chapter 11, The Innovation Systems Approach to Agricultural Research and Development.

While suggesting the innovation systems approach coupled to a value chain approach as appropriate for bringing together actors across government, civil society, and the private sector, the *Sustainable Livelihoods* framework still maintains its value as a holistic framework to characterize the situation in which families and communities find themselves. At the farm level, the *farming systems approach* is still valid to understand the interaction between components of the farming system (crops, livestock, trees, soil, water, nutrients, etc.).

Whatever the approach, the best of agricultural science must be retained. There is still an acute need for competent agronomists, livestock health and nutrition specialists, soil scientists, social scientists, climate change experts, and other disciplinary specialists, as well as those who are able to read and work with the bigger picture.

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Chapter 4

Farming Systems for Sustainable Intensification

Sieglinde Snapp and Barry Pound

INTRODUCTION

Future food security is a challenging proposition in the face of rising food demand, a degraded resource base, and a changing climate. The situation is already acute, with over a billion people suffering from malnutrition and severe nutritional deficiencies (Godfray et al., 2010) (Partly this is a *food distribution* problem and a *food access* problem as much as an under-production problem as explained later in this chapter). Understanding the trajectory of farming systems, including productive capacity and adoption factors, is key to the long-term ability of agriculture to meet future food needs. Sustainable intensification (SI) is an approach that has risen to the top of the agenda, following the definition by Pretty et al. (2011) that SI is a strategy to "produce more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services." SI focus is on locally appropriate agricultural technologies that meet both present and future needs (Pretty, 1997). SI is clearly one of humanities "Grand Challenges," and an essential project in the coming decades.

The principles included in the definition of SI are as applicable to high-input agriculture as they are to smallholder farmers in the developing world. In this chapter our focus is on the latter. The rapid increase achieved in Asia of food production in the 1960s and 1970s is referred to as the "Green Revolution." This was achieved essentially on the same agricultural land with modest expansion. This is evidence that agricultural production can be increased at least in line with population

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growth, at least in Asia under conditions where irrigation and market infrastructure support high production (Tilman et al., 2011). There are major questions, however, regarding environmental costs. There are also concerns about equity; who gains and who loses as production systems are intensified? Coupled with increases in agricultural production have been (in some locations) salinization of productive land, depletion of aquifers, pesticide effects on health, nitrate pollution, loss of biodiversity, further dependence on fossil fuels, the depletion of rock phosphate reserves (http://phosphorusfutures.net/files/2_Peak%20P_SWhite_DCordell.pdf), and a rise in greenhouse gas (GHG) emissions. Issues have been raised regarding access to food, food security at different scales, equity in control over production, and achieving nutritional security along with environmental security (Loos et al., 2014). These indeed are integral to SI which includes human dimensions as well as environmental and economic considerations. We explore here definitions of SI, what it involves, the evolution of pathways of farming system transformations, and possible ways forward.

To understand SI, an overview of key drivers and consideration of historical trajectories of agricultural change is useful. Ester Boserup is a pioneering thinker on agricultural intensification and land use change processes across Africa and Asia. Population density is the driver of change that she first considered 50 years ago—based on a synthesis of worldwide literature on tropical agricultural systems (Boserup, 1965). As population density increases, she noted that community mobility decreases and villages tend to become static and develop permanent fields. Short-term fallows often replace shifting cultivation and pastoralism, and may in turn be replaced by continuous cropping (Table 4.1). Communal lands that are primarily natural forest or grasslands, and used for hunting, grazing, and foraging, come under pressure, and may be replaced by crop production. Human population densities, through migration and/or in situ growth, may come to put such pressure on land use that its quality declines. As soils degrade, and out-migration becomes common, investment in agricultural production intensifies. This generally leads to more frequent cropping and controlled forms of livestock management, as shown in Table 4.1.

The role of population density is important, but today we know that other factors require consideration as well. These include the environmental context, the size, accessibility, and type of markets, the availability of capital and labor, historical traditions and culture, political stability, technological innovations, and political edict (Jayne et al., 2014). Not all of these factors are static. The dynamic nature of market linkages will be considered here, as a driver of innovation and change in farming systems. Another dynamic factor is environment, and Chapter 13, Climate Change and Agricultural Systems, considers in some detail how climate change is influencing agriculture, and adaptation responses to this including intensification.

TABLE 4.1 The Relationship of Population Density to Intensification in Agricultural Production Systems

Population Density				
Very sparse (<4/km^2)	Sparse (4–16/km^2)	Medium (16–64/km^2)	Dense (64–250/km^2)	Very dense (> 250/km^2)
Crop Intensification				
Natural area fallow (forest or grassland) Foraging or occasional cultivation	Bush fallow of 5- to 20-year intervals between periods of crop cultivation	Short fallow of 1–5 years with frequent crop cultivation	1. Continuous cultivation, annual crops (seeds of improved varieties) 2. Extensification, with conversion of more land to agriculture, is common	1. Continuous multicropping of diverse food crops, input use (seeds, other inputs) 2. Continuous sole crops with high inputs and mechanization[b]
Livestock Intensification				
Natural area fallow and free roaming livestock Transhumance in some cases[a]	Bush fallow with common land for grazing livestock Transhumance	Constrained common lands for grazing	Dedicated pasture areas for livestock, some investment in pasture (seeds)	Confined feeding livestock using "cut and carry" and improved pastures (seeds, other inputs)

[a] *Livestock moved around with availability of grazing land.*

[b] *An alternate pathway to intensification, one that has been pursed in rice – rice and rice – wheat systems, as well as many maize-based production systems.*

Source: Adapted from Boserup, E., 1970. Woman's Role in Economic Development. London: Allen and Unwin (Boserup, 1970).

As we consider intensification, it is important to consider that both sustainable and unsustainable versions of this process are underway. Extensification and expansion of cropped land area is pursued to a varying extent across much of Africa. It remains attractive in situations where maximizing production per unit labor cost is the main driver. It is important to be aware that it is still under way in many nations, as shown by changes in agricultural production area over time. The larger areas farmed in this way keep overall production up to an acceptable level.

THE WHAT AND WHY OF SUSTAINABLE INTENSIFICATION

The world is becoming more populous, and incomes are rising along with the demand for food, while arable land suitable for production and water supplies are essentially finite. Land that can be utilized for cropping without massive investment varies across Africa, with recent estimates ranging from 15% in Malawi to 60% in neighboring Zambia (Jayne et al., 2014). These drivers bring SI to the fore. We need to use arable, grazing, and forestry land (as well as aquatic environments) more efficiently to provide for the needs of the present and the future. Production needs to increase between 60% and 110% between now and 2050 according to many projections in order to satisfy the demands of a larger, more urban population, and growing demand for animal products (Hertel, 2011). Agricultural production could be increased by mining soils of their fertility, depleting fossil water reserves, and converting rainforest to arable land, but only for the short-term, and only by compromising the environment. According to FAO figures, world agricultural production almost tripled between 1961 and 2013, while population grew from 3 to 6.8 billion. Urbanization and income gains have driven an even faster rise in the demand for animal products, with concomitant pressures on farming system production (calories produced and directly consumed as grain are up to sixfold more energy efficient than through indirect grain consumption via livestock production (van Zanten et al., 2015), although some land used for livestock is not suitable for arable production). Over the last decade, world cereal production has risen by about 2% per annum (http://reliefweb.int/report/world/fao-statistical-yearbook-2013-world-food-and-agriculture).

The green revolution drove production growth with new germplasm, inputs, water management, and rural infrastructure. Undeniably dramatic gains in crop yields have been achieved, notably a threefold increase in wheat and rice productivity in some regions. Further attention is urgently needed to protect future global capacity to produce food, fuel, fiber, hides and skins, beverages, timber, and medicines from agricultural and natural habitats. These are provisioning services that are vital to mankind's future wellbeing. However, conversion of natural areas such as forests and wetlands has led to tremendous loss of biodiversity, including species extinction and loss of habitat (Garnett et al., 2013). Environmental services such as flood control, water quality, and air quality are other vital functions that have been diminished in the face of agricultural expansion, while the conversion of forest to arable use contributes to global warming.

SI has been defined as a form of production wherein: "yields are increased without adverse environmental impact and without the cultivation of more land" (http://www.fcrn.org.uk/sites/default/files/SI_report_final.pdf). Elsewhere it is said to "increase production from existing farmland while minimising pressure on the environment" (http://www.futureoffood.ox.ac.uk/sustainable-intensification). Both definitions stress the need to produce more from *existing farmland*, in recognition that there are few parts of the world where arable cropping can be significantly expanded without severe negative consequences.

A third definition of SI is a system in which "inputs and capital provide net gains in productivity, but also protect land and water, and enhance soil fertility over time" (Reardon et al., 1995).

The reference in all three definitions to the environment emphasizes that the long-term stability of agricultural systems is underpinned by its natural resource base. However, the evidence suggests that this resource base is being depleted in ways that threaten production in the long-term. The world loses 12 million hectares of agricultural land each year to land degradation, and inefficient pre- and postharvest practices make agriculture the largest source of GHG pollution on the planet (see http://www.cgiar.org/consortium-news/world-scientists-define-united-approach-to-tackling-food-insecurity/ from 2012).

Most definitions of SI focus on, or infer, an emphasis on food production, and particularly crop production. However, other types of farm products (e.g., meat, milk, eggs, beverage crops, skins and hides, fibers, medicines, dyes, timber, construction poles, and biofuels) also contribute to livelihoods and the rural economy, as well as (directly and/or indirectly) to food security. Many farming families have complex livelihood strategies and links to rural as well as urban networks along kinship, friendship, and value chain lines (see chapter: Farming-Related Livelihoods). Families often resort to off-farm and nonfarm activities (laboring, house construction, weaving, tailoring and basket making, brewing, processing, and petty trading, etc.) to supplement on-farm production as—even with intensification—the small area of productive land available to many families is not enough to maintain an adequate livelihood. Such supplementary activities enable a larger population to occupy the land than if they relied on farming alone. In the future, farmers may also be paid for environmental services, such as soil C-sequestration, protection of water quality, biodiversity conservation, amenity access, and practices that minimize GHG emissions.

Intensification can be defined in terms of resource use efficiency (output per unit of land, water, labor, or capital), but *sustainable* intensification must include environmental, social, political, and economic aspects (see Table 4.2).

TABLE 4.2 Aspects of Sustainability Required to Ensure That Future Generations Are Able to Maintain Intensified Production

Intensification	Sustainability Components			
	Environmental	**Social**	**Economic**	**Political**
Increased production per unit of land, water, labor, or capital	Biodiversity conservation	Stabilization of local and global populations	Adequate economic return to capital and labor Appropriate input supply and market prices	Fair and secure land tenure, ownership, and distribution
	Maintenance of ecosystem services (provisioning, regulatory and cultural)[a]	Maintenance of social cohesion and improvements in social and gender equality	Adequate cash flow to meet family needs throughout the year	Ensuring personal security for families and communities Support for well-functioning community organizations
	No increase in GHG emissions	Respect for food sovereignty and intellectual property rights	Ability to achieve livelihood aspirations	Policies encouraging local and global food security
	Protection of landscape amenity access and value	Maintenance of cultural identity	Economic safety nets, such as savings and credit groups, and insurance against production and market failure	Investment in good quality support services (research, extension education, regulation, market and weather information, etc.)

[a] *http://www.unep.org/maweb/documents/document.300.aspx.pdf*.

Indeed, SI cannot be considered in isolation, and a recent review by IIED (Cook et al., 2015) positioned SI within local and global food systems that include not only food production, but also food processing, marketing, distribution, food access (availability and affordability), and food sovereignty. ("Food sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts those who produce, distribute and consume food at the heart of food systems and policies rather than the demands of markets and corporations." http://www.foodsovereignty.org/forum-agroecology-nyeleni-2015/).

Garnett et al. (2013) consider SI from the whole food system view, to take into account the demand for resource-intensive foods such as meat and dairy products that use productive land inefficiently. They point out that reducing food waste and developing governance systems that improve the efficiency and resilience of the food system are important to improving global food security. They go further by adding a social equality dimension—that food should be accessible to, and affordable by, all. This is consistent with the view of SI put forward by Loos and colleagues (2014). However, this is contested, and narrower, production-focused definitions of SI are still widely held, particularly by agronomists and crop scientists (Petersen and Snapp, 2015; Tilman et al., 2011).

SI tends to look at the *supply* side, but there is a need to also understand the *demand* side, and ensure that there is compatibility between the two. For instance the rise in urbanization and of the "middle class" in emergent and developing countries means an increasing demand for meat and milk products. While some land is well suited to livestock production, many argue that the use of potential arable cropland for the production of fodder or livestock feed is inefficient and unsustainable. While there is evidence that sunlight, soil, and water resources can be used most efficiently to produce food crops that feed people directly, the farmer has to decide which system and which products give him or her the best financial return to labor and capital, as well as to land. Such decisions can be influenced by governments through guaranteed markets, subsidies, and tax breaks on the supply side, as well as education and taxation that influence the demand side.

Table 4.3 shows that different stakeholders each have a unique perspective of the functions of SI. This table is not comprehensive, but serves to show how different the priorities can be. It illustrates that while some stakeholders (farmers, urban consumers, and the private sector) are looking for private goods (mainly agricultural products that they can use to feed themselves or make a profit), others (international organizations, government, and NGOs) are also looking to farming systems for provisioning of public goods (ecosystem goods and services for the benefit of the wider society). This

TABLE 4.3 What Different Stakeholders Want From Sustainable Intensification

International Bodies	Governments	NGOs	Private Sector	Farmers	Urban Consumers
Contribution of food security to world peace	Food security leading to political stability	Environmental sustainability	Sale of inputs and services (profit)	Food security for family	Reliable supply of cheap food of good quality
Safeguarding of global goods (climate change, conservation of biodiversity)	Import substitution and export potential by locally-produced crops, livestock, and trees contributing to the national economy	Social justice	Reliable supply of good quality products for processing and retailing	Net income (revenues minus costs), including payment for safeguarding the environment Justice	Supply that reflects changes in demand (e.g., increasing livestock products)
Contribution to Millennium Goals and post-2015 sustainable development goals[a]	Tax revenues	Food sovereignty	Carbon trading opportunities	Reduced risk and vulnerability	
Respect for global treaties (e.g., environmental protection and GHG emissions)	National public goods (clean water, environmental buffering, access to and amenity use of land, cultural heritage)	Equity (ethnic, wealth, and gender)		Access to good advice and reliable inputs for sustainable land productivity, with a range of production options	

[a] United Nations (2014). The Road to Dignity by 2030: Ending Poverty, Transforming All Lives and Protecting the Planet. *Synthesis Report of the Secretary-General on the Post-2015 Agenda. UN—particularly Sustainable Development Goals 2 and 15: Goal 2:* End hunger, achieve food security and improved nutrition and promote sustainable agriculture; *Goal 15:* Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

raises the question whether farmers should receive payment for providing these public goods, and if so how they can be remunerated. This is touched on in the "Way Forward" section of this chapter.

ALTERNATIVES TO INTENSIFICATION

Before exploring the merits and processes of SI, we should consider briefly if there are alternatives to SI. Some will argue that there are land uses that are more pressing or important than food production, including urbanization, amenity use, and conservation of wild species in national parks. Some land is unsuitable for SI, and is better used for extensive agriculture such as wildlife ranching or pastoralism. In many countries farming is a low prestige occupation that provides modest returns, such that the youth are more interested in nonfarm occupations, and often move off the land altogether. By contrast, some initiatives are trying to raise the standing of agriculture by creating a cadre of professional farmers who understand "farming as a business," and the principles behind good husbandry, the use of information, and value chain management.

Novel food production systems such as hydroponics, or new food products such as those based on microalgae or the conversion of food waste by insects (see http://www.fao.org/docrep/018/i3264e/i3264e00.pdf) have yet to make a significant contribution to global food production, but could become important in the future if food prices rise and supply lags behind demand.

Education (especially of women and girls) and population interventions (family planning, tax incentives, and the one child policy in China) seek to balance the equation involving people and food by reducing demand, rather than by increasing supply. Both will need to be applied if the world is to be fed adequately and equitably in the years to come.

Garnett and Godfray (2012) make the case that SI is required whether or not there is need for more food, because it is necessary to increase productivity per unit of resource in order to conserve resources. They see SI as one of several components of a sustainable food system, and feel that family planning, the reduction of food losses and waste, improved governance, and demand management should be implemented alongside SI (Fig. 4.1).

SUCCESSFUL SUSTAINABLE SYSTEMS

SI as an explicit concept is relatively recent (Petersen and Snapp, 2015). However, many successful civilizations have depended on long-lasting, intensive farming systems. Diverse examples of systems that have lasted for hundreds or, in some cases, thousands of years include the remarkable terrace systems in the Philippines (http://whc.unesco.org/en/list/722), the Aztec field systems (*Chinampas*) in Peru (http://www.aztec-history.com/aztec-farming.html), the irrigated land served by the Ma'rib dam in Yemen (http://en.wikipedia.org/wiki/Marib_Dam), and the horticultural food production

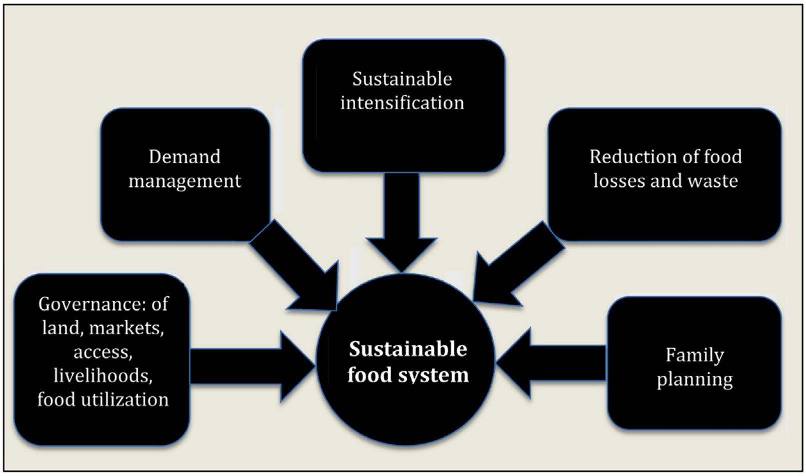

FIGURE 4.1 Sustainable intensification in relation to food demand, waste, governance, and population. *Used with permission, Garnett and Godfray (2012).*

systems of Paris "fueled" by a million tons per year of horse manure (http://www.chelseagreen.com/content/history-of-winter-gardening-the-17th-century-french-garden-system/). All of these display technical *and* organizational brilliance. It is also important to understand that they required substantial resource inputs to build an infrastructure (terraces, field systems, irrigation, heat distribution systems) that augmented the natural environment and reduced the risks of failure.

Environmental services such as regulating water through hydraulic design coupled with strategic conservation of forested patches in between terraces has been a key feature of the Ifugao Rice Terraces in the Philippines. There are challenges faced today, including out-migration, and extreme weather events, but the terraces have survived for centuries and embody innovative approaches to a harmonious farming system that is integrated with natural areas (Gu et al., 2012).

A relatively recent success story is the restoration of land in Machakos, Kenya, that was so degraded in the 1930s that the then colonial "experts" declared the land useless for agriculture. They were proved wrong by investment by local people in soil and water conservation techniques that have stabilized and improved soils, such that agricultural output has been greatly enhanced. The population density increased fivefold over that when the land was written off some 60 years previously (Tiffen et al., 1994). In this case, the resources to carry out this long-term land restoration came from those working in Nairobi who invested part of their earnings in rehabilitating their home lands.

In other situations, a failure to look to future consequences has resulted in unsustainable land management practices that have caused civilizations to collapse, such as on Easter Island (http://www.sciencedirect.com/science/article/pii/S0341816205000937), or the Great Plains of the United States (http://science.howstuffworks.com/environmental/green-science/dust-bowl-cause.htm).

WHEN IS SUSTAINABLE INTENSIFICATION RELEVANT?

The relevance of SI to any situation requires an understanding of the context in which it is being considered. Each country has a unique history, a specific set of circumstances and resources, and its own vision going forward. For some countries SI is a sensible and necessary strategy in response to extreme pressures on the land, and the need to feed populations from their own resources (e.g., Rwanda and Ethiopia). The vast majority of the world's farms are small or very small, and in many lower-income countries farm sizes are becoming even smaller as rural populations increase. In low- and lower-middle-income countries 95% of all farms are smaller than 5 ha (FAO, The State of Food and Agriculture, 2014). Below a certain size, a farm may be too small to constitute the main means of support for a family. In this case, agriculture may make an important contribution to a family's livelihood and food security, but other sources of income through off-farm employment, pensions, or remittances are necessary. These small and medium-sized farms are central to global natural resource management and environmental sustainability, as well as to food security. Many small or medium-sized family farms in the low- and middle-income countries could make a greater contribution to global food security and rural poverty alleviation through SI, depending on their productive potential, access to markets, and their capacity to innovate. The FAO believes that through a supportive agricultural innovation system, these farms could help transform world agriculture (FAO, The State of Food and Agriculture, 2014).

Two examples help to illustrate how SI can be relevant in quite different circumstances: Zambia historically has experienced a relatively low population density in rural areas. However, the high population growth rate (3.2% per annum) means a doubling of the population every 26 years, and 50% of the population is under 15 years old. The government is now encouraging smaller families (http://www.healthpolicyinitiative.com/Publications/Documents/1179_1_Zambia__Poplution_and_National_Development_2010_Marc.pdf). Meanwhile, the rise in the rural population and consequent expansion of land under cultivation has led to deforestation, soil erosion, and land degradation. SI can mitigate some of these pressures by reducing the necessity to expand the cultivated area and by supporting better ecological practices. By contrast, Rwanda is a small country with a high pressure on the land. The public sector family planning program increased the modern contraceptive prevalence rate fourfold in 5 years, significantly reducing the total fertility rate (http://www.moh.gov.rw/fileadmin/

templates/Docs/Rwanda-Family-Planning-Policy.pdf). At the same time, there are agricultural development goals, including the intensification and development of sustainable production systems. While there is a strong intensification direction, the sustainability component is questionable. Indeed, the policy requires land use change from natural swampland to monoculture rice, widespread use of inorganic fertilizer, more livestock (especially cows, which produce methane), and increased mechanization, all of which contribute to increased GHG emissions.

SUSTAINABLE INTENSIFICATION INDICATORS

Recent efforts in SI and agricultural development have focused on a better understanding of how to monitor SI over time, and improve understanding of trade-offs among different domains of SI. This approach is being advocated as a means to better detect synergies and conflicts, and minimize unintended negative consequences. Although the use of indicators and metrics of SI is just one aspect of SI research, it can provide a warning if one or other of the domains is out of step with the overall intention, to support a sustainable trajectory of change. Consideration of SI domains and accompanying metrics is also an important means to take into account interactions among domains, and expand the concept of SI through systematic assessment. The domains and indicators suggested by Smith et al., in review, is a good start (Table 4.4), but consideration might also be given to policy and institutional aspects (e.g., research, extension, carbon-credits, and market support). The concluding chapter of this book (see chapter: Tying It All Together: Global, Regional, and Local Integrations) revisits this topic and provides a holistic view, including consideration of policy, cross-sector initiatives, and infrastructure.

After Smith et al., in review.

TRADE-OFFS AND SYNERGIES

SI from some viewpoints is an impossible goal. How can one get more from the same resources? Something has to give, or something has to be invested in order to balance the equation. We acknowledge that SI will have to accommodate compromises (trade-offs). For example, crop residue utilization for animal feed necessarily means less residues available for fuel and soil cover. At the same time, synergistic interactions among domains also occur, such as improved farmer knowledge, which can support production of high-residue crops that simultaneously address production, economic, and environmental goals. Finally, an important reason to pay attention to SI indicators is that interactions among domains become clear, thus providing a knowledge base upon which conscious, evidence-based choices can be made.

Overall, trade-offs are common between short- and long-term production, or between intensification to maximize production and concomitant enhanced

TABLE 4.4 Sustainable Intensification Indicators and Metrics

Domains	Indicators
Productivity	Crop and livestock product yields per farm and per season
Economics	Total agricultural profits per household
	No. of households selling agricultural products
	Poverty headcount
Human wellbeing	Farmer knowledge
	Family food security
	Family nutrition
Environmental	Vegetative cover
	Biodiversity
	Soil organic matter
Social	Equity (distribution of productivity, income, and assets) Women's empowerment
Whole system	Trade-offs and synergies (see below)

generation of GHG emissions (Robertson et al., 2014). The quest for higher yields of commodity crops may see increased use of monocultures, involving a small range of high yielding varieties and a reduction in mixed cultures with diverse minor crops and local landraces (with a consequent loss of biodiversity, culture, and family nutrition). Rwandan agricultural policies promoting consolidated, sole cropping production systems is a case in point (Isaacs et al., in press). The use of chemicals (fertilizers and pesticides) might alter the above- and below-ground fauna and flora, thereby compromising the resilience of the ecosystem. Regulated ecosystem management that optimizes production by growing only what is suited to the environment might restrict individual enterprise choice and innovation. A quest for high productivity might be at the cost of reliability, and incur risks of harvest failure, while the use of external inputs might raise the price of food beyond what can be afforded by some sectors of society. Increased water use for irrigation (and therefore greater reliability and productivity) in one location might mean less water is available for downstream users. Harnessing water for agricultural uses has been frequently shown to have unintended negative consequences for equity, as recent migrants to an area, women, ethnic minorities, and poorer farmers can become marginalized during the process of institutionalizing water rights and irrigation infrastructure development (see chapter: Gender and Agrarian Inequities, for in-depth consideration).

On the positive side, there are prospects for synergies. Careful inputs of nutrients and supplemental water can transform degraded soils with low organic matter into productive, resilient soil that is easier to cultivate and better buffered against climatic and biotic threats. Carefully integrated crop/tree/livestock systems can enhance the efficient cycling of nutrients and inter-enterprise benefits, such as shade and shelter for livestock, and draft power for cultivation, weeding, and transport. Intensively cultivated areas and farmer organizations can produce a surplus that can attract services (inputs, credit, infrastructure, research and extension, transport, markets, etc.) and negotiate higher prices, educational services, and equitable returns. Intensification might lead to more community cohesion and improved education, health, and communication services, leading in turn to improved knowledge, skills, capacity, and contacts.

THE ELEMENTS OF SUSTAINABLE INTENSIFICATION

We next consider in-depth the main elements required for SI that raise outputs without compromising the environment. There are two important pathways, enhanced efficiency through integration and related investments, and reduction of losses and risk (Fig. 4.2). Aspects of an enabling environment are shown in the figure as well. Note that investment in social and natural capital is key. This includes enhancement of social organization and knowledge, but also the application of ecological principles to agricultural systems to build genetic resources (new crops, livestock), soil resources (soil organic matter, biodiversity), water and nutrient resources, and infrastructure for

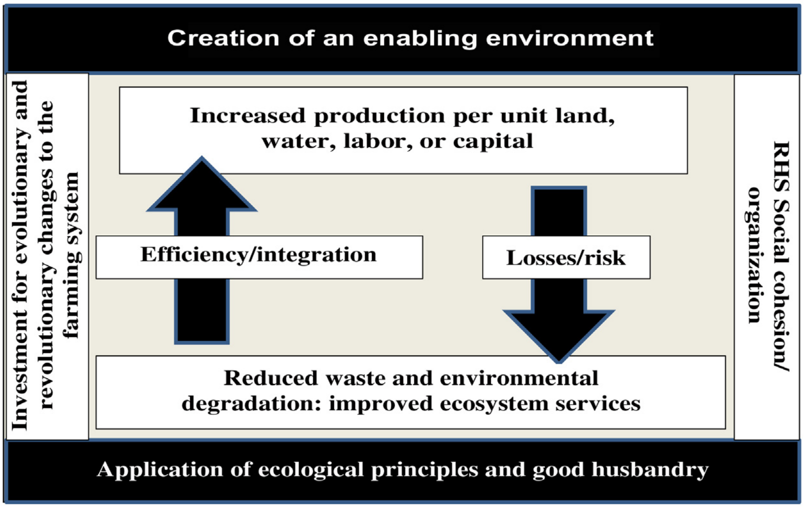

FIGURE 4.2 Summary of the elements of sustainable intensification.

livestock, manure capture and reuse, and markets. The agroecological aspects are a major topic of this book and are explored in some detail in Chapter 2, Agroecology: Principles and Practice, and Chapter 5, Designing for the Long-term: Sustainable Agriculture.

An Enabling Environment

To provide over-arching support for SI, an enabling context is required. This includes appropriate research, extension, training, credit, supportive policies, fiscal and legal structures, as well as peace and stability, disaster management, and infrastructure such as roads, transport and communication networks, storage, processing facilities, and markets. This enabling environment will normally be part of a government's agricultural strategy, which will in turn be part of a national development plan. In an ideal scenario, civil society, nongovernment organizations, donor projects, and the private sector will work in the same direction as the government, providing extra support and fulfilling functions that the government cannot or does not provide.

Another aspect of an enabling environment is social cohesion within communities; this provides a common vision and an agreed, long-term, commitment to the concept and activities of SI. This can be facilitated through local and village governance structures, and also through different forms of *social organization*, including clubs, societies, religious bodies, associations, cooperatives, or innovation platforms providing forums for solidarity and mutual support, and some specialization of roles and responsibilities. These social structures provide an efficient means for sharing information, labor, and materials, for seeking support, and for tracking the progress of SI initiatives.

Reducing Losses

Central to SI and environmental goals is improved efficiency, which requires careful attention to reducing losses and conserving resources. All the glory is in scoring goals, but saving them is equally important. Perhaps this underlies the under-appreciated nature of this topic, reducing losses. Farmers' knowledge of biology and chemistry applied to day-to-day farming choices can enhance effectiveness of pest control and nutrient utilization, for reduced losses. Examples are provided in Box 4.1. The principles involved, that support enhanced water and nutrient recycling, are a central subject of Chapter 5, Designing for the Long-term: Sustainable Agriculture, and Chapter 7, Ecologically Based Nutrient Management. Reducing the loss of water, soil, and nutrients from the farm is an obvious, but difficult, aspect of waste reduction, because soil and water conservation involves investment in labor, materials, and the sacrifice of some land and management flexibility.

A single farmer operating in isolation may not be able to control the forces affecting his or her farm, but needs to operate in concert with

BOX 4.1 Practices That Conserve Resources and Prevent Losses

Specific examples of practices that reduce losses to *improve system efficiency*, include:

- Careful husbandry that optimizes the growing season, and applies nutrients and pest (Including parasite and disease control in livestock, as well as inputs in crop production) management chemicals precisely in terms of type, quantity, and timing;
- Improving farmer knowledge of the *principles behind good husbandry* (an example would be a knowledge of the relationship between evaporation, evapo-transpiration, and leaching at different stages of plant growth, so that adjustments can be made by the farmer resulting in greater efficiency of production);
- Soil moisture management to increase the output per unit of available water and reduce water losses from the farm (e.g., rainwater harvesting, irrigation, mulches, soil and water conservation, increasing water-use efficiency through deeper rooting and better plant nutrition, planting trees strategically to aid rainwater capture and percolation);
- Use of reliable and productive genetic material resistant to pests and diseases, adapted to the environment, and suited to their end use;
- Measures to minimize losses from hail, frost, flood, drought, and wind (e.g., planting dates, cold-tolerant varieties, physical and biological flood and wind defenses);
- Intercropping, relay cropping, and multistory "gardens" to optimize use of soil, water, and light resources;
- Postharvest management to reduce losses due to pests, diseases, and climatic spoilage;
- Use of local weather and market forecasts to support decisions on planting, fertilizer, and pesticide application.

neighbors to channel storm water or plant trees to reduce wind speeds, or bind soil on steeply sloping communal land (at the same time capturing moisture through improved percolation). Terraced land management such as is found in Yemen (Fig. 4.3) requires a high degree of community participation, not only in the planning and construction of such works, but over the long-term for maintenance. Physical structures and conservation measures require social structures as well, for equitable distribution of labor, access to land, and dispute resolution. See Table 4.2 "Dimensions of sustainability" for an exploration of the complexity involved, particularly when considering soil and water conservation at the watershed and landscape scale.

Some countries in sub-Saharan Africa are starting to use digital technology to greatly refine fertilizer recommendations in terms of the blend of nutrients and the quantity of fertilizer to be applied for specific crops. An example is the Ethiopian Soil Information Service (EthioSIS) launched in

FIGURE 4.3 Terraces with stone risers in Yemen. These require a large investment of labor in the short-term for a long-term payback.

2012 (Bellete, 2015). A first-of-its-kind national initiative in Africa, the project uses remote sensing satellite technology and extensive soil sampling to provide high-resolution fertility soil mapping for each region. An example for Tigray region is shown in http://www.ata.gov.et/highlighted-deliverables/ethiosis/. The recommendations are supported by high-volume fertilizer blending facilities in each region. However, even at the higher resolutions now made possible by digital imagery and automated sample analysis, the highly dissected topography of Tigray means that there is considerable in-farm variability in soil fertility (due to rainfall, slope, aspect, cropping history, soil cover, etc.). Therefore the farmer will need to observe and adapt the improved recommendations for different parts of his or her farm. It is also important to keep in mind that nitrogen and phosphorus are the primary drivers of crop productivity worldwide, and augmentation of soil organic matter is essential to support crop response to fertilizer and address the majority of micronutrient imbalances (with rare exceptions due to nutrient-poor soil parent material). See www.msu.learninglabafrica/Nitrogen—*It's what's for dinner*, for the on-going conversation on the rationale behind the focus of Chapter 7, Ecologically Based Nutrient Management, on the management of soil carbon, nitrogen, and phosphorus, as a foundation for sound crop nutrition. This is as relevant for farmers in Ethiopia as elsewhere.

Preventing loss includes attention to pre- *and* postharvest production, and to animal as well as crop system components. Livestock feed is often wasted though trampling, soiling, or rotting through contact with wet ground. Simple, improved feed troughs made with locally available materials can reduce this dramatically, as shown in the example in the photo from Ethiopia (Fig. 4.4).

FIGURE 4.4 Locally made improved livestock feeding facilities to reduce wastage are a sometimes underappreciated aspect of sustainable intensification; example shown here from Ethiopia.

The loss of nutritional value of fodder through spoilage can also be minimized by simple storage structures that reduce the impact of rain, contact with wet soil, and damage by pests. Attention to the quality of feed through balanced diets, based on locally available residues and forage, are also key to improving efficiency of forage utilization and livestock health. This is illustrated by research for development efforts in Ethiopia that have identified fodder and feed as key interventions for improving production and livelihoods based around small ruminants such as sheep (http://www.ilri.org/node/1159).

Livestock losses to intestinal worms, external parasites, and disease are easier to manage when the stock is adequately housed or zero-grazed. That is, where feed is brought to the animal. The collection of manure and urine for application to crops is facilitated by intensified animal production which enhances nutrient cycling efficiency on a farm. There are controlled grazing approaches to improved crop – livestock integration as well as zero-grazing, but all require a step-change initiated through the intensive management of livestock. Forage quality improvement, livestock genetic potential, credit available to invest in stock, facilities and inputs, and good veterinary support are all part of an enabling environment for livestock intensification. Chapter 9, Research on Livestock, Livelihoods, and Innovation, explores livestock innovations and intensification options in more depth.

Improved genetic resources for clonal plants also requires close attention to preplant storage and handling, to reduce losses and enhance planting material quality. In the mountains of Ethiopia, seed potatoes are traditionally stored in earth clamps and planted without sprouting (chitting). This results in 50% of the seed rotting in the clamps or in the soil after planting. The

FIGURE 4.5 Diffused light storage for potatoes in highland Ethiopia to reduce rotting and promote sprouting.

Africa-RISING project (http://africa-rising.wikispaces.com/ethiopia_highlands) has introduced diffused light storage facilities that have greatly reduced losses both in storage and after planting, *and* resulted in higher yields due to the controlled and prolific sprouting of the seed potatoes before planting (Fig. 4.5).

Risk Mitigation

Farmers face multiple risks. A single landslide can wipe out the work of a lifetime, while a machete accident can render an able-bodied person unproductive for a season. Insecurity and violence hold back or disrupt development in general, but can decimate an individual farmer's assets (e.g., through cattle rustling) overnight. Market fluctuations can mean that a well-grown crop has little value in the market place. This is especially devastating for perennial crops with less flexibility from year to year. Schemes such as Fairtrade can offer a safety net "minimum price" for products, including perennial crops such as coffee. The minimum price is set at or above the cost of production so that farmers can at least maintain their coffee bushes until the price recovers (http://www.fairtrade.net/standards/price-and-premium-info.html).

Farmers are unlikely to adopt new practices if they incur substantial risk. This particularly applies to farming families already in vulnerable situations. It is therefore sensible to consider risk reduction measures together with intensification initiatives. Government or community disaster relief funds can assist those afflicted. Farmers associations can offer moral and material support, and savings and credit groups can help provide seasonal or emergency needs for cash and avoid reliance on predatory loans. Improved weather forecasts and market information systems can play their part in reducing risk in decision-making. Insurance against crop failure or livestock death is being considered in some counties. However, access to reliable and timely information about weather remains a major problem for smallholder farmers around the world, and a recent review found this access gap precluded the success of crop insurance schemes with a few exceptions (Tadesse et al., 2015). Other approaches to buffer risk include trustworthy market contracts, secure land tenure, and competent service provision (advice and inputs). These would go a long way toward encouraging long-term investment in farms, and confidence in trying out new technologies.

While some of these can be provided by external agencies, and community organizations, farming families are highly experienced at risk mitigation, a major component of rural survival strategy. Spreading the risk of failure through diversification, intercropping, the integration of crops, trees and livestock, and a mix of farming and nonfarming income are important aspects of risk reduction. These are time-tested approaches to enhance the ability of farms to protect against disasters, and bounce back from extreme events. Agricultural development efforts and advisors have in some cases focused on innovations that maximize production under good conditions, with inadvertent consequences such as overexposure to risk. Local traditions and indigenous knowledge are often important sources of technologies and practices that enhance farm resilience and stable production in the face of climatic extremes. An example of paying attention to risk-mitigation while promoting improved livestock and gardening practices is provided by the "Send-A-Cow" nongovernmental organization operating in East and Southern Africa (Fig. 4.6). This holistic approach involves education, and resources for farm infrastructure to reduce risk from livestock loss and drought (www.sendacow.org).

Biodiversity is an important strategy for enhancing system resilience and reducing risk, as described in Chapter 5, Designing for the Long-term: Sustainable Agriculture. In Nepal, some individual farms in the lower mid-hills have more than 10 different varieties of rice—both for different uses and occasions, but also to use niche planting situations efficiently and to spread risk. In Ethiopia, some farmers plant mixtures of sorghum landraces in the same field—some with open panicles that are difficult for birds to settle on, some with red seed coats that are bitter to pests, and some with closed panicles in case of good rains and successful bird scaring (Fig. 4.7).

In many parts of the world, farms are made up of multiple plots that are spread about the landscape to provide a range of environments for different enterprises. This spreads risk and gives all farmers in a community access to some arable land and some grazing land.

Chapter 6, Low-Input Technology: An Integrative View, by Rob Tripp provides an in-depth analysis of the challenges associated with many low-input,

FIGURE 4.6 The NGO Send-a-Cow has introduced risk-reduction technology to Lesotho. The netting roof reduces damage by hail, snow, and heavy rain. The fence reduces livestock intrusion, and the raised "keyhole garden" enables scarce water to be used efficiently for nutritious vegetable production.

FIGURE 4.7 Mixed plantings of sorghum varieties that buffer risk through a diversity of plant traits that prevent damage from weather, bird predation, and fungal disease, while maintaining potential for good yield and nutritious grain.

sustainable production systems that may reduce risks, but also require substantial investments of labor and other resources.

INTEGRATION OF SYSTEM ELEMENTS

An important strategy for *sustainable* intensification is based on the integration of diverse farm enterprises. This can include cultivated

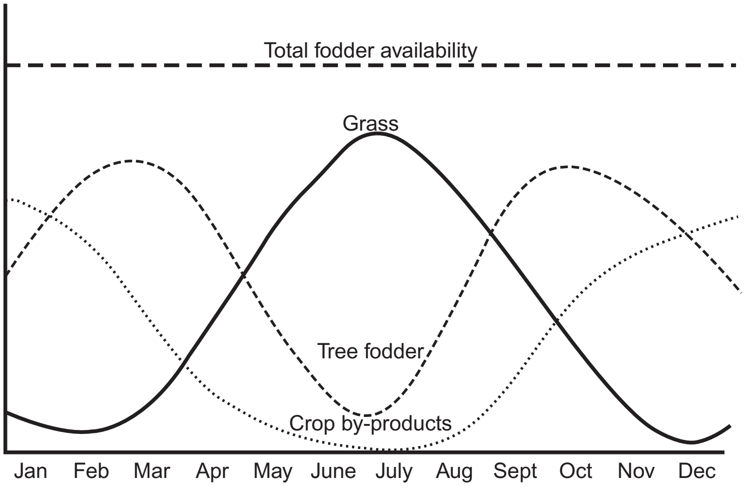

FIGURE 4.8 Integrated fodder production from trees, fodder crops, and grazing.

crops – livestock – trees, as well as wild fauna and flora. Such diversity will help achieve synergy and raise the overall output of mixed-enterprise farming systems. Thus, livestock can utilize crop by-products, and also provide draft power and manure for crops. Trees can provide shelter, construction materials, and fodder, and recycle nutrients for crop growth (e.g., *Faidherbia albida* in central Africa), while common property resources can provide a wide range of materials (e.g., fuel, building stone, pollen for bees, bamboo for basket making, indigenous medicines, and bush meat). Understanding the scientific basis for the benefits of integration can help to refine choices, management, and governance of resources, so that they contribute more to raising the productive output of geographically finite systems.

Fig. 4.8 shows how the integrated manipulation of a range of fodder sources can provide stable amounts of fodder throughout the year.

Similarly, with informed thought and a well-designed combination of enterprises, an integrated choice of farming enterprises can provide food and income throughout the year. In some cases income can be smoothed out by savings, credit schemes, and some off-farm income, while food can be supplemented by purchases paid for by selling what is surplus to family requirements.

Most research looks at individual crops or livestock species, with limited study of farming systems as a whole at household or landscape scales. At the household scale, it is instructive to look at whole farm budgets, and to work out biological and financial returns to land, labor, and capital for each enterprise. This can help the farmer make decisions based on facts that complement his or her own experience and gut feelings.

BOX 4.2 Balancing Nutrient Production in Ethiopian Communities

Africa-RISING (a USAID project managed by ILRI) has been investigating cropping systems in Debre Birhan in highland Ethiopia. Barley and wheat are currently the major staple crops. Preliminary results showed that the current production system does not satisfy human nutrition both in quantity and quality of the required nutrients, being especially deficient in calcium, vitamin A, and vitamin C. Preliminary analysis suggests that a shift in the cropping system by reducing the area under barley by about 35%, expanding the land area planted to legumes by 16%, and integrating more vegetables and subtropical fruits could be beneficial to household nutrition. The project plans to use these results in negotiation with the community to facilitate change toward a more food secure landscape.

Africa-RISING 2014: Technical report, 1 April 2014–30 September 2014 (http://africa-rising.net/about/outputs/).

At the landscape level, one can look at the overall amounts of nutrients produced from farming against the population size to see how these compare to recommended levels of carbohydrates, protein, and vitamins (Box 4.2). Where these differ significantly, action can be taken to rebalance the nutrition profile.

Garnett et al. (2013) point out that a balanced approach to SI involves attention to diversified output of food that meets nutritional family needs for calories, protein, and micronutirents (vitamins, essential amino acids, and other important nutritional components). In contrast, the focus of some agricultural development schemes involve a few high-yielding varieties of staple foods that have an unbalanced nutritional make-up, and a fragile genetic base. In Rwanda, e.g., mixed cropping has for centuries supported diverse diets and helped meet cultural and spiritual needs. In 2009 this included the production of seven to twenty crop species per farm family, with an average of four tuber species, five legumes, four cereals, cucurbits, and two perennials, all grown in mosaics and relay intercrops (Isaacs et al., in press). However, a land consolidation policy in recent years has drastically reduced the number and types of species grown as each region in Rwanda is encouraged to specialize in a few crops, grown as monocultures. This rapid change in farming systems has been brought about by persuasion, policies, and subsidies, as well as coercion through fines, and violence on occasions. Civil society in the form of NGOs and farmer associations have raised questions about the wisdom of suppressing diversified production systems, particularly in terms of negative consequences for family nutrition, given the imperfect functioning of local markets and income constraints.

In order to achieve *sustainable* intensification, present levels of natural resources (farmed and wild fauna and flora, soil properties, water) need to be maintained, or even improved (Box 4.3).

BOX 4.3 Precision, Integrated Soil Water, and Nutrient Rehabilitation in West Africa

Farm rehabilitation initiated through reclaiming degraded soils has been achieved successfully across substantial areas in West Africa. In the drier regions of Burkina Faso, e.g., water harvesting technologies have been invested in, with farmers planting basins (*zai* holes) and bunds. These improved planting basins are targeted for precision application of crop residues, organic manure, in some cases microfertilization and improved seeds. This has rehabilitated degraded soils through the judicious targeting of nutrients and water to enhance plant growth, and lead to a virtuous cycle of increased organic materials being produced and recycled, as well as doubling and tripling of crop yields (Lotte et al., 2015). The *zai* hole technology requires considerable investment in labor to dig planting basins and apply nutrient-enriched materials; it has been sustainably adopted in drier regions (less than 800 mm rainfall), and where degraded soils are available for reclamation. Such soils involve issues such as crusting and nutrient depletion, and can be successfully reclaimed through the integrated approach of improved planting basins. There is a social component as well: women and other marginalized groups of farmers have in many cases been among those most willing to make the investment to reclaim land to expand their agricultural enterprises. In Niger, e.g., women's groups planted vegetables and fruit trees in *Zai* holes that allowed abandoned land to be reclaimed for their use. The returns to soil rehabilitation and the value of crops grown must be considered carefully for successful adoption of high labor requiring technologies (see chapter: Low-Input Technology: An Integrative View).

SI involves consideration of "private" services and goods, such as the soil rehabilitation example described in Box 4.3, but these often contribute to "public" conservation and output of agriculture as well. Farmers' individual choices and rural communities play key roles in producing both food *and* environmental services that society has an important interest in promoting (see http://www.risefoundation.eu/images/pdf/si%202014_%20full%20report.pdf).

Such environmental or nature's services include clean water and water regulation, clean air, biodiversity, and the reduction of GHG emissions. These deliver mainly public goods rather than private goods, so much of the investment should come from national or international sources. How to operationalize and initiate policies that enhance returns to support conservation investments by scattered smallholder farmers is a major challenge facing societies today, to ensure a sustainable future.

PATHWAYS TO SUSTAINABLE INTENSIFICATION

SI occurs within a dynamic situation, with changing markets and environment that require constant experimentation and adaptation by farmer-innovators,

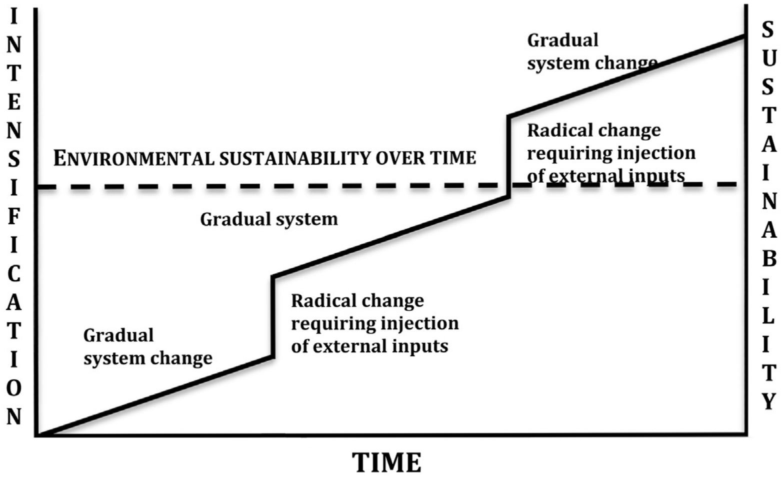

FIGURE 4.9 A schematic of how progressive intensification can involve both incremental and radical changes, while maintaining natural resource levels.

and by private and public bodies of both technological and organizational structures. Improvements can be *evolutionary* (incremental improvements of existing technologies—such as the adoption of new varieties or parasite control in livestock), or *revolutionary* (new ideas and directions that can radically alter the status quo), producing a "step-change" in productive potential (Fig. 4.9). Such revolutionary changes can mean radical changes to the farming system, and require the learning of new skills, major capital or labor investments, and social reorganization.

In some cases the capital investment can be found within the community, an example being the transformative changes described by Tiffen and others in Machakos, Kenya, where remittances financed soil and water conservation, and the adoption of high-value fruit and vegetable production on previously degraded land (Tiffen et al., 1994).

An example of social and technical inputs transforming agricultural systems is the adoption of minimum tillage in Brazil that was enabled by the establishment of Clubes Amigos da Terra ("Friends of the Land" clubs), the development of appropriate machinery, and the availability of effective herbicides (FAO, 2001).

In some cases a crisis is needed before a step-change is acceptable to the majority in the community, by which time some natural resource may be irreversibly lost.

The impetus for a change from extensive to restricted grazing might come from several factors (internal and/or exogenous) working together (e.g., erosion resulting from grazing of fragile areas, conflicts between crops and livestock, and a new road opening a market for milk products) to bring about the change from extensive (unregulated) grazing of livestock to one which is regulated (perhaps by "social fencing" as in India (http://www.zef.de/fileadmin/downloads/forum/docprog/Termpapers/2009_1_Girma_Manh.pdf)), and eventually to a situation where all livestock is zero-grazed or stall-fed. Such a step change often requires agreement and cohesion among the whole community, and discipline enforced by village leaders. Once applied, a range of new cropping options become available and the planting of trees for soil and water conservation, amenity, food, and animal feed becomes viable. Manure and urine capture are more efficient, providing the potential for more efficient cycling of nutrients. Farming families then have to decide on a new balance of livestock and cropping enterprises to suit their labor availability, household needs, and market opportunities. This step change is normally followed by a period of adjustment and gradual improvement.

All of these examples bring in a range of new opportunities and challenges, technical, organizational, and social. In many cases those with resources are better able to take advantage of a new opportunity, further exacerbating the gap between poorer and better-off farmers, unless particular support is given to the resource-poor farmers. As shown in Fig. 4.10, different approaches to supporting SI pathways may be appropriate depending on the resources and education of the farmers involved. Farmers with access to markets and the ability to invest may benefit from integrated value chain approaches to agricultural development, where crops are grown as commodities (see the maize – soybean rotation trajectory in Fig. 4.10). Ensuring a sustainable mode of intensification primarily involves promoting

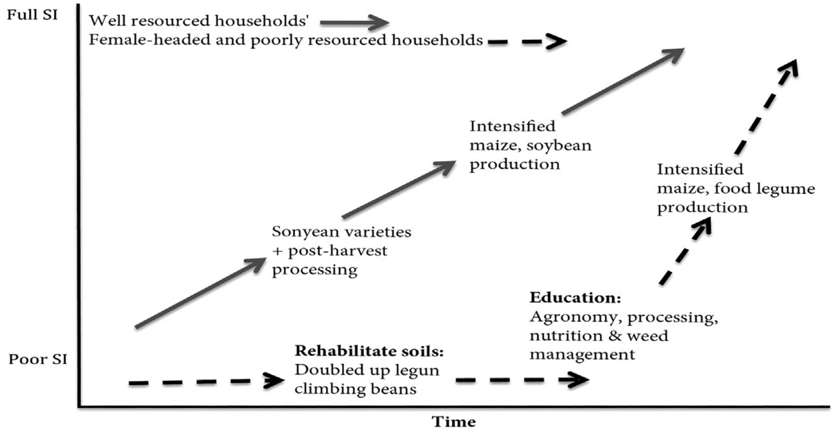

FIGURE 4.10 Alternative pathways to Sustainable Intensification for differently endowed households, where well-off households can be supported through market access, whereas poorly resourced households require considerable investment, in education, food crop processing and nutrition, as well as resource rehabilitation.

agroecological practices and conserving natural resources. Other farmers are much less resource endowed, with poor education, remote locations and often, degraded lands. Outreach to this group requires considerable attention to education, on production and postharvest, from agronomy to family nutrition (Fig. 4.10). As described in Chapter 12, Outreach to Support Rural Innovation, there are many extension modes by which farmers can be supported to develop alternative SI approaches. As shown in Box 4.4, Africa RISING is an example of how participatory action research can engage with farmers across a wide spectrum of resource-endowment, and provide options to help catalyze a range of SI trajectories.

Some locations and situations can provide SI gains in the short-term. These are the "low-hanging fruit" for SI, and include fertile soils in accessible locations that have been underexploited to date. These situations can provide long-term productivity increases through modest levels of external inputs and good husbandry methods. However, such places are becoming scarce, and in the near future SI will require greater investment for the same net gains in productivity. Marginal and degraded areas are where many smallholder farmers are situated, and most such locations require investment in soil resource rehabilitation before it is possible to intensify agriculture in even a small way.

There is a danger that governments will regard some locations as being underutilized and an opportunity for intensification, when they are in fact vital components of the coping strategies of the poor and marginalized. For example, many irrigation projects involve development of land and water

BOX 4.4 Africa-RISING: An Example of Support for Sustainable Intensification Pathways Underway in the Central Malawi Districts of Dedza and Ntcheu

Since 2012, over 1500 farmers, dozens of extension educators, and an interdisciplinary team of researchers have collaborated as part of "Africa-RISING." This multicountry project is supported by USAID to conduct farmer participatory research on SI. Crop diversification, livestock, and the introduction of multipurpose, leguminous perennials are at the foundation of more integrated, environmentally, and economically sound production practices. Technologies include soybean intensification with improved varieties and rhizobium, in rotation with hybrid maize and recipes for soybean utilization. For farmers with degraded soils, we are investigating the ability of a doubled-up legume system with pigeon pea to improve soil properties and crop response to inputs. This is being tested out with farmers in a participatory mother and baby trial design, combined with education on agronomy, food processing, and family nutrition to support capacity building, soil resource rehabilitation, and enhanced sustainable production. See Fig. 4.10 to show these two pathways to SI for different farmer resource groups.

resources that are traditionally managed, common-property resources that sustain or supplement land-poor or landless families with food, saleable products, and fuel. Such areas often have an important ecological role as well, such as wetlands that are important to regeneration of water quality. Other examples are grazing areas that provide vital livestock food in drought years, and swampy areas that play an important hydrological role in controlling floods.

THE WAY FORWARD

To intensify production sustainably with attention to the environmental, human, and social domains requires farmers and other landowners to take on dual roles—producing food and safeguarding environmental services (http://www.risefoundation.eu/images/pdf/si%202014_%20full%20report.pdf). This dual role is sometimes recognized, and farmers are encouraged through mechanisms such as government payments (e.g., in the European Union through the Basic Payment Scheme) to farm in an environmentally friendly way (https://www.ruralpayments.org/publicsite-rest/fscontent/repository/portal-system/mediadata/media/resources/greening_booklet_for_online_-__february_2015 ~ 1.pdf). Indeed, Garnett et al. (2013) see an urgent need for mechanisms that compensate farmers for meeting SI objectives, such as climate change mitigation or biodiversity protection, where this involves actions that have an economic cost to the producer (i.e., the farmer should not be expected to cover the costs of public goods). It has been difficult to develop such mechanisms that function well for smallholder farmers. Organizing large numbers of farmers to receive incentives through cooperatives, and policies that link education and subsidies to promote resource conserving practices, are some of the approaches being considered. Overall, there is growing support for the approach of support for farmers as land managers, whose choices determine whether agricultural lands provide a range of ecosystem services. This is embedded in the philosophy of land *sharing* (sharing land functions through mixed landscapes that achieve environmental and social services along with agricultural provisioning). Land *sharing* stands in contrast to an emphasis on land *sparing* (where high-input agriculture with consequent high yields potentially frees up land that can be devoted to nature and ecosystems services)—which has rarely been achieved in practice. Further research is needed to understand pathways and fiscal arrangements that lead to food systems that are productive and sustainable, *and* meet public and private needs.

A think piece on SI by IIED (Cook et al., 2015) suggests that SI should focus on the supply side of the global food system. It is fully acknowledged that additional approaches will be needed to tackle consumption and consumer waste, food access and entitlements, markets, and power. They agree with the need to provide incentives to farmers to drastically reduce the environmental impacts of crop and livestock production, but in addition recommend the following:

- Promote low-cost approaches under local control by farmers and communities;
- Enable and invest in innovation and adaptation (including adaptation to climate change);
- Recognize the important role of public sector funding for agricultural research;
- Discourage the use of highly productive croplands to grow animal feed;
- Address the energy needs of smallholders while limiting fossil fuel intensity and reducing GHG emissions;
- Strengthen the voice of smallholders and vulnerable groups in decisions about agriculture and land use;
- Focus on enhancing the economic value of farming, as well as its productivity.

These are important goals, ones that require the ingenuity and innovation of current and coming generations. To provide benchmarks along the way, we strongly support the development of indicators of SI, with practical metrics that are widely agreed upon and used in the field. These are needed to clearly define the functions of and expectations from SI, and to monitor progress and performance against these. The domains of SI have been expanded beyond production, economics, and environment to include social and human wellbeing, with an emerging consensus that sustainability is more than environmental protection, it is rooted in local knowledge and justice (Loos et al., 2014). One of the grand challenges facing agronomists and change agents in agricultural development is how to support SI, and agree on metrics that reflect all five domains as a crucial next step along that road.

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Chapter 5

Designing for the Long-term: Sustainable Agriculture

Sieglinde Snapp

INTRODUCTION

In a world where change is occurring at an increasingly rapid pace, developing sustainable and adaptable farming practices is central to rural livelihoods. In locations where farmers are at the edge of survival, it is possible to see widespread cutting of trees for fuelwood or charcoal production, and tillage of steep slopes (Fig. 5.1A and B). At the same time, farmers everywhere attempt to protect their children's heritage, soil productivity, natural resources, and water quality. Technical advice for sustainable management should focus on improving adaptability and resilience in the face of uncertainty, while retaining the potential for improving productivity and profitability.

There is no defined set of practices that comprise sustainable farm design, because agroecosystem management takes place within an inherently dynamic (nonstatic) context. Increasingly, as the world economy continues to globalize, and with projections of severe impacts due to climate change and population increase, farmers face an unpredictable environment (Fig. 5.2A–C). Farmers are responding to these pressures in many ways. Some farmers are increasing intensified agricultural production, producing higher value crops, and using water control methods such as drainage and informal irrigation systems. Intensification is both an opportunity and a challenge: it can provide greater food security and the potential for income generation, but there are concurrent environmental and financial risks. Intensification involves increased labor and inputs, which requires farmer investment of scarce resources, and often involves increased exploitation and tillage of areas which may be environmentally sensitive. There are specific circumstances where increasing intensity of land use and a higher population density has led to improved natural resource management (NRM), as documented in the book called "More People, Less Erosion: Environmental Recovery in Kenya" (Tiffen et al., 1994).

Agricultural Systems. DOI: http://dx.doi.org/10.1016/B978-0-12-802070-8.00005-0

FIGURE 5.1 (A) Charcoal is often produced by those with few livelihood options; shown here being transported to urban markets in southern Malawi. (B) Production on steep slopes is also common in southern Malawi, where population densities are high and land is used intensively.

Farm families require technologies that help reduce risk and enhance productivity, but at the same time avoid biodiversity reduction and resource degradation. Conservation and productivity enhancement are not necessarily competing agendas. However, they may be points of contention and community tension. Agriculture can have a profound influence on water quality and supplies, and the regenerative capacity of an ecosystem. Intensification of production in wetland and riverine areas, e.g., is a highly efficient strategy for optimizing return to scarce resources and enhancing food supply around the year, but it can profoundly alter this environmentally sensitive land and water interface. Changes in use at the land – water interface often impinge on the user-rights of those with less voice, such as pastoralists who use the

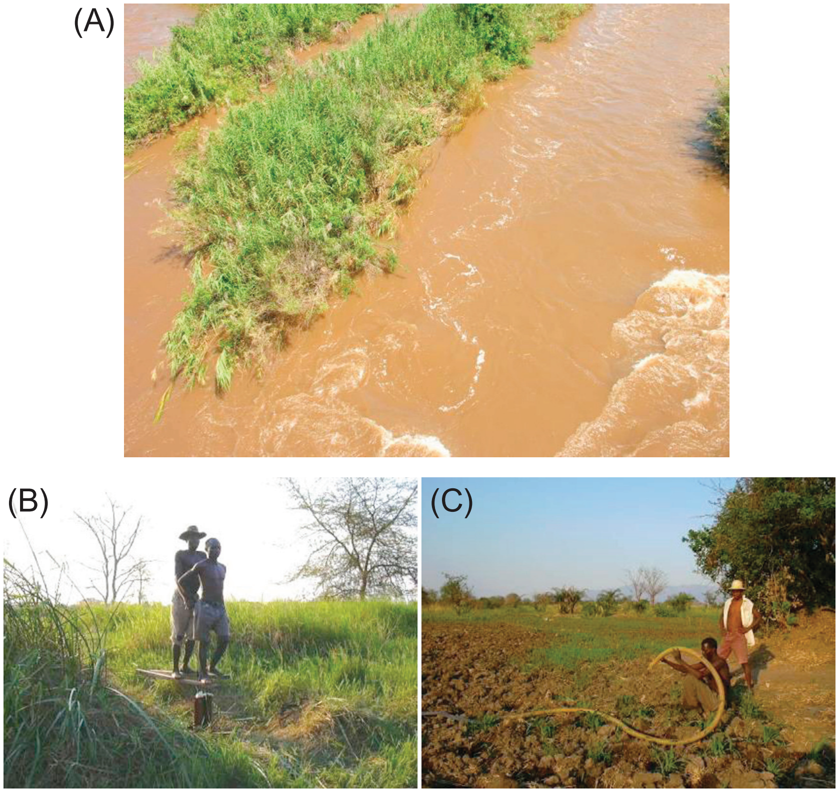

FIGURE 5.2 (A) Floods are becoming more frequent, devastating smallholder farms in southern Africa. (B) and (C) Increasing population pressures, globalization of markets, and drought are pressures increasing intensification of agriculture in many parts of Africa, and enhanced reliance on irrigation systems such as treadle pumps.

wetlands as emergency grazing in dry spells, or women who gather thatching grasses and other resources.

Indigenous System Models

Smallholders have devised sophisticated and complex farming systems that utilize the variability associated with specific microsites and climates. Along the slopes of Mt. Kenya, e.g., farmers use their knowledge of soil type, climate, and market demand to determine which mixture of annual crops and perennials to grow at different locations (Fig. 5.3A–C). Some crops are widely adapted and produce staple grains, so appear frequently in the landscape, such as rice and maize. Many crops have specific climatic requirements, such as the adaptation of cotton to hot, dry conditions and clay soil types, or potato to cooler climates and well drained soils. Box 5.1 illustrates

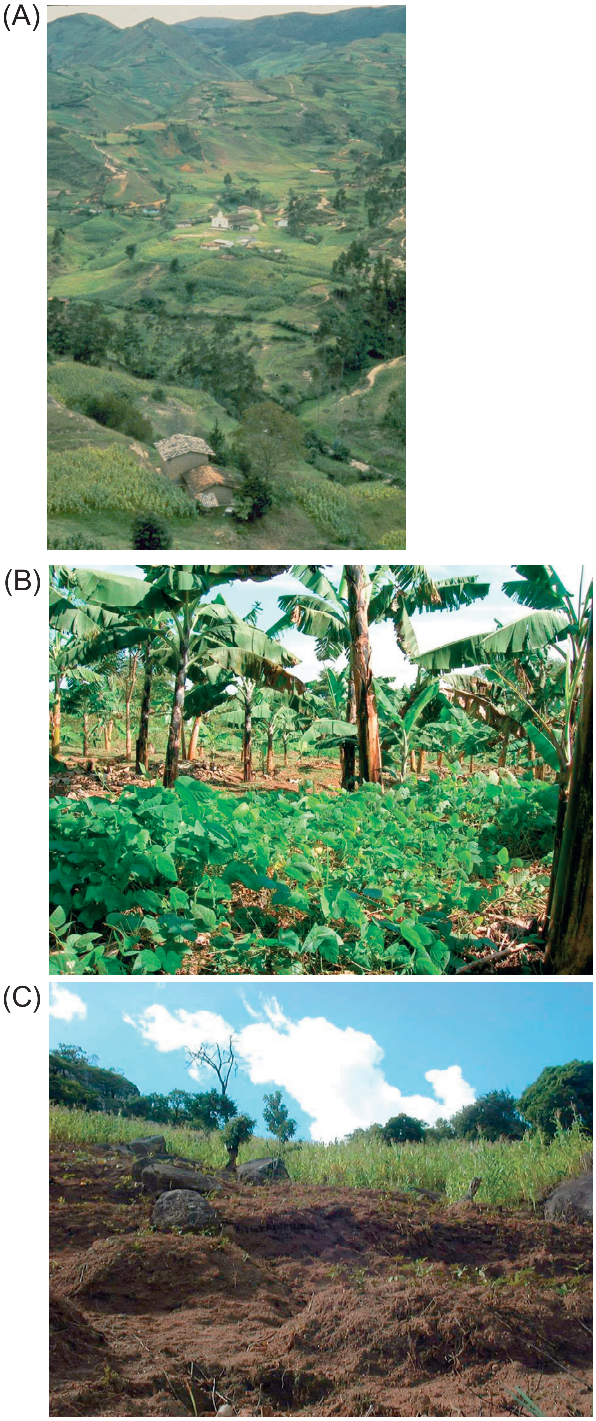

FIGURE 5.3 (A) A range of crops are grown along mountainsides in Eastern Africa. (B) Banana and *mucuna* are commonly grown at low spots in the landscape. (C) Maize and cassava are often grown on well-drained, steep slopes.

BOX 5.1 Smallholder Farming System Innovations in Northern Thailand

Near Chiang Mai, in Northern Thailand, mountain farming systems involve a tremendous diversity of vegetables, fruits, and grains for market and home consumption (Fig. 5.4A and B). Thai mountain farming is evolving rapidly through farmer innovations. For example, integrated pest management and organic production has been improved using a technique called "netted farming." As shown in Fig. 5.5, crops are grown under tunnels of netted material. This helps control—without pesticides—a range of tropical pests, and produce unblemished vegetables for a market that demands high quality. In addition to controlling foliar pests, farmers are developing novel methods to control soil-borne pests. Compost preparations and biofumigants are being experimented with, to prepare healthy soil in the planting beds and support vigorous crop growth.

FIGURE 5.4 (A) Diverse vegetables are sold in Northern Thailand markets. (B) Diverse fruits are sold in Northern Thailand markets.

(*Continued*)

BOX 5.1 (Continued)

FIGURE 5.5 Netted tunnels used for organic production of vegetables and flowers in Northern Thailand.

the complex landscape management and farming methods used by smallholders in Northern Thailand to produce hundreds of crops.

Agricultural development addresses the complex, heterogeneous environment of the smallholder through different approaches, including improved genetics, knowledge-based interventions, and livelihood strategies (Table 5.1). Variability in soils, climate, and water availability are often buffered, through inputs. New plants and animals are then introduced, to utilize this high potential environment. Productivity gains have been tremendous from this Green Revolution approach to plant breeding. Local resource cycling efficiency is often enhanced as well, as plant genotypes are adopted that utilize nutrients, and other inputs. Over the long-term, the sustainability of this approach will depend upon the level of inputs required, the resource-use efficiency, and the scale of the system under consideration (Table 5.1). The resource efficiency of a Green Revolution approach at a regional scale is going to be different than locally, as cropping systems with high yield potential varieties rely on mining, for nutrient procurement, as well as energy-intensive processing and transport.

There are complex ramifications of productivity gains, which do not lead directly to food security gains. That said, it is important to note that crop improvement has made recent progress, moving beyond irrigated systems in developing countries. In Latin America and Southeast Asia, yield gains of over 800 kg/ha have been documented over the last decade, improving average grain crop yield to 2700 kg/ha. In sub-Saharan Africa (SSA), however, the yield of the staple grain crops—maize, wheat, and rice—have remained

TABLE 5.1 **Sustainability and Agriculture Development Approaches, Within the Heterogeneous and Constantly Changing Environment Faced by Smallholders**

Agricultural Development	Genetics	Agroecology	Livelihoods
Historical approaches	• Breed high yield varieties for irrigated and fertilized environments • Continuous breeding for resistance	• Characterize environmental variation • Design farming systems on agroecological principles	• Characterize farmer livelihood strategies • Visioning to develop new opportunities • Catalyze development of value chains
New approaches	• Breed varieties adapted to stressed environments • Participatory plant breeding	• Participatory action research to improve knowledge and innovation capacity • Local adaptation of ecologically sensible options • Community scenario building • Web-linked WikiAg[a] information	• Support effective, demand-driven extension through farmer organizations • Education for nutrition and market opportunities
Socioeconomicconstraints to sustainability	• Ensuring smallholder access to new genotypes • Seed systems	• Inadequate education • Conflicting interests • Organizational inadequacies	• Stable and transparent government • Market and policy limitations
Biological constraints to sustainability	• Challenges to reproduction of organisms • Epidemics	• Environmental constraints • Erosion of resource base • Reliance on external inputs	• Insufficient options that are ecologically and economically sound

[a] *Wikipedia approach to community refereeing of agricultural and technical information generation. The following website is a portal to agricultural information http://www.iaald.org/index.php?page=infofinder.php.*

at the same level for several decades, at around 1000 kg/ha. This may in part be due to risk mitigation strategies of sub-Saharan African farmers.

Overall, genetic improvements related to stress tolerance have proved elusive to develop. The complexity of yield improvement in a heterogeneous, poorly resourced environment requires a multidisciplinary approach, and a tremendous research effort. There have been promising developments in maize breeding targeted to smallholder farms in southern and eastern Africa, based on multienvironment trials and participatory breeding. The maize genotypes are being bred with attention to locally acceptable quality traits, as well as improved tolerance to drought, and in a few cases, tolerance to low N fertility (Bänziger et al., 2000). Similar efforts are underway to improve stress tolerance and farmer quality traits into improved varieties of sorghum in West Africa, and upland rice in Southeast Asia (see chapter: Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers). As more genotypes adapted to smallholder environments become available, this will expand options and help build more sustainable farming systems.

Moderate-scale producers with limited resources tend to rely on strategies that take advantage of resource heterogeneity, rather than focus on ameliorating variability through inputs. Agroecology-based approaches to development have focused on documenting this environmental complexity (Table 5.1). Targeted planting of crops in different niches across a farmscape are risk avoidance strategies, as performance will vary with climatic conditions. Rather than optimizing yields, many smallholder farmers attempt to ensure sufficient food supply and distributed food supply through multiple planting dates and management practices.

Farmers rely on multifunctional systems that encompass not just fields but "common use" areas of fallow, unimproved forage, savannah, semiwild borders, and woodland. The poorest among the community, in particular, often rely on marginal lands and small gardens for survival. Semidomesticated foraging areas often do not produce large amounts of staple food, but they do ensure the provision of multiple services, from protecting soil and water quality to maintaining cultural integrity (Bennet and Balvanera, 2007).

It is important to be aware that modernizing production by ameliorating a heterogeneous and semidomesticated area can have negative impacts on the environment, and on disadvantaged members of the community. Rural people are keenly aware of the wide range of ecosystem services conditioned by land management choices: water quality regeneration, climate regulation, erosion and water flow control, disease regulation, and cultural services. These are integral to sustainable practice, and have begun to be considered by economists as valued products in addition to the conventionally valued production of food, fiber, timber, and biofuels (Fig. 5.6).

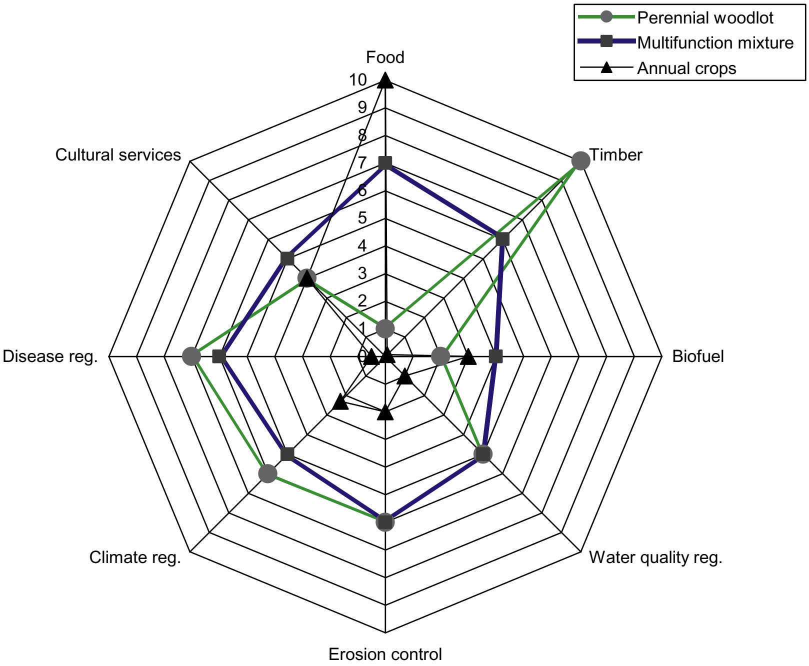

FIGURE 5.6 A radar chart shows the different ecosystem services provided by different types of land use systems, where annual crops are the most effective at producing food, and woodlots at producing wood, while a mixed farm system can incorporate a wider range of services. *Adapted from Bennet, E.M., Balvanera, P., 2007. The future of production systems in a globalized world. Front. Ecol. Environ. 5, 191–198.*

Sustainable Agriculture Design

There is growing evidence that some key, ecologically based concepts inform sustainable agriculture design. Building on the agroecological principles discussed in Chapter 2, Agroecology: Principles and Practice, core practices were chosen to expand on here:

- Biodiversity;
- Resource efficiency;
- Productivity and economics;
- Farm system resilience.

Biodiversity

Central to sustainable farm design is the complex challenge of maintaining biodiversity. There is debate among agroecologists regarding how much biodiversity is enough to promote system stability, and the scale at which biodiversity should be promoted. Here we consider the individual species level, and diversification at the community level. Soil ecology is a rapidly growing field with recent advances in methodologies to study and document biodiversity that can provide a foundation for improved management. Plant biodiversity is a key factor influencing soil biota, and is one of the most important tools farmers have to ensure that agriculture is sustainable. The planned combination of plant types and growth habits—such as mixtures of annual and perennial species—is crucial to providing many environmental services (Fig. 5.6). These include the closing of nutrient cycles, protection of soil and water quality, and regulation of pest populations. Chapter 2, Agroecology: Principles and Practice, describes in more depth the biological theory behind combining growth forms in systematic ways to develop community "assemblages" of complementary species.

Soil biodiversity One of the most important and least understood of resources that shape agroecosystems is out of sight, and in many cases, out of mind. This is the soil biome below our feet. The limited knowledge of this ecosystem is in part due to the methodological challenges to identifying and monitoring the tremendous diversity and enormous numbers of soil micro flora and fauna, particularly in the active rhizosphere zone (Giller et al., 1997). Agricultural topsoil contains on the order of 10^9 microbes per gram of soil, and as much as a million species (Gans et al., 2005). This diversity has only begun to be explored, and immense investment in DNA sequencing methods has in many cases highlighted how much remains to be characterized. Until recently it was only possible to culture about 1–3% of microorganisms under laboratory conditions, which placed severe limitations on understanding the nature of organisms that play critical roles in soil processes that regulate plant growth, and ultimately, the sustainability of food production systems. These include water and nutrient cycling, aggregation and organic matter formation, as well as decomposition and soil-borne disease incidence and regulation.

Understanding the life strategies of soil macro and microorganisms is critical to what has been called "wrangling soil biota," or management of the microrealm.

The growth types, resource acquisition mechanisms, and other key competitive and survival traits are just as critical as for plants, and research is flourishing on microorganism functional types (Barrios, 2007). How functional types such as competitors, stress tolerators, and opportunistic ruderal types of soil organisms interact is an important consideration in the design of agricultural systems (see chapter: Agroecology: Principles and Practice). Two major soil biological actors are fungi, which generally follow a stress tolerator life strategy, and the contrasting life strategy of bacteria, which involves opportunistic responses, and often high intrinsic growth rates. Within bacteria, life strategies can be characterized along a spectrum of response to nutrient supply: copiotrophs proliferate in the presence of abundant nutrients, and oligotrophs in a resource-scarce environment (Schmidt and Waldron, 2015).

The importance of resource supply is highlighted by recent findings from incubation of soils collected from long-term field experimentation. In the field, altered management has often been shown to induce variation in microbial community composition. Yet an unexpected recent finding is that amendment with plant litter can be more important than the controlling factor for soil respiration function (Birge et al., 2015). This provided a way to test which came first, or the "chicken or the egg" question in soil biology; is soil function determined directly by the organisms present, or does land management alter both soil biology and function? Put another way, can altering resources through amendment with compost or plant residues regulate soil respiration rate, regardless of the microbial community composition present? Soil respiration is a microbially mediated process. But studies such as those carried out by Birge and colleagues (2015) demonstrate that addition of residue amendments can drive this function in the presence of quite different soil biota. This is suggestive that there is high redundancy in the function of soil microorganisms, and the choice of plants grown as crops or green manure is very important in determining soil biological functioning.

To sum up, altering the plant species present is one of the most important tools that farmers have to influence microorganisms (Drinkwater and Snapp, 2008). This is both directly and indirectly, through impact on soil aggregation and soil organic matter supply. The energy, nutrients, and biochemical properties of residues and exudates are what support the growth of the biome below ground. See Chapter 7, Ecologically-Based Nutrient Management, for a discussion of how to apply ecology to manage nutrients.

There are also negative impacts from farm management practices, such as disturbance through tillage or chemical additions (Giller et al., 1997). There are some agricultural chemicals that are much more harmful than others for soil organisms, particularly macrofauna (Box 5.2). These should be avoided, notably the class of fungicides, nematicides, and all types of fumigants. The positive impacts of farm management practices include irrigation, as soil moisture favors soil biota, and organic matter amendments also provide the habitat and food sources that support enhanced soil biology.

BOX 5.2 Impact of Agricultural Chemicals on Soil Organisms

Herbicides

Minimal known effects on soil fauna and soil microorganisms
Some may harm certain algae

Insecticides

Some effects on nontarget soil insects
Some effects on earthworms

Fungicides and soil fumigants

Significant negative effects on a wide array of fungi and soil fauna

Efforts to manage soil microbial biomass must take into account how fast they grow and reproduce, as well as how fast they die off. Bacterial biomass has been shown to vary by 50% over a growing season, and fungal biomass to vary by almost double that (Schmidt and Waldron, 2015). At the same time, the impact of past management casts a long shadow: microbial community composition has been shown to reflect land use several decades in the past, and it can take decades to recover diversity (Schmidt and Waldron, 2015). An example is shown by studies of soil biota in field experimentation comparing monoculture maize production under intensive management practices to alternative, diversified crop rotations with five species (including cover crops) and judicious use of inputs (Mpeketula, 2016). Differences in mychorrhizal species diversity were detected between monocultural maize and the diversified, rotational maize system. However, a comparison of arbuscular mychorrizae spores from recently sampled and archived soils showed that shifts in arbuscular mychorrizae spore diversity were slow over the two decades of the experiment.

Considering that microbial diversity takes time to alter, and that management can drive function, it appears justified to focus primarily on plant species composition as a practical means to improve soil biology and function. Residues that are low in nitrogen content will almost all have a wide C:N ratio, such as 30 C to 1 N or more. This biochemical property is often referred to as low quality (as more recalcitrant to decomposition by microorganisms), and tends to foster fungal growth at the expense of bacteria (Six et al., 2006). Thus, amendment of soil with low-to-medium quality residues such as cereal straw or manure will often promote the presence of fungal species, as will reducing tillage. If decomposition of organic materials that are resistant to breakdown is a goal, along with efficient incorporation into soil organic matter, then promotion of fungal species may be warranted. However, bacterial species are also required in large amounts, particularly to support rapid nutrient cycling. Knowledge of an appropriate fungal-to-bacteria balance is an area of active research inquiry, and clearly will vary with environmental conditions and agricultural goals.

Other management practices that influence the soil food web and fungal-to-bacteria balance include no-till and surface mulch. Less disturbance of the soil through conservation tillage practices is an important means to promote soil organisms such as earthworms, and fungal species, by minimizing the destruction of filamentous hypha strands (Six et al., 2006). Mulch provides important benefits to soil life by buffering temperature swings, and enhancing soil moisture. The addition of inoculum—with the notable exception of *Rhizobium* inoculum applied to legume species—should not be considered as a means to alter microbial communities. This is based on the overwhelming numbers of microbial species propagules present in soil, which ensures competition and effective suppression of organisms added through inoculum (Whipps, 2001). If plants are being grown in sterile media, such as seedling establishment and containerized systems, then inoculum may be beneficial.

Experimentation with inoculating seed is another potentially beneficial technology, but it has not yet proved itself in the field.

Diversifying plant species Highly simplified cropping systems have come to dominate much of the world's agriculture, including continuous rice, maize – soybean, and wheat – rice rotations. These are highly productive systems in terms of calorie returns to investment, and in terms of economic returns within current policy environments. Many of these monoculture and biculture systems are, however, dependent on substantial inputs in the form of externally purchased nutrients and pesticides. The wheat – rice system, e.g., is fertilized as often as seven times per year (Fig. 5.7). There are considerable ecological gains to be made from increasing diversity, even modestly, in these highly simplified systems. This is shown by the successful control of a rice pathogen in China by growing a mixture of rice varieties, using what has been termed a multiline approach (Zhu et al., 2000).

Resource efficiency and resilience can be markedly enhanced by diversification, as will be explored further in this chapter; however, it is important to keep in mind that carbohydrate production will often decline on an area basis when a cereal is replaced with another crop. An example of this tradeoff is the replacement of wheat with the grain legume chickpea in the wheat – rice double crop system; this reduced N fertilizer requirements by 60%. However, there was a concomitant change in the quality and quantity of grain produced, as chickpea produces a high protein grain at lower yield potential than wheat. For farmers that have some measure of food security, it may be possible to reduce the total amount of calories produced and enhance

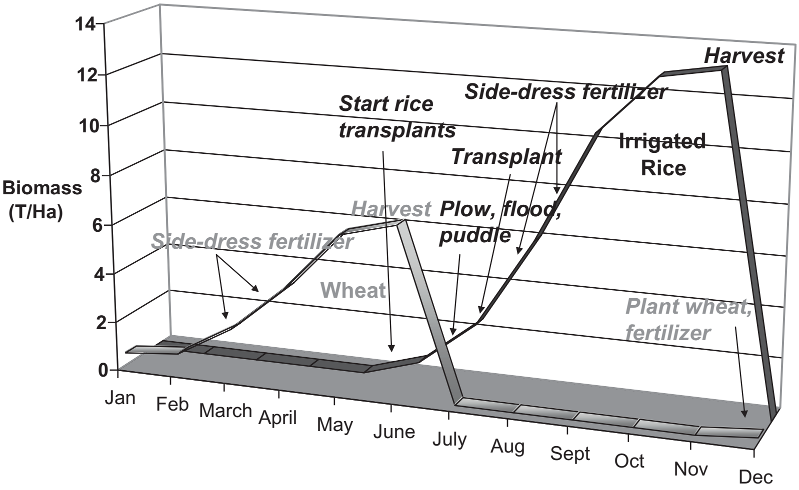

FIGURE 5.7 Wheat – rice doublecropping system, where wheat operations are shown in gray and irrigated rice operations in black. The biomass productivity of this system is very high, as are the labor, fertilizer, water, and seed requirements.

the sustainability of the cropping system by integrating a grain legume in place of a cereal.

Enhancing diversity through a focus on plant species is an important strategy in agroecology, because plants are the primary producers that support herbivores, and the entire soil food web of micro- and macroorganisms. This is termed “bottom up” management in ecological terms: the plants provide the biochemical quality, and quantity, of root and shoot residues that regulate food and habitat availability. Plants also act as “top-down” regulators through supporting the presence of natural enemies that suppress pests. Indeed, plants are the key providers of shelter, nectaries, and other alternate food sources for beneficial insects. In a few cases plants act as repellants, producing volatile biochemical compounds, such as odors, that discourage insects from landing or feeding nearby. See Fig. 5.8, which illustrates the use of basil as an intercrop with eggplant by an organic farmer. Basil is a strongly aromatic plant that provides protection against flea beetles and other pests.

The introduction of new species will enhance diversity to the extent that they have different physiology, morphology, growth habits, and diverse reproductive strategies. These traits impart functional diversity, which is a central principle in the design of buffered, resilient, and sustainable systems. Integrating plant diversity can be accomplished over space and time by using “accessory crops” (Drinkwater and Snapp, 2008). Accessory plants are not grown primarily for economic sale or consumption, they are instead planted for a wide range of ecological purposes, and often have multiple functions, producing minor crops of medicinal or cultural significance. Examples of accessory plants include green manure crops grown to enhance soil organic matter and nutrient availability to subsequent cash crops. Many agroforestry species are accessory crops, and provide multipurpose functions such as soil improvement, fuel wood, fodder, or fruit production (Table 5.2).

FIGURE 5.8 Basil intercropped with eggplants on an organic farm in Michigan, USA.

TABLE 5.2 Polyculture Farming Systems From Around the Globe

System Name and Description	Species Components	Sites
Improved Fallow ● Perennials grown to improve soil, followed by a cash crop	*Gliricidia sepium* and *Erythrina peoppigiana* trees for stakes and soil improvement, followed by a climbing bean cash crop	Costa Rica, East Africa highlands, Malawi
	Sesbania sesban, *Sesbania rostrata* (stem-nodulating legume) or *Crotalaria ochroleuca* 1–2 years, followed by rice	East Africa, Tanzania
	Tephrosia vogelii bush 2 years (first year relay-intercropped with maize), followed by maize	Malawi
	Sesbania sesban trees 2–3 years (first year intercropped with maize), followed by 2 years maize	Zambia
Green Manure/Mulch ● Vegetative and indeterminant annual or biannual (often a legume), followed by a cash crop	*Mucuna pruriens* green manure system or slashed mulch, followed by maize or maize – bean intercrop	Central America, humid to subhumid tropics
	Tephrosia vogelii, *Canavalia ensiformis*, *Crotalaria ochroleuca*, and *Lablab purpureus* relay-intercropped with maize, followed by maize	Kenya, Malawi
Agroforestry intercrops ● Perennial intercrop with a cash crop	Coffee and Cacao	Central America
	Coffee and *Eucalyptus deglupta*	Costa Rica
	Coffee and *Erythrina poeppigiana*	Central America
	Maize intercropped with pigeon pea (*Cajanus cajan*)	Eastern and Southern Africa
	Maize intercropped with *Gliricidia sepium*	Malawi
	Leucaena leucocephala hedgerow intercrops in annual crop fields, terrace edges, rice paddy bunds	South east Asia (promoted elsewhere—rarely successful)

(*Continued*)

TABLE 5.2 (Continued)

System Name and Description	Species Components	Sites
	Low density mango tree intercrop with the maize – bean – squash complex	Subhumid to humid tropics
	Faidherbia albida tree (sheds leaves in growing season) intercropped with a cereal	Semiarid tropics
Silvopastoral ● Animal grazing or forage production under trees	*Pinus ponderosa* trees intercropped with *Stipa speciosa* native grass	Argentina
	Populus species, trees intercropped with *Bromus unioloides, Trifolium repens,* and other forage species	Central and South America
	Alnus acuminate trees intercropped with *Pennisetum clandestinum* grass	Central America
	Faidherbia albida tree grazed with native species	West Africa, semiarid to arid tropics

Over many generations, farmers have developed highly successful combinations of plants. These include the sorghum – pigeon pea intercrop in semiarid India and Eastern Africa, and the complex, multistory intercrop of maize – bean – cucurbit (pumpkin or squash) and low density of mango trees that is popular among smallholder farmers throughout the subhumid tropics, from Mexico to Malawi. Agroforestry systems are among the most complex, as they include plants with different life spans, from annuals to short-lived perennials (often a shrub), and longer-lived perennials, such as trees that may require decades to mature and produce fruit (Table 5.2). Indigenous forest dwellers in Amazonia and West Africa sustainably exploit the characteristics of a wide range of plants and sites in a sophisticated succession; this is very different to large-scale slash and burn than can convert forest into wasteland in one or two generations (Redondo-Brenes, 2005).

Polycultures provide multiple ecosystem services and efficient use of resources, but they are knowledge-intensive systems that require considerable experience to adjust timing and spacing, and manage the different growth habits. Often researchers have tested species for integration into a cropping system as single plant introductions, whereas smallholder agriculturists have developed dynamic and complex cropping systems that demand study in their own right. There is considerable value in experimenting with more than one new species at once, through the combination of likely candidates based on an ecological assessment. Review of indigenous systems is also an important place to begin. Research on improved fallows has begun to work with farmers to test mixtures of short and long-duration species that combine stress tolerance features (Arim et al., 2006). This is in contrast to conventional attempts to identify the single best species for a system.

Candidate species and mixtures for diversification purposes should be evaluated carefully based on the best information available, using different sources of information whenever possible. Some species are "championed" by organizations without sufficient attention to the ecological zone of adaptation, or potential problem traits. Awareness of invasive species is beginning to grow among development educators, and all new species should be carefully assessed for invasive potential before introduction. There are websites listed at the end of this chapter that provide a starting place for obtaining a balanced view of how species perform.

Promising legume species that have been characterized as "best bets" for diversifying East African farming systems are presented in Table 5.3. These are legumes that can be used as green manures, and grown in rotation with a staple crop, or as an intercrop. Some of the legumes are multipurpose, providing benefits beyond soil amelioration such as livestock fodder, or food products (in some cases after processing the seed). A general observation is that there is a trade-off between insect damage and edible product. Legumes that produce high quality grain and leaves that can be directly consumed

TABLE 5.3 Green Manure and Multipurpose Legumes That Are “Best Bet” Species From Testing Conducted On-farm Across Kenya and Malawi

Legume Species	Time to Maturity	Uses	Biomass Yield[a]	Comments
Large Seeded				
• *Mucuna pruriens*	4–12 months	• Weed suppression • Soil fertility enhancement • Food (after processing grain) and fodder	5–9 T/ha	Toxin = L-Dopa Highly effective weed suppressor Medicinal uses
• *Canavalia ensiformis*	6–12 months	• Moderate weed suppression • Soil fertility enhancement	4–6 T/ha	Toxin = Canavalian Not edible Fodder of dried plants
• *Lablab purpureus*	3–10 months	• Food (seeds, pods, leaves), and fodder • Weed suppression • Soil fertility	5–8 T/ha (fast growing)	Drought tolerance (varies) Edible Insect susceptible
• *Cajanus cajan*	4–24 months	• Food (seeds, pods and leaves), and fodder • Soil fertility (Higher in year 2) • Secondary uses: fuel wood, medicinal	2– 10 T/ha (ratooned/ cut year 1, for more biomass	Edible Phosphorus and N enhanced residues Insect susceptible

Medium seeded • *Vicia benghalensis*	4–5 months	• Soil fertility enhancement • Fodder	5–8 T/ha	High altitude crop >1800 m asl
				Not edible
				Mod. antinutritional
Small seeded • *Crotalaria ochroleuca*	3–4 months	Soil fertility enhancement, rapid Some food (vegetable), and fodder	6–8 T/ha (fast growing)	Edible vegetable, and fodder
				Insect susceptible
				Mod. antinutritional effects on animals
• *Desmodium uncinatum*	8–12 months	• Soil fertility enhancement • Fodder	3–9 T/ha	Insect susceptible
				Not edible
				Striga suppressor

asl, altitude above sea level; Mod., moderate.

[a] *Biomass yield presented as dry matter, T/ha where* T = *1000 kg.*

Source: Adapted from the Legume Research Network Project, http://www.ppath.cornell.edu/mba_project/CIEPCA/exmats/LRNPbroc.pdf; Soil Fertility Management for Smallholder Farmers, Malawi Ministry of Agriculture and Irrigation and the International Crops Research Institute for the Semi-Arid Tropics, 2000.

tend to be susceptible to insect herbivores, while legumes with tissues that contain toxic products are less desirable to insects.

Two particularly promising legume species for diversification of staple crops are pigeon pea and *Mucuna pruriens* L., also known by the common name of velvet bean. Research from Kenya and Malawi shows the high production potential (biomass and grain) and widespread adaptation of *M. pruriens* to smallholder farms in the humid tropics (Table 5.3). The weed smothering features and cereal-yield enhancement associated with a *Mucuna* rotation has led to greater than 70% adoption within hillside maize production in some regions of Central America (Fig. 5.9; Buckles et al., 1998), and the dense ground cover reduces erosion of hillside soils dramatically. Pigeon pea is favored by many farmers as it produces large amounts of food compared to other multipurpose legumes, as well as fuel wood, leafy vegetation, and a large root system for tremendous biological nitrogen fixation potential in marginal environments (Snapp et al., 2010). Pigeon pea has growth traits uniquely suited to intercropping with a cereal or with other grain legumes, this includes a slow early growth pattern that minimizes competition, and leaves that drop in the field mid-season, depositing N and P which enrich residues for soil improvement.

It is recommended that researchers and educators consider farmer indigenous knowledge, and local shrubs. Legume species from the genera *Acacia*, *Calliandra*, *Centrosema*, *Crotalaria*, *Desmodium*, *Gliricidia*, *Leucaena*, *Mimosa*, *Sesbania*, and others are widely found in the tropics and subtropics.

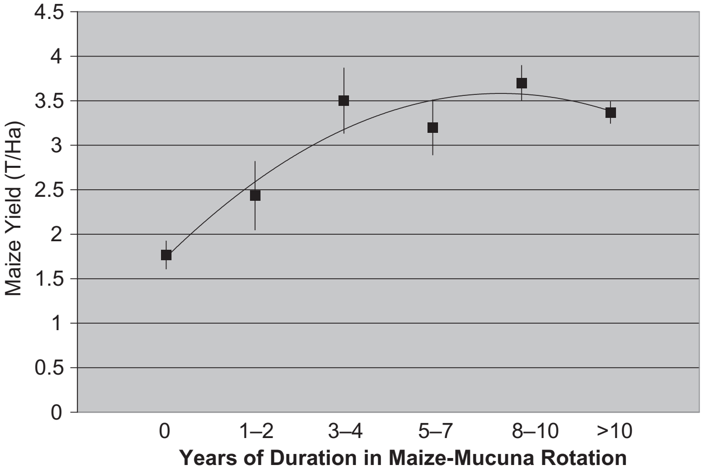

FIGURE 5.9 Transect of Central American farmer fields show the enhanced maize grain yield associated with increasing years of duration within a maize – Mucuna rotation system. *Adapted from Buckles, D., Triomphe, B., Sain, G., 1998. Cover Crops in Hillside Agriculture: Farmer Innovation with Mucuna International Development Research Centre, Ottawa, Canada. http://www.idrc.ca/en/ev-9307-201-1-DO_TOPIC.html.*

It is worthwhile investigating the wild species growing in an area to see which may be adapted for use as an accessory plant.

Community diversity Plant mixtures require management that minimizes competition with the main crops. Combinations of short and tall statured species or plant canopies that are complementary in the structuring of branches and leaves, and deep versus shallow root systems are all means to reduce competition. However, even with complementary architectural traits, plants will compete to some degree for limited resources. Separation of plants in time or space will reduce competition. Crop management practices to partition plants include placement, where one crop is located on the top of a ridge, e.g., and the other crop in the furrow between ridges in a ridge – furrow cropping system (see chapter: Agroecology: Principles and Practice). Another means relies on separation in time. An example is a relay intercrop, where plants are seeded into the understory of a main crop, often after a main crop is weeded (Table 5.2).

Hedgerow intercrop systems are a form of agroforestry designed to reduce competition through frequent pruning of the hedge, and placement of hedge species on ridges at some distance from crop rows. This system was promoted widely in the tropics, where legume trees such as *Leucaena leucocephala* were planted as hedgerow species intercropped with crops such as maize or cassava. When managed intensively, crop competition was shown to be limited to nil, and there were considerable soil-building benefits; yet large-scale extension efforts did not lead to farmer adoption of hedgerow intercrops. As illustrated in Box 5.3, some of the challenges were biological, others were socioeconomic in nature.

The hedgerow intercrop system illustrates well a central challenge of ecological management, how to promote diversity of species, soil building organic inputs, and weed suppression, without excess labor demands, or unacceptable competition with the main crop. Green manure crops that produced multiple benefits, including food for consumption or forage for animals, and that are relatively easy to manage through slashing, rolling, or chemical control, may have a unique role to play as living accessory plants that provide services such as pest suppression and soil building. An outstanding example is the push – pull system which has seen modest but steady and growing farmer adoption (Box 5.4). Another example is the doubled-up legume technology released in 2016 as a soil-improving technology, with decided benefits for resource-poor farmers in Malawi (Fig. 5.10). As shown by this radar chart, maize rotated with a doubled-up legume technology can produce as much maize grain in the 1 year of maize as 2 years of continuous sole maize, with the addition of extra-nutritious grain from the grain legumes, and high fertilizer efficiency in the maize phase of the rotation. The increased yield stability of maize grown after multipurpose legumes should also be noted (Snapp et al., 2010).

BOX 5.3 Challenges and Opportunities in Agroforestry: The Case of Hedgerow Intercrops

In a hedgerow intercrop system, trees are intensively pruned to develop hedges spaced 1–5 m apart, while crops are grown in the alley or space between the hedges. Nutrient recycling is accomplished through the deep rooting of the tree component, which ideally forms a "safety-net" below the crop root zone. The presence of hedges reduces light penetration, and combined with mulch (derived from hedge cuttings), this substantially suppresses weed growth between crop cycles, in addition to limiting wind damage. *Leucaena leucocephala* and *Cassia spectabilis* were identified as promising hedgerow species, being easy to establish, with high growth rates. Hedgerow intercropping was promoted widely as a sustainable alternative to bush fallows (Young, 1989). Frequent pruning was recommended to reduce tree transpiration demand, and to enhance root turnover. Over time it became clear that hedgerow species often competed with crops, particularly under on-farm conditions where pruning was more sporadic. The hedgerow species *C. spectabilis* was found to be a non-N-fixing legume, and highly competitive for water and nutrients.

Overall, agroforestry performance was variable, and appeared to be best adapted to sites with minimal moisture competition, such as high organic matter soils in humid environments, or sites overlaying shallow ground water. Farmers have on occasion incorporated novel hedgerow species into boundary plantings and gardens, but have not adopted hedgerow intercrops on a large-scale. Further research is needed to reduce labor requirements, minimize competition, and enhance the consistency of returns (Snapp et al., 2002).

BOX 5.4 Agroecology in Action: Illustrated by Push – Pull Technology

An agroecological system that has seen slow but sustained adoption by farmers in East Africa is the push – pull technology developed in Kenya. It involves establishment of two perennial forage species in a planned design within a maize field, to achieve integrated pest and crop management (Cook et al., 2007). It was originally designed to control harmful insect predation and a parasitic weed in maize; the global pests stemborer and *Striga hermonthica*. A perennial leguminous forage species *Desmodium* is planted in between maize rows, where it acts as a repellant or "push" species to stemborer (Khan et al., 2008). *Desmodium* is severely cut back at the beginning of each planting season to allow planting of maize and intercrop species such as bean. Around each field Napier grass hedges are established—this is the "pull" to attract and destroy stem borers. The desmodium has the additional benefit of building up soil fertility, resulting in striga control and superior crop growth. Images of this innovation are available, see: http://www.scienceinpublic.com.au/wp-content/uploads/magazineSP08Consolata-James-push-pull.jpg

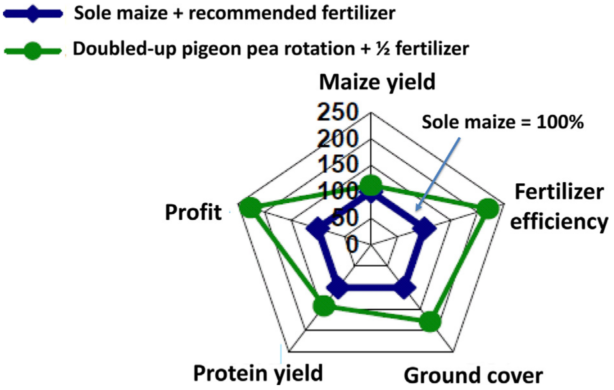

FIGURE 5.10 Radar chart showing multiple services associated with a maize rotation with a doubled-up legume system (pigeon pea intercropped with groundnut or soybean) at half fertilizer dose, relative to performance of continuous sole maize grown at a recommended fertilizer rate of 92 kg N/ha. Sole maize is taken as the 100% check system. Based on data from on-farm experimentation in Malawi. *Adapted from Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. PNAS 107, 20840–20845.*

There are unique benefits that accrue from diversification with longer-duration shrubs such as pigeon pea, but there are other plant growth types that have unique roles to play as well. Short-lived cover crops from genera with rapid growth cycles, such as *Brassica* or *Crotalaria*, are biological technologies that have a "built-in" off switch. They are programmed to produce biomass, then die quickly. Other ruderal (Ruderal plants are usually annuals, fast growing, and adapted to disturbed environments; see discussion of plant growth strategies in Chapter 2, Agroecology: Principles and Practice) type plants may be usefully developed by agricultural scientists, to provide farmers with means to produce layers of living and dead residues that provide complementary and continuous cover. This smothers weeds, as well as reducing water, nutrient, and soil losses from a system. Herbicide management or vigorous mowing can also be used to suppress growth at critical time points, leaving behind a mulch of residues which can be used for no-till planting of crops.

A diversity of plant species will generally support healthy crop plants and suppress pests. Rotational cropping systems are often associated with ~15% higher yields compared to monocultures; this has been termed the "rotation effect." Continuous wheat is one of the few exceptions, as it appears to be a long-term viable monocultural cropping system. The soil conservation properties of this long-duration crop, and its large, finely branched root system, may explain the apparent sustainability of long-term wheat production. The observation of rotational yield responses in most cropping systems could be due to many reasons. A few of the better documented processes are: suppression of soil diseases and organisms, improvements in nutrient synchrony from diverse residues, and crop-health promoting mycorrhizal interactions.

Diversifying at larger scales Across rural landscapes there are tremendous opportunities for diversification, at different scales (Table 5.4). The pattern of managed and wild components in a landscape is a determinant of air flow, nutrients, water, soil, and biological elements. Dispersed or aggregated combinations of domesticated and natural areas will determine the extent of interface area. Corridors can be developed to link wild areas, facilitate conservation of wildlife, and enhance the extent of interface areas, which are often highly productive and biodiverse. This illustrates that there are foci in the landscape where inserting species can have a regulator influence, such as planting perennial species strategically to maintain wildlife corridors. Perennial strips can act as buffers in a landscape, including plantings along riverine areas to protect water quality by acting as living filters to take up excess nutrients or silt. Landscape ecology provides important insights into the influence of landscape structure and land use patterns on resource flow, and insect dynamics (Landis et al., 2007).

In pastoral and transhumance areas, migration corridors are important to enable animals to move without unduly conflicting with settled cropland. There may be some interdependence as well as potential conflict: in Nepal, e.g., overnighting of migratory flocks of sheep and goats on their

TABLE 5.4 Illustration of the Influence of Biodiversity on Sustainability and Pest Management, at Different Scales

Scale of Diversity	Components of Sustainable Management of Pests
Plant	• Defense compounds that resist insect herbivores and aromatic biochemistry that drive away pests
Community	• "Bottom up" control from diversified resources and habitat that confuse pests • "Top down" control through fostering beneficial insects and dampening of predator and prey dynamics • Layers of dead and living plant tissues that suppress weed germination and foster soil health • Rotate crops with biofumigant plants to alter soil flora and fauna and control soil-borne pests
Landscape	• Insert species at critical foci in the landscape to regulate pest management, e.g., tall species to filter wind-blown pests • Structure diverse plantings of multiple age groups to reduce vulnerability to pest outbreaks

way to/from high pastures provides in situ manuring of fields. Recent research in Mali has shown the value of innovative approaches to supporting agropastoralist and farmer communities in designating agreed upon livestock corridors, and norms for migratory use of fields and water sources. See http://Africa-rising.net

Resource Efficiency

Resource concentration and utilization are central to agricultural management practices. Many farmers use mined fertilizers to augment nutrients in cropping systems. Many also rely on practices that concentrate organic sources of nutrients, then grow successively less nutrient-demanding crops until the nutrient supply is spent. Traditional slash-and-burn techniques such as bush fallow utilize this approach, and are sustainable if farmers have a sufficient land-base to support very long (decade or more) rotations. In a bush or natural fallow system, a regenerated area is cleared after 10 or more years of growth, plant materials are piled and burned, then nutrient demanding cereal crops such as millet or maize are planted, followed in a rotational sequence by a crop with tolerance to low fertility such as cassava.

This system is called *chitemene* in Zambia, and is highly suited to acid, infertile, and leached soils. Nutrients are less susceptible to leaching losses when applied in an organic residue form compared to a fertilizer source. A widely used variation throughout southern Africa involves grass residues that are not burned, but instead are piled in the center of a mound of soil which is then planted to crops with low nitrogen requirements such as beans, sweet potato, or cassava (Fig. 5.11).

FIGURE 5.11 Grass mounds from Northern Malawi planted with cassava.

Recycling of nutrient resources and efficient use of energy are widely recognized hallmarks of sustainability. Besides reducing dependence on nonrenewable resources, minimizing use of expensive inputs can reduce farming costs, which is vitally important to limited resource farmers. The bush – fallow cropping system described above requires a long time horizon and sufficient land, but is an effective means to recycle nutrients. Soil type will often determine which management strategies are sustainable. The maintenance of soil organic matter, nutrient pools, and yield potential is challenging in arable sandy soils, unless large doses of organic inputs are applied in the form of manure or rotational soil-improving crops. Heavier soils have sufficient buffering capacity to be able to maintain productivity with inputs of mineral fertilizers alone, or with moderate doses of manure combined with fertilizer.

The stable production of moderate yields at levels that provide acceptable rates of return, rather than attempting to optimize the production of high yields, is an overlooked goal of many smallholders. Efficiency of returns from small doses of fertilizer or pest control measures can be quite high, compared to the incrementally smaller returns from inputs at the high end of the yield response curve.

Long-term experimental trials carried out in SSA have provided some of the best evidence that integrated nutrient management (INM) strategies—e.g., modest doses of fertilizer, less than 50 kg nutrients per hectare, combined with a modest rate of manure of 2–4 T/Ha—can support stable production in a legume – cereal rotation. This is illustrated by the maintenance of crop yields in a peanut – cereal rotation over several decades on a sandy Alfisol (Pieri, 1992). Yet it is notable that INM has only been adopted sporadically in SSA, in specific localities. Small-scale farmers instead tend to rely on the relatively low labor-input, fertility enhancing systems of bush fallow, or in some cases, fertilizer. In other regions of the world integrated use of organic and inorganic fertility sources are common, and there is evidence that experimentation with INM is increasing in SSA, along with increased market access and education opportunities.

Examples of intensified soil management and organic amendment use by smallholders tend to be associated with land being in short supply. Consider, e.g., the tremendous diversity of intercrops, compost systems, and complex land and water management technologies historically documented among Chinese peasant farmers, and among Central American farmers (Netting, 1993). An African example is from the island of Ukara, in Tanzania, where indigenous farming systems capitalized on the soil-replenishing nature of the leguminous green manure *Crotalaria striata*, grown as a relay intercrop in bulrush millet (*Pennisetum typhoides*) (Ludwig, 1968). More recently, in Zambia, the use of organic inputs from improved fallows and animal manure are being successfully combined with small doses of fertilizer in maize-based cropping. Suppression of the parasitic weed “striga” has driven much of the interest in INM in Zambia. Pest management issues are interrelated with soil fertility as land use intensity increases, as serious infestations of parasitic weeds are often associated with continuous cropping of staple cereals.

The nutrient balance required for a sustainable cropping system can be approximated by estimating nutrient inputs added to and removed from the farm system, and adjusting the addition of nutrients accordingly. Chapter 7, Ecologically-Based Nutrient Management, provides detailed descriptions of how a mass balance approach can enhance understanding and the practice of INM. This has been advocated as a means to assess long-term sustainability of a farming system. It does provide an indication of the trajectory for nutrient sustainability. However, it is important to remember that available nutrient pools are different than total nutrient stocks, especially in the case of phosphorus, where availability to crops of P often depends on the crop species present and long-term management practices, rather than on recent inputs. Thus, budget approaches often overestimate nutrient loss pathways, and do not take into full account the effect of enhanced efficiency or small changes in nutrient availability—e.g., shifts of P from inaccessible to accessible pools can alter P availability to plants more than P input rate. The scale of analysis is also essential to consider, as erosion losses from one part of the watershed may lead to deposition in other areas of the watershed. Further discussion of the complexity of INM can be found in Chapter 7, Ecologically-Based Nutrient Management.

Farmers often focus resources on landscape positions that provide the highest rates of return, e.g., low lying areas. The ingredients for high returns to investment are in place, as water is available, soil fertility is potentially high, and market demand is high for out-of-season produce. Intensification is occurring throughout southern Africa, and other regions undergoing rapid rural development, particularly at wetland and riverine sites where high efficiency and productivity can be achieved. The AIDS epidemic is another driver of changing land use, as high returns to labor are critical to household survival in southern Africa.

Conservation, productivity, and equity issues are all raised at this crucial interface where land meets water. The ecosystem function of wetlands and riverine areas are profound, protecting fresh water quality and quantity for communities all along the watershed. Riverbank cultivation is prohibited in many countries, precisely to protect this vulnerable ecosystem. Yet complete prohibition of use is rarely enforceable. It is not usually compatible with local demands and priorities, nor does it engage local communities in developing sustainable land use practices of these “at risk” sites. Group conservation activities, in particular, require engagement rather than proscription.

Wetlands are important sites of intensification across Asia, and are rapidly growing as a nexus of contestation in Africa. There are examples of environmentally sound approaches to intensification of agriculture at this productive interface of soil and water. This is illustrated by a case study of bean production in Chingale, a watershed in Southern Malawi (Kadyampakeni et al., 2013). Agricultural development near the water's edge occurred through the actions of individuals supported by nongovernmental organizations, and technical advisors (extension and researchers); however, this development was fully integrated with local communities, and soil conservation practices were followed to protect wetlands. Soil organic matter and nutrient status were stable across land forms near wetlands, for both male and female farmers (Snapp et al., 2005). Surveys indicated that hillsides, in contrast to wetlands, were not under the control of traditional authorities, and community norms to preserve steep slopes had broken down. This led to soil degradation, related to activities associated with illegal charcoal production and cultivation along steep slopes (often carried out by youth and migrants with few viable options). Officially, these areas were under government management, yet control mechanisms had broken down. Participatory action research documented that community leaders in the watershed were aware of the destruction, and required support to engage policy makers, rather than technical education on conservation. This is an example of resource conservation at the water – land interface being maintained and even regenerated through agriculture, and of the complexity of efforts to conserve resources, given that practices are continually evolving. It demonstrates that who is involved may vary markedly over time and space. It is apparent that effective support for sustainable development includes continuous educational efforts, and attention to sustaining institutions and mechanisms involved in local control of resources. Further, a comprehensive, watershed level approach is needed to address the full range of environmental pressures.

Productivity, Economics, and More

Productivity within a sustainable farming context should not be defined simply through measurement of yield. Economic return is one important means of assessing performance within or across farming systems. Economic assessment through net benefit or gross margin analyses are one of the only means to compare technologies that are very different in nature. Organic and inorganic sources of nutrients, e.g., have quite different costs, rates of return, and opportunity costs. Economic tools provide insights into comparing such contrasting technologies. Fig. 5.12 provides an example of net benefit returns from soil fertility enhancing technologies, as a means to evaluate performance within maize-based cropping systems in Malawi. There are inherent challenges in economic evaluations, since product and input prices vary markedly over time and location, particularly where storage facilities are not well developed, and for minor crops such as legumes. Labor is also difficult to value appropriately within the context of a smallholder farm family. Given all these challenges, it is still markedly insightful to evaluate

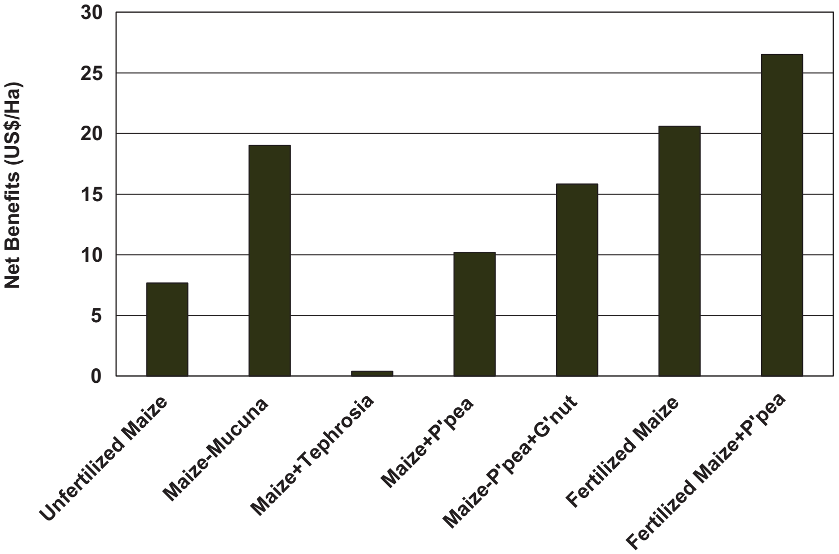

FIGURE 5.12 Net benefit economic analysis of soil fertility-enhancing technology performance, based on maize yield value and input costs associated with seeds and fertilizer, from on-farm trials conducted in Central Malawi from 1997 to 99 (Snapp, unpublished data).

technologies on the basis of net returns, and often insights emerge regarding adoption potential and the relevance of technical recommendations.

Development of systems that prioritize the stability of production over high yields is particularly important to risk averse farmers, many of whom live in highly variable environments. The timing of production, when harvestable products are ready over the year, is critically important to farmers who face food insecurity on a recurring basis. Developing varieties and planting arrangements that provide harvestable yield early, as well as late, in the season has particular significance to farmers who suffer through a hungry season before crops mature. Postharvest storage is an ongoing challenge, and a source of tremendous losses among poor farmers. Production goals must include diversification of harvest times, to the extent feasible, given environmental constraints of rainfall and temperature. Integration of livestock into farming systems can further diversity and buffer against shocks through sales in times of need, as explored in Chapter 9, Research on Livestock, Livelihoods, and Innovation.

Direct comparison of products from different species or plant parts, such as evaluating cereal yield in relationship to tuber yield or animal products, is not meaningful, since fresh weight and biochemical constituents vary tremendously. An ecological concept that can be used here is "net primary productivity," a term commonly used to assess species performance within ecosystems. Measurements of biomass, calories, lipids, or proteins provide diverse means to assess farming system productivity. The production of high levels of calories in cereal grains may be somewhat offset by the production of nutrient-enriched, more valuable, legume grains. Nutrient-enriched foods should be rewarded on the marketplace with high prices. However, markets are not always responsive to nutrition, and calories remain an essential "coinage" for comparing productivity of systems, as they are closely related to fulfilling family food requirements (Fig. 5.10 provides an example, where protein produced is used as one indicator of system performance in a radar chart comparison). There is growing interest is how to compare the performance of agricultural systems in ways that take into account nutrition and other products important to human welfare. See Chapter 4, Farming Systems for Sustainable Intensification, for a discussion of indicators of sustainable intensification, which can include nutrition as well as production, economics, and environmental criteria.

An on-farm study in Malawi compared calories produced by unfertilized maize to calories produced by legume − maize rotation systems (Fig. 5.13). The legume products have nutritional benefits that complement cereals and support children's health and growth, and educational efforts on human nutrition have been shown to encourage farmer adoption of legume crops (see chapter: Gender and Agrarian Inequities). Protein is important, but there is also an urgent need to diversity production and diets to enhance the availability of vitamins and micronutrients. It has been estimated that some 40% of Africa's children are at risk of vitamin A deficiency. This is the premise

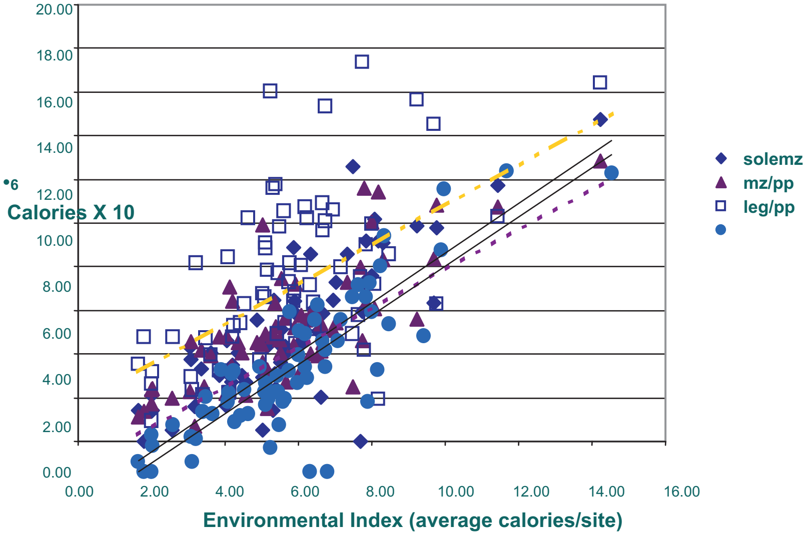

FIGURE 5.13 Calories produced in on-farm trials by maize-based cropping systems, with and without legume diversification (Snapp unpublished data, 2000).

for widespread promotion of orange-fleshed sweet potatoes, that are high in vitamin A. Many varieties provide nutritious leafy greens as well (www.harvestplus.org/content/vitamin-sweet-potato).

Attention is starting to be paid to the potential trade-offs between nutritionally enriched foods and those that are high in calories; few cropping systems are able to produce high yields of foods that are packed full of protein. Attention to the right type of diversification can help support nutrient-complementary approaches that do not jeopardize calorie returns, and perform as well or better than current systems (see Snapp et al., 2010 for one such example of performance associated with multipurpose legumes in maize-based farming systems of Malawi). It is vitally important that new crops or farm innovations meet farmer goals and taste preferences, as well as not requiring excessive amounts of labor; it is essential that they provide sufficient and timely returns to labor, and to land.

Sustainability requires attention to the entire process of developing, testing, and supporting the adoption of a new practice. It must not only perform well over time, it must meet local criteria for performance, and be supported by innovations in local regeneration of the technology. How the technology will be maintained is a key sustainability question. Can farmers obtain access to a new variety or technology over the long-term; is there an effective seed system and local technical expertise? What are the economics of reproduction of plants and animals, and manufacture and repair of equipment? These issues are an integral part of the regeneration of a technology, and its long-term prospects for adoption and performance.

Resilience

Sustainable resource management is essential to the resilience of rural livelihoods. Building soil quality is at the foundation of a farming system that can respond to disturbance or disaster. Long-term experiments have been carried out around the globe to test the sustainability of farming practices, by examining changes in soil organic matter and yield potential over time. These trials consistently show an initial, rapid decline in topsoil organic matter as tillage and grain removal enhance C loss. Over time, soil C loss is slowed or reversed in cases where tillage is reduced, if at the same time organic inputs are enhanced through applying manure, growing perennials, or cover crops (Robertson et al., 2014). Recent evidence from several long-term trials document that organic systems that rely on high disturbance (e.g., tillage for weed control) are associated with stable soil aggregates, and such systems can build soil organic matter, if a leguminous cover crop, pasture rotation, or manure inputs are present. There is growing consensus among scientists that reduced tillage alone is not enough to improve soil organic matter, it is roots and compost additions that build soil organic matter (Powlson et al., 2014). Thus, diversification is the first principle of soil C sequestration.

The key to sustainable use of fertilizers is to ensure that residues accompany soluble fertilizer use. There are many sources of residues, including recycling residues by livestock-feeding and amending the soil with manure, or directly through incorporating residues from crops, green manures, or even weeds. The challenge in a developing country context is that there are multiple, competing demands for residues, including burning, removing for sale, and feeding to livestock. This reduces the residues available to replenish soil organic matter.

Protecting soil from erosive factors, and replenishing organic matter, are critical to building system resilience; thus, it is crucial to promote long-duration soil cover through vegetative growth, wherever feasible, in a given farming system. However, it must be acknowledged that it is challenging to find plant species that are high performers in environments that are marginal and climatically unreliable. In the experience of this author, plants and animals that have high tolerance to stress are some of the only technologies within the reach of the majority of smallholders, including many who cannot afford fertilizer or labor-intensive technologies. However, improving organism tolerance to climatic stress and poor soils is not an easy target, and gains may be incremental compared to readily observable increases in yield from high yield potential varieties grown under optimum conditions.

Understanding and enhancing tolerance traits deserves a higher profile in agricultural science; farmers urgently need access to species that perform well in marginal environments. Scientists in Australia and Kenya are assessing drought tolerance in legumes such as lablab (*Lablab purpureus*), a promising food, forage, and green manure species (Table 5.3; Pengelly and Maass, 2001). Availability of novel species types with functions approved by farmers is a key ingredient to supporting innovation, and sustainable farming. To this end, we discuss in Chapter 8, Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers, and Chapter 9, Research on Livestock, Livelihoods, and Innovation, a range of participatory and multidisciplinary approaches to support farmers in developing systems to systematically evaluate plants and animals, and how to support integration drawing upon indigenous and exotic species.

Resilient plant communities Sustainable management relies on knowledge-intensive practices and ecological manipulation, replacing the use of purchased inputs wherever possible. Biology is manipulated to improve plant access to nutrients, to build soil capacity and to reduce the susceptibility of crops to pests. Assembling plant communities based on ecological understanding of functional traits is described in some detail in Chapter 3, Farming-Related Livelihoods, which presents information on complementary and redundant combinations of species. The three plant group types discussed here are presented in Fig. 5.14 and represent a continuum from brassicas with no symbiosis, to cereals with one symbiotic fungal partner,

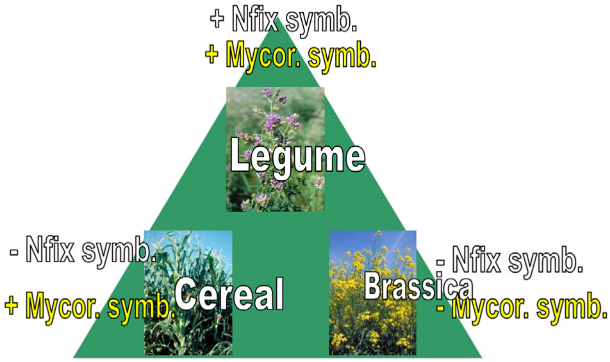

FIGURE 5.14 Functional traits that vary in plant groups, here are shown three types of symbiotic groups, from zero symbioses (brassica) to two symbioses (legumes).

BOX 5.5 Multidisciplinary Research and Soybean Improvement in Brazil

There are examples of cropping systems that combine high productive capacity and reliance on BNF. This is illustrated by an example from Brazil. Multidisciplinary, concerted effort has markedly improved soybean BNF rates in commercial cultivars, while at the same time enhancing yield potential by 40% (Alves et al., 2003). The team combined expertise in soil microbiology, agronomy, and plant breeding, and worked together over two decades to achieve this remarkable improvement in plant – symbiont performance. A negative example is the inadvertent selection against BNF activity within Asian rice cropping systems, linked to increasing reliance on N fertilizer.

vesicular – arbuscular mycorrhizal fungus (VAM), and legumes with two symbiotic partners, VAM and rhizobia.

Enhancing farming system reliance on biologically fixed nitrogen (BNF), substituting for purchased nitrogen in the form of fertilizer, is an instructive example of the ecological role that N-fixing symbiotic associations play. Legumes, the N-fixing bacteria *Rhizobium* spp., and the alga species associated with *Azolla* in rice systems, are primary examples of BNF-reliant farming systems. Nitrogen fixation capacity has been improved in Brazilian cropping systems, as explored in Box 5.5.

A sustainable property of systems that rely on biological N fixation is the feedback mechanism within the BNF process: this feedback reduces the rate of N fixation in the presence of soluble N. This reduces the potential for N losses within farming systems that rely on BNF, and enhances N cycling efficiency. However, these same feedback mechanisms and the high energy demanding requirements of the BNF symbioses tend to limit the yield potential of BNF crops. Further, cropping systems that rely on BNF require investment of labor, and often land and relatively expensive seed as well.

Break crops for healthy, resilient crops A radical diversification strategy could have mixed consequences, as illustrated by considering the inclusion of a "no symbiosis" plant type, the brassicas shown in Fig. 5.14. There are conflicting research findings on the consequences of rotating with brassica species, but under specific circumstances, substantial soil and root health benefits have been seen. It may be that brassica species enhance the impact of a crop rotational strategy through altering soil flora and fauna communities. Brassica species, and some other crops such as sorghum – sudangrass, have been shown to be effective biofumigation agents. In the soil, plant tissue biochemical compounds break down and produce isothiocynates (ITC), which kill or suppress the growth of many soil-borne diseases (e.g., *Rhizoctonia*, *Pythium*), plant parasitic nematodes, and even weed seeds. It is important to consider the potential negative impacts as well. For example, some crops, such as onions and cassava, are highly dependent on mycorrhizal infection for normal growth, and a brassica crop might have an inhibitory effect. In contrast, crops such as potatoes are highly susceptible to soil-borne diseases, and rotation with a brassica "biofumigant" crop may significantly enhance tuber and root health (Snapp et al., 2007).

Results are not always dramatic, biofumigation is a complex and biologically mediated process. The release of active chemical compounds depends on many factors, from the plant genetics and tissue biochemistry, to soil environmental conditions and farm practices used to mow and incorporate residues. In some regions and soil types, notably coarse soils where few brassica crops are currently being grown, substantial benefits have been observed. Farmers have adopted the use of biosuppressive cover crops in southern Italy and the USA Pacific Northwest over large acreages of high value crops such as potatoes and vegetables (Box 5.6). More research is needed to define where brassicas are beneficial. Preliminary evidence points to benefits being highest in systems that are dominated by few crop species, that lack diversity, and that have limited residue inputs.

Brassicas are adapted to a cool environment. There is need to identify biofumigant or similar "break crops" for tropical environments. One species that has shown potential in Kenya is the green manure crop *Canavalia ensiformis* (Jack bean). Plant parasitic nematodes such as *Pratylenchus* species cause widespread and often under-appreciated damage to root health and crop yields for staple crops such as maize and potatoes. An increased maize yield of 20–35%, and concurrent suppression of *Pratylenchus zeae* infection, was shown in maize grown after a green manure of *C. ensiformis* (Arim et al., 2006). *Mucuna pruriens* was found to be less effective at nematode suppression in this study, but other research has documented its potential as a break crop that can alter soil-borne pest populations. *Mucuna pruriens* is a

BOX 5.6 Biofumigant Cover Crop Adaptation for Potato System Health

Potato production in the Pacific Northwest and the Upper Midwest regions of the United States is a case study of where brassica cover crops are being rapidly adopted. Research had shown the potential impact of an oriental mustard cover crop on crop health, where plant tissues were as effective as chemical fumigants in producing healthy potato tubers (Snapp et al., 2007; Fig. 5.15A–C). Farmer experimentation was critical to developing practical, and effective, means to manage cover crops for biofumigant activity. This included choosing the correct genetics, varieties that had biofumigant compounds at high levels (which turned out to be the ones with leaves "hot" to the taste), and determining the window within crop rotation sequences where mustards could be grown without interfering with cash crops. Planting in late summer for fall growth, with supplemental irrigation in dry weather, was found to support high biomass production, and a flail-mowing operation was adapted to incorporate macerated, green tissues in the soil for maximum biofumigation. This intensively managed cover crop has been shown to enhance the health and yield of subsequent crops, particularly disease-susceptible crops such as potatoes.

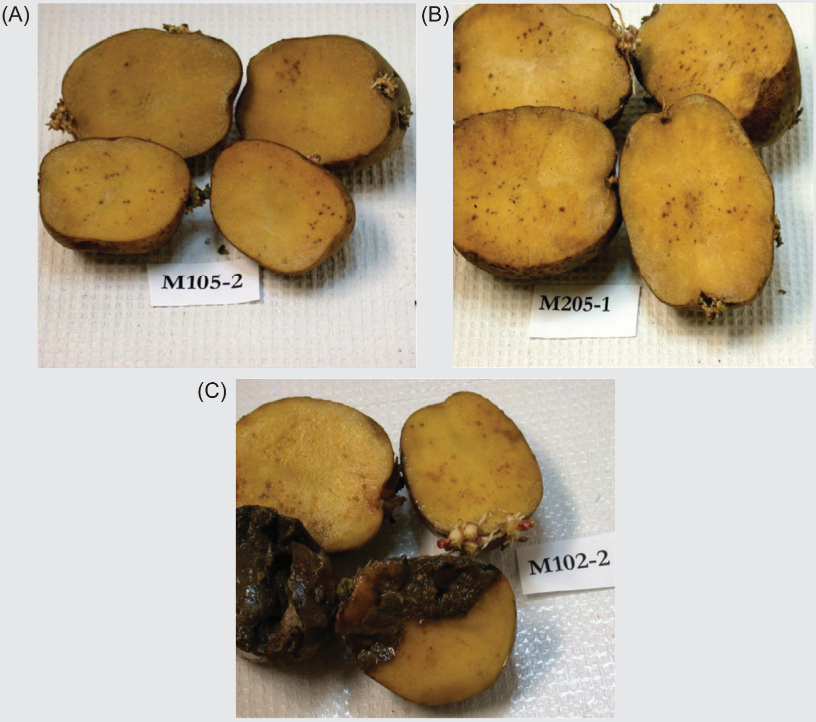

FIGURE 5.15 (A) Potatoes from chemically fumigated soil. (B) Potatoes from "biofumigated" soil where previously an oriental mustard cover crop was grown. (C) Potatoes from a fallow control soil.

widely adapted green manure crop, as shown by farmer uptake in the subhumid and humid tropics, from Honduras to Benin.

It is important to consider the overall impact of a green manure crop, does it enhance health of the main crops in the farming system? Some green manure species can have negative effects through enhancing plant parasitic nematodes or soil-borne pathogens. Although nematicidal and other biocides are produced by many legume species, particularly *Crotalaria* species, *M. pruriens*, and *C. ensiformis*, other legumes such as *Tephrosia* species and pigeon pea (*Cajanus cajan*) have been shown to enhance pathogenic species of nematodes. All experimentation with new species should be carried out carefully, to test for potentially negative impacts as well as positive.

A central feature of resilient systems is diversity. Providing diverse habitat and food sources supports biota above and below ground, which will tend to damp the cycle of pest and prey to more steady cycles (Table 5.4). A habitat for beneficial insects is one basis for reduced occurrence of pest outbreaks in diversified farming systems. Seed predators such as beetles can help reduce weed pressure, and are favored by growing borders or including some long-duration growth habit plants with annual crops. Pests are not, however, always suppressed in polyculture systems, and the complexity of managing multiple crops should not be underestimated. Growth stage, as well as species, influence pest population dynamics, and a diversity of age groups is often present in a polyculture. The presence of multiple crops can have a negative impact through the provision of secondary hosts for pests.

As described in Box 5.3, the "push – pull" system of diversification has been devised to suppress parasitic weeds such as striga (*S. hermonthica* and *Striga asiatica*), a devastating pest on cereals in SSA (AATF, 2006). An intercrop of *Desmodium uncinatum* is planted between maize plants, to exude root chemicals that induce dormant striga seeds to germinate, and then die for the lack of an appropriate host root (Khan et al., 2008). At the same time, *Desmodium* produces allelopathic compounds that are toxic to striga seedlings, and as a perennial leguminous cover crop enhances soil fertility through biological nitrogen fixation and soil organic matter inputs. The potential for high quality forage cuttings from this system enhance its profitability, and have supported slow but steady adoption by hundreds of farmers. Over time, the impact of agroecology-based interventions can have a cumulative effect that moves a system into a more resilient mode of operation.

There are many reports of low levels of pests in indigenous cropping systems, as reviewed by Morales (2002). This may be related to the preventative aspects of polycultures, where natural regulation of potential pests tends to prevent outbreaks. It is also possible that smallholder farmers in some cases report low pest incidence due to high tolerance for pest damage, as partially damaged grain can be used for local consumption.

Farmers also remove infected plants (e.g., farmers in Yemen selectively use sorghum plants affected by stem borer) to feed to livestock. They may anticipate a percentage “offtake” when they plant, and use greater seed rates.

The main staple crops grown in many places are also relatively pest tolerant, which is a notable achievement of selection by plant breeders and generations of farmers. Marketed horticultural crops, by contrast, often require production to a high quality standard. There are many examples of farmers having to overcome severe pest problems when first growing a new crop. Considerable patience is required to address pest dynamics and interaction with an introduced species, as diversification and pest management strategies may take years, or indeed decades, to develop. Research over long time scales may be necessary to understand the processes involved in biological management of pests.

PUTTING SUSTAINABLE AGRICULTURE INTO PRACTICE

Soil protection and natural resource regeneration are at the foundation of a biologically smart, efficient, and resilient farming system, but this requires tremendous investment by individuals and by communities. Often, soil and water management involve large gaps between perceived personal returns, and societal-wide costs and benefits. Environmental problems suffer from this challenge overall, as change is often slow and difficult to understand. Cause and effect may not be easy to ascertain, as in global climate change. Soil conservation projects, in particular, often experience mixed results, as incentives do not always match the short-term realities of food insecure farmers. Subsidizes may be required if they are to address long-term goals of protecting resources for future generations, and protecting public goods today.

Lessons can be drawn from recent changes in farming practice; in some areas reduced tillage systems have been adopted through a combination of lower farming costs (fewer equipment passes), and perceived soil building benefits. Farmers had to overcome social norms that equated good farming practice with clean (e.g., no residue) fields, and often spent years adapting their equipment and practices before adopting no-till. In many areas, reduced tillage has not been adopted, or is only used for specific crops. There are few examples of resource-poor farmers adopting reduced tillage, which is not surprising given a lack of economic incentive or access to herbicides. Recent interest has emerged in southwest Mali in using a preemergence herbicide to facilitate direct planting of peanuts into weed residues, without tillage. This system may be driven by labor constraints and interest in a reduced requirement for weeding, rather than perceived environmental benefits. Peanut production has expanded in areas where this technology is being experimented with, at the initiative mostly of women farmers. The innovation is driven in part by interest in new market opportunities, along with family nutrition (Snapp and Weltzien, unpublished data, 2007).

Rural livelihoods and sustainable practice in a globalized economy involve increasing dynamic linkages among farming enterprises, and evolving markets. This is illustrated by the above experience in southwest Mali. Rural family members move in and out of diverse livelihood strategies, and market opportunities change rapidly—globalization forces are changing market demand at regional and international levels, and altering urban food preferences. Responding to this rapidly changing environment, and developing sustainable responses, requires labor, and often complex negotiations. There are conflicting time pressures on smallholders, to conduct on-farm work, and to pursue waged labor and other off-farm activities. Further, at the center of family and labor decisions is the issue of who benefits. Sustainable development requires attention to equity: new technologies should complement current efforts, and not shift burdens unduly.

A case study of farmer adoption of grain legumes in Northern Malawi is discussed in Chapter 10, Gender and Agrarian Inequities. Here the gendered aspects of intrahousehold discussions are highlighted to illustrate the shifts in labor requirements that often accompany biologically based technologies (Box 5.7).

The case study illustrates the close linkages between resource conservation and farmer decisions regarding when and where to invest energy.

BOX 5.7 Improved Management Through Crop Diversification and Household Task Sharing

Legume residues are more effective at enhancing soil fertility if they are incorporated into soil. However, residue incorporation is a laborious task, particularly if it is carried out at the agronomically optimum time when the soil is dry and very hard. Residue incorporation quickly became a contentious issue within households who adopted new legumes for soil improvement in a Northern Malawi watershed (Bezner-Kerr et al., 2007).

Traditionally, in this region, crop residues were incorporated as part of weeding operations during the growing season, or as part of land preparation at the start of planting, which commenced with the rainy season. Burning of residues after harvest was also quite common as a means to reduce labor, and suppress weeds, in the arduous process of hand-hoe agriculture. The new recommended management—to obtain maximum soil fertility benefit from residues—was post-harvest incorporation of legume residues. This could be construed as a late weeding operation (the implication being that women should be responsible, as traditionally women lead on weed management), or as an early land-preparation operation (the implication being that men should be responsible, as traditionally men lead on planting preparation). In order for a more sustainable cropping system to function in this Northern Malawi watershed, complex negotiations were required on household task-sharing of new duties in residue incorporation (Fig. 5.17).

Intensification or extensification strategies may be appropriate, depending on the environmental and social context. Participatory action research acknowledges that farmers are at the center of this complex decision-making, and require support to enhance local adaptation, innovation, and knowledge. In participatory approaches to NRM, resource and energy flows are documented through farmers and researchers working together. Information generated is used to derive policy and management recommendations for sustainable production. Participatory NRM has been used in diverse contexts, from Bolivia to Kenya (De Jager et al., 2004). Interventions such as compost production and crop diversification have been shown to enhance the portfolio of sustainable options for management of energy and nutrients (Sayer and Campbell, 2004).

Centuries of farming have been maintained in China, and other regions of the world, showing the potential for long-term sustainability. At the same time, rising populations, poverty, and shifting land use are drivers of rapid change in NRM.

The World Bank Agricultural Development Report (2008)

http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTWDRS/EXTWDR2008/0,,contentMDK:21410054~menuPK:2795178~pagePK:64167689~piPK:64167673~theSitePK:2795143,00.html

Documents the complexity of resource management, as farmers often ameliorate some areas within a farmscape while depleting other areas.

The Biocomplexity of Sustainable Development

Agricultural development requires close attention to understanding processes involved in complex systems, as introducing new practices or technologies can have unpredictable consequences. To promote sustainable development, it is important to build on current practices and indigenous knowledge. Chapter 11, The Innovation Systems Approach to Agricultural Research and Development, explores development approaches that catalyze innovation, enhancing local capacity to adapt to the changing world.

Overall principles include collaboration with farmers and a wide range of stakeholders, paying attention to indigenous knowledge and local practice, and developing scenarios with community members to envision futures. Iterative learning and consideration of future scenarios can help evaluate the potential for negative, unintended consequences, as well as unexpected positive outcomes (Fig. 5.16).

It is not just ecological consequences that researchers need to be aware of; it is important to consider power dynamics within communities as well. Complexities of social change, equity, and livelihoods will be discussed in more depth in Chapter 10, Gender and Agrarian Inequities, but a cautionary example is provided here. Irrigation can greatly enhance production potential, but it is a particularly problematic development intervention. Research

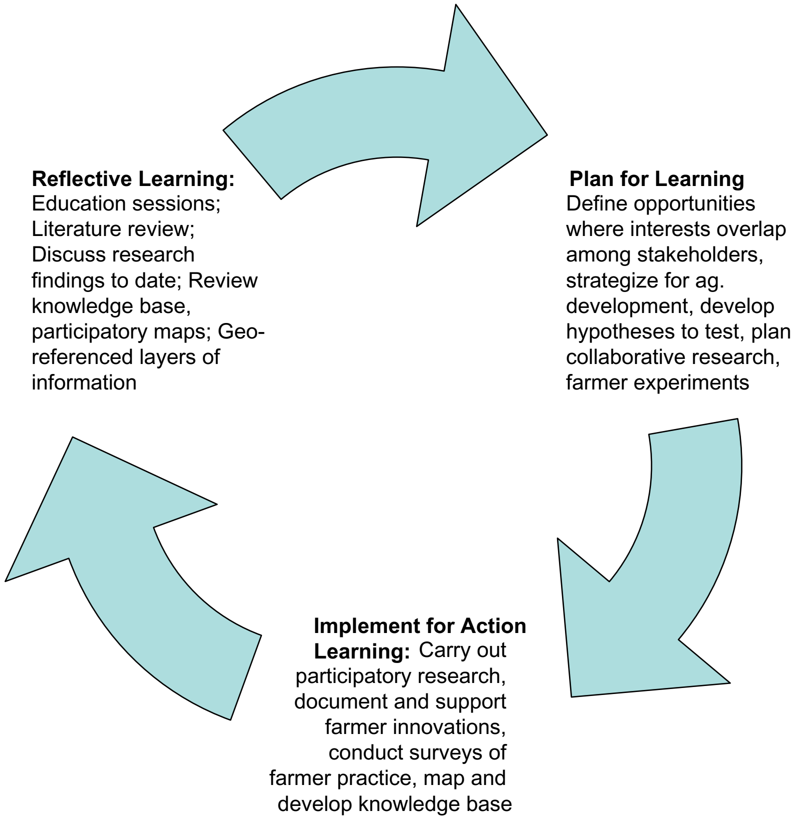

FIGURE 5.16 Iterative learning cycles to support development of sustainable agriculture.

has shown that large-scale and mechanized irrigation schemes have the potential to degrade soil if not implemented properly, through local salt build-ups, and soil quality decline. In addition, irrigation projects often alter community power relations. Enhanced income and water access is primarily captured by male-headed and well-off families. This is most notable if customary land access pathways are disrupted through implementation of formalized land titles and irrigation committee membership, which are often conferred on only one household member (e.g., the male head of household). Households using less formal irrigation methods, such as recessional flood agriculture, shallow well, or treadle pump irrigation, may lose out in the development process as the implementation of new irrigation schemes divert water and alter land access. Irrigation projects are not implemented in a vacuum. This is illustrated by photos from Malawi showing the intensity of informal irrigation and high value gardens displaced by a formal irrigation scheme (Fig. 5.17A–C).

FIGURE 5.17 (A) and (B) Malawi cultivation of riverine habitat through informal irrigation. (C) Formal irrigation scheme replacing informal irrigation systems in Malawi.

A partnership approach is suggested here as the foundation of sustainability. It values local, indigenous, and science-based knowledge. Enhancing the local knowledge-base and innovation capacity requires a base of trust and quality relationships. This requires attention to bridging world-views, and working across different vocabularies. Thus, it is important not only to document indigenous knowledge, but also to spend time on translating, both across languages and across terms used. The theory and practice of a participatory action approach to agricultural research is presented in Pound et al. (2003). Case studies are developed that provide guidance on "good practice," and techniques that promote co-learning, relevance, and scaling-up in participatory NRM.

The bottom line is that iterative cycles of learning are at the core of sustainable agriculture. Some components of a learning cycle are outlined in Fig. 5.16, to illustrate how researchers and farmers can systematize attention to reflection and reviewing priorities over time, to continually learn together and correct the course of development as it unfolds.

Gauging the effectiveness of sustainable development requires benchmarks or success criteria. Conventionally, the value of a sustainable practice, such as compost making, has often been determined by measurements of crop yield or biomass productivity over time. Here we suggest that assessment of sustainable systems should consider a range of indices, such as

FIGURE 5.18 There are many farming tasks, and careful consideration is required of new labor demands.

impact on ecosystem services, environmental goods, economic returns, and variability of returns. Farmers and rural stakeholders have their own criteria, which can be documented (Vernooy and McDougall, 2003). Multidisciplinary teams of economists, social scientists, ecologists, agronomists, farmers, and community members can work together to develop criteria. This requires commitment to a co-learning process, and communication to bridge different conceptions of sustainability (Fig. 5.18).

Future Directions in Sustainable Agriculture

A rapidly changing world requires that sustainable agriculture focus on supporting local knowledge generation, to provide rural people with options rather than set recommendations, and to support innovation (Table 4.1). Biologically sound principles need to be taught, and adapted to different circumstances. Biodiversity, resource efficiency, economic viability, and resilience are all components fostering a sustainable trajectory. Farmers can improve the efficiency of nutrient, water, and energy cycles if knowledge is adequate, and if the cultural – economic context is supportive.

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INTERNET RESOURCES

A USAID Feed the Future project that aims to "transform agricultural systems through sustainable intensification projects in three regions of Africa," resources on the following website: http://africa-rising.net

A learning lab resource focused on action agroecology and sustainable agriculture in Southern and East Africa is at http://globalchangescience.org/eastafricanode

Links to sustainable and alternative agriculture systems information, in the USA and beyond: http://afsic.nal.usda.gov

Information on agroecology research and tropical farming systems of Latin America can be found at CATIE, in Costa Rica: http://www.catie.ac.cr/es/

A website that provides access to green manure and cover crop newsletter and resources around the world: www.plantpath.cornell.edu/mba_project/ciepca/allnews.html

HarvestPlus focus is on agricultural diversification with nutrient-enriched crop species

www.harvestplus.org/content/vitamin-sweet-potato

Organic agriculture searchable database: Organic Eprints is an international open access archive for papers related to research in organic agriculture. The Danish Research Centre for Organic Farming (DARCOF) and the Research Institute of Organic Agriculture (FiBL) in Switzerland are managing an open access Organic Eprints archive.

http://orgprints.org/

http://www.worldagroforestry.org/ The World Agroforestry Centre has information on many perennial − annual farming systems, around the globe.

http://globalchangescience.org/eastafricanode This is a new website that provides a platform for learning about sustainable agriculture in Africa, within the dynamic context of climate change and globalization. The focus is on Snapp's research group and partners engaged with participatory action research and extension in Central Malawi.

Chapter 6

Low-Input Technology: An Integrative View

Robert Tripp

INTRODUCTION

A systems approach to agricultural development emphasizes the importance of taking advantage of as many resources as possible to improve farm productivity. The role of plant breeding often captures significant attention, including both the contributions of modern crop varieties and farmers' development of local varieties. The role of crop management is equally important, but often less apparent. As with plant breeding, advances in crop management can occur through the use of both external resources and local ingenuity, and the source of innovation is sometimes used to distinguish agricultural development strategies. In particular, there are many instances where it makes sense to take advantage of local resources; on the other hand, the use of external inputs (principally synthetic fertilizers and pesticides) may be discouraged or proscribed. Such instances include various versions of "low external input agriculture."

This chapter reviews experiences with the promotion of technologies that support low external input agriculture. The focus of the discussion is not on a particular development philosophy, but rather on the lessons that can be learned from endeavors to incorporate new biological resources and innovative techniques in crop management for resource-poor farmers. Because most of the attempts to encourage this type of technology have been part of projects that emphasize farmer organization and capacity building, the lessons that emerge should be useful beyond the bounds of a particular type of technology, and should provide guidance for more general strategies of small-farm development.

The chapter is organized as follows. The first section provides an introduction to low external input technology (LEIT), and reviews some of the

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evidence for who is likely to take advantage of this kind of innovation. Because LEIT assumes that a primary input for farm improvement is household labor, the next section reviews the role of labor in choices about agricultural technology. LEIT also emphasizes the importance of developing farmer skills and knowledge, and the following section reviews the nature of farmer knowledge and how LEIT projects attempt to strengthen farmer skills. The final section summarizes findings, and discusses the design of more effective agricultural development strategies.

LOW EXTERNAL INPUT TECHNOLOGY

The technologies that concern us in this chapter are a collection of crop management inputs and techniques for soil conservation, soil fertility enhancement, crop establishment, and pest control. They are distinguished principally by what they are *not*: manufactured, "artificial" inputs introduced to the farming environment. Although this distinction may seem clear, the role of LEIT is sometimes confused or contested because it can be linked to various visions of agricultural development. It may be part of development philosophies that promote autarkic, self-sufficient farms, or that rely on local resources for environmentally sustainable small-scale farming (Reijntjes et al., 1992). In contrast, LEIT may be a key to strategies that promote active participation in the market by offering a distinctive, environmentally friendly brand, such as organic agriculture (see Fig. 6.1). In addition, LEIT may be seen as a basis for wider political or social movements (e.g., Holt-Giménez, 2009), a situation also

FIGURE 6.1 New market opportunities provide an incentive for farmers to adopt alternative agriculture practices, as shown here for organic cabbage production in Thailand.

encountered when trying to define the boundaries of the discipline of agroecology (Wezel et al., 2009). LEIT is also frequently associated with what some see as distinctive methods for promoting technologies, such as farmer field schools (FFSs), or other group activities. This chapter does not assess these various interpretations of LEIT, attempt to identify a group of technologies or methods as belonging to a specific development philosophy, or judge them because of particular associations. The review that follows is compatible with a positive, integrative, and pragmatic view of LEIT that sees LEIT as an underutilized resource and an essential element in broad strategies for agricultural development based on agroecological principles. A number of the examples in this review include the combination of LEIT with external inputs. At a time when the phrase "sustainable agriculture" is increasingly being replaced by calls for "sustainable intensification" (Garnett et al., 2013), it is imperative that as comprehensive a set of technologies and methods as possible be available for consideration.

Examples of Low External Input Technology

Examples of LEIT are given in Box 6.1. The technologies include physical crop management (such as methods of terracing, tillage, and planting), and the use of biological resources (such as intercrops, mulches, and biocontrol agents). Although all of these are based on labor, implements, or biological inputs that might be locally available, they are not necessarily indigenous. Many of the innovations in LEIT are based on the transfer of a plant species or other organisms from one environment to another, or the elaboration of novel crop management techniques. In addition, although the inputs may be theoretically available within the farm household or community, there are markets for some of these inputs (such as biocontrol products or manures), and the major input, labor, can be a market commodity as well, as we shall see below.

The technologies included within LEIT range from the mundane and traditional to the novel and exotic. Similarly, the amount of attention given to the promotion of LEIT varies considerably, from modest behind-the-scenes attempts to strengthen farmers' skills in crop management to well publicized campaigns, sometimes engendering considerable controversy (Giller et al., 2009; Basu and Leeuwis, 2012).

As much of LEIT represents iterative modifications to crop management practices it is not always easy to assess progress, but it is possible to distinguish some successes and failures. Some of the successes have been the result of formal development projects, such as IPM in irrigated rice (Tripp et al., 2005); others have benefited from both project support and farmer innovation, such as the spread of the velvet bean cover crop in Central America (Buckles, 1995); and others have relied primarily on farmer

BOX 6.1 Examples of Low External Input Technology

Soil and Water Management

- Terraces and other physical structures to prevent soil erosion. These may be the result of large-scale external investment or may be developed, often over many seasons, by hoe or plow, or by the arrangement of stones to form barriers.
- Contour planting, in-row tillage, tied ridging. Ploughed or hoed ridges are laid out along contours on slopes; tillage only along the cropped row (in-row tillage) develops mini-terraces (Bunch, 1999); tied ridges created by plow or hoe help conserve moisture and nutrients.
- Hedgerows and living barriers. Trash lines along the contour gradually form a bund; various shrub and grass species planted as intercrops on the contour form a living barrier against erosion.
- Reduced tillage systems, conservation tillage (Giller et al., 2009). A number of techniques promote a reduction in tillage; most require alternative planting systems and innovative ways of controlling weeds; some of the most prominent include the use of herbicides.
- Mulches, cover crops. Mulches may be derived from crop stover in the field, or cut and transported from elsewhere; cover crops are usually grown in association with the field crop and may serve various purposes, including weed control and fertility enhancement (Anderson et al., 2001).

Soil Fertility Enhancement

- Manures and composts. Manure from grazing animals or transported from stalls; various composting techniques including vermicompost.
- Biomass transfer and green manures. A crop is grown in a separate field and cut and carried to provide organic matter (Cooper et al., 1996); green manures are leguminous crops planted with the field crop, or in rotation.

Crop Establishment

- Planting pits. Small pits or basins dug throughout the field, used as planting stations where fertility and moisture are concentrated; often used for rehabilitating degraded land.
- SRI. Rice seedlings are transplanted earlier than normal and planted at wide spacing; the soil is kept well drained, and irrigation is managed to provide short periods of wetting and drying (Stoop et al., 2009).
- Intercropping. A traditional practice in many areas that can enhance weed control and soil fertility, as well as reduce risks.

Controlling Weeds and Pests

- Intercrops and rotations. Weeds and insect pests may be controlled by selection of appropriate rotations or intercrops.
- Integrated pest management (IPM). Insect control based on an understanding of ecological principles and employing a wide range of biological and, when necessary, chemical methods to keep pest damage below an economic threshold.

initiative, such as improved soil conservation in dryland Kenya (Tiffin et al., 1994). The failures range from the many attempts at crop management improvement that have been quietly devised, tested, and abandoned; to high-profile initiatives such as the attempt to introduce alley cropping in tropical Africa (Carter, 1995).

The Adoption of Low External Input Technology

There have been relatively few attempts to document the extent of adoption of this class of technology. A review of 25 years' experience in promoting water harvesting methods concludes that monitoring and evaluation has been particularly deficient (Gowing and Critchley, 2012). In addition, efforts to assess the uptake of LEIT suffer from problems of rigor and definition. In many cases there is over reliance on self-reports by project staff (Andersson and D'Souza, 2014). In addition, the gradual, iterative nature of many of these management changes makes it difficult to define who is an "adopter," and in many studies a clear definition is not provided. It may be that a complex set of practices is only partially adopted or modified, on a fraction of a farmer's land (Ly et al., 2012). Time scale is also important and considerable changes, further adoption, or abandonment may take place in the years subsequent to a project's lifetime (De Graff et al., 2008). The detailed case studies discussed in this chapter (Boxes 6.2–6.4) are drawn from a study that attempted to overcome some of these difficulties by conducting fieldwork that examined the long-term consequences of three prominent LEIT projects (Tripp, 2006).

Perhaps the most surprising conclusion from this review of LEIT adoption patterns is that those who tend to take up and use such technology exhibit many of the characteristics associated with adopters of conventional technology. That is, they tend to be farmers with relatively more resources (land, education, access to finance) (see Fig. 6.2), and those who rely more on agricultural markets. There are, of course, many variations and exceptions in these cases, but the overall pattern is quite clear. This challenges the view of many LEIT supporters, who see these technologies as an alternative path for those farmers left behind by conventional, external input-based agricultural development.

Research on adoption provides explanations for the similarities observed in uptake patterns. Rogers (1995) review of the diffusion of all types of innovations concludes that the most common consequence of technology diffusion is to favor the better-off, thus widening socioeconomic gaps. This is of course not an inevitable conclusion, and there is evidence that well-planned agricultural development efforts can at least limit such biases, but it should be clear that there is little evidence that LEIT follows a radically different pathway. There is no need to be unnecessarily despondent about the

BOX 6.2 The Adoption of Soil Regeneration Technology in Honduras

In the 1980s and 1990s several NGO projects operated in Honduras promoting sustainable hillside farming, with particular attention to methods for soil fertility enhancement, and soil and water conservation. A study revisited two areas in central Honduras where previous slash-and-burn agriculture has evolved to permanent cropping on hillside plots and farmers plant twice a year, with maize as the principle first season crop, followed by beans in the second season. The NGO projects promoted farmer experimentation, and featured techniques such as in-row tillage and the use of cover crops. Although farmer leaders were identified from among project participants, the projects were sufficiently flexible that a wide range of farmer participation was possible.

An examination of who participated in the projects shows that those farmers with links to agricultural markets, particularly those with irrigation and commercial vegetables, were more likely to take an interest in the activities. Indeed, earlier project activity had helped many of these farmers enter into commercial vegetable production for the first time.

	Participants ($n = 79$)	**Nonparticipants ($n = 46$)**	**Statistical Significance**
Education (years)	2.7	2.3	No
Age	44.7	51.7	$< .05$
Percentage farms with irrigation	60	35	$< .05$
Percentage farms with vegetables	43	22	$< .05$
Maize yield (kg/ha)	1105	806	$< .05$
Total chemical fertilizers (kg)	163	145	No

Not surprisingly, these initial differences in interest among the farmers are reflected in the final record of adoption, five or more years after the projects were completed in the study villages. The majority of the new technologies were applied to cash crops rather than subsistence crops.

Technology	**Percentage of Farmers Using ($n = 172$)**
In-row tillage with maize	16
In-row tillage with beans	17
In-row tillage with vegetables	45
Organic fertilizers on maize	12
Organic fertilizers on vegetables	28

Source: Richards, M., Suazo, L., 2006. Learning from success: revisiting experiences of LEIT adoption by hillside farmers in central Honduras. In: "Self-Sufficient Agriculture. Labour and Knowledge in Small-Scale Farming" (R. Tripp, Ed.), pp. 95–124. Earthscan, London (Richards and Suazo, 2006).

BOX 6.3 Labor Deployment and the Adoption of Soil Conservation in Western Kenya

Kenya's National Soil and Water Conservation Program operated from 1988 to 1998 and featured a catchment approach, where communities were encouraged to learn about and establish soil and water conservation techniques. Elected local catchment committees served as major actors in the project. A study examined the aftermath in a set of communities in high- and low-potential areas of Nyanza Province, western Kenya. The principal subsistence crop is maize, but beans, banana, groundnut, sweet potato, and sorghum are also grown. The project featured the promotion of vegetative and unplowed strips, simple terraces, and retention ditches.

Soil conservation technology often requires high labor inputs. The study found a total of 23 different types of soil and water conservation activity undertaken by farmers, but the technologies with lower labor requirements (such as grass strips and unplowed strips) were much more commonly adopted than those that required more labor (such as terraces). In addition, the strips take relatively little space, and Napier grass can be grown on them to feed to cattle. Although many farmers adopted some kind of conservation structure, their spacing on the slope was less than one-third the recommended density for effective erosion control, another possible indication of labor constraints.

An examination of the nature of farmers who adopted the conservation technology also shows how labor opportunities influence interest in technology. In the high potential areas (where the majority of the adoption took place), adopting farmers had more labor available (measured by household labor resources), relied more on crop sales, were less likely to be involved in nonfarm business, and hired more labor.

	Adopters ($n = 41$)	**Nonadopters ($n = 13$)**	**Statistical Significance**
Landholding (acres)	6.8	3.2	No
Number of cattle owned	3.0	2.0	No
Percentage of crop sale as most important source of income	59	15	<0.01
Percentage business of petty trade as most important source of income	7	39	<0.01
Percentage low labor availability	9	31	<0.1
Percentage hire labor for weeding	68	46	No
Percentage derive income from casual labor	12	14	No

Source: Longley, C., Mango, N., Nindo, W., Mango, C., 2006. Conservation by committee: the catchment approach to soil and water conservation in Nyanza Province, western Kenya. In: "Self-Sufficient Agriculture. Labour and Knowledge in Small-Scale Farming" (R. Tripp, Ed.), pp. 125–159. Earthscan, London (Longley et al., 2006).

BOX 6.4 Farmer Field Schools for IPM in Sri Lanka

From 1995 until 2002, a program of FFSs for introducing IPM and other crop management techniques to rice farmers in Sri Lanka was managed by the Department of Agriculture, with assistance from FAO. A study was conducted in communities in Southern Province, among farmers with access to irrigated paddy land. The project concentrated on helping farmers lower the use of insecticides, particularly early in the season. It also supported the incorporation (rather than burning) of rice straw, and promoted more rational fertilizer management through single-nutrient fertilizers.

Each FFS could accommodate about 20 farmers, on a first-come, first-served basis. An examination of the characteristics of participants reveals few differences with nonparticipants in terms of income source, age, or education; however, farmers who also worked as casual laborers were much less likely to participate.

The effects in terms of technology change are remarkable and apparently sustainable five or more years after participation in the FFS. A comparison of FFS farmers, neighbors in the same irrigation tract, and control farmers from a nearby irrigation tract in seven locations showed that only FFS farmers experienced significant change.

Practice	**FFS Farmers ($n = 70$)**	**Neighbors ($n = 70$)**	**Statistical Significance of Difference Between FFS and Neighbors**	**Control Farmers ($n = 70$)**
Insecticide applications (2002 − 03 season)	0.6	1.7	<0.001	1.7
Report lower insecticide use (%)	80	49	<0.001	49
Use triple superphosphate (%)	83	51	<0.01	54
Use muriate of potash (%)	83	53	<0.01	56
Incorporate rice straw (%)	86	73	<0.1	60

A remarkable feature of these adoption patterns is the fact that there is virtually no difference in technology use between the neighbors of the FFS farmers and those in control villages several kilometers away. (The only possible exception is the incorporation of rice straw.) This is one indication of the fact that although the FFS was responsible for significant changes in farming practices, the message did not spread to other farmers.

Another indication of the low degree of information diffusion is the response of neighboring farmers about lessons learned from the FFS farmers. The only practice for which there is much evidence of communication is the

(*Continued*)

BOX 6.4 (Continued)

incorporation of rice straw, a practice whose visibility may make it more amenable for farmer-to-farmer transmission.

Information	**Number (and %) of Neighbors Who Received Information From FFS Farmers ($n = 70$)**	**Number (and %) of Neighbors Who Acted on the Information ($n = 70$)**
Use of insecticides only as last resort	8 (11%)	6 (9%)
Importance of beneficial insects	4 (6%)	4 (6%)
Use of straw as soil amendment	21 (30%)	19 (27%)
Use of single-nutrient fertilizers	10 (14%)	5 (7%)

Source: Tripp, R., Wijeratne, M., Piyadasa, V.H., 2005. What should we expect from farmer field schools? A Sri Lanka case study. World Dev. 33, 1705–1720.

FIGURE 6.2 Investment in training and farmer's time is required to adapt new technologies to local circumstances, as shown here for improved cultivars of sweet potato in Uganda.

consequences of technology adoption. Some of the early observers of the Green Revolution in Asia predicted a widening gap, and there is evidence of undeniable instances of inequality (see "Introduction" section). Yet long-term studies of areas that benefited from the seed – fertilizer technology associated with the Green Revolution provide a picture of more equitable long-term consequences (Lanjouw and Stern, 1993). Nevertheless, it is misleading to claim that particular agricultural technologies are the answer to correcting broad inequalities in access to resources.

Some examples from the literature illustrate instances in which LEIT adoption favors better-resourced farmers, even where poorer households have at least equivalent access to the innovations. A study of natural resource management practices in an area of western Kenya over a period of 13 years showed that wealthier households are more likely to use both external inputs (inorganic fertilizer) and low-input soil management techniques (stover lines, agroforestry, and manure) (Marenya and Barrett, 2007). In Niger, the introduction of planting pits has helped rehabilitate degraded land, and has contributed to an emerging land market, but the purchasers are concentrated among a rural elite (Hassane et al., 2000). FFSs for potato IPM in Ecuador tended to attract wealthier farmers (Mauceri et al., 2007). The examples are not confined to developing countries. A movement toward "restorative agriculture" in the United States in the early 19th century (featuring a shift from extensive cultivation toward more careful soil management and the use of manure) was distinguished by the fact that "the majority of improving farmers held a fortune somewhere above middling, including merchant-squires of great wealth.... Those who incorporated restorative methods almost always lived close enough to market towns to turn surplus into cash" (Stoll, 2002, p. 28).

There is also often a relationship between commercial, market-oriented agriculture and the uptake of LEIT (see Box 6.2 for an example from Honduras). Cramb et al. (2000) compare the experiences of several soil conservation efforts in the Philippines, and find that adoption is highest in an area where proximity to large urban markets gives farmers an incentive to conserve soil. The spontaneous adoption of planting pits in Zambia is higher among cotton farmers than among those who grow only food crops (Haggblade and Tembo, 2003). There is evidence that many instances of adoption of soil conservation measures (particularly terracing) for food crops in parts of eastern Kenya are related to a village's proximity to markets, and in some cases to the ability to invest windfall profits from high coffee prices in labor for terrace construction (Zaal and Oostendorp, 2002). The opportunity for expanded commercial production may also be an incentive for the adoption of LEIT.

These examples are far from conclusive, but they certainly indicate that LEIT is not immune from distributional biases. It is of course misleading to simply classify farmers as wealthy or poor, because resource and motivational distinctions in rural communities are multidimensional. A study of a soil conservation program in the Philippines showed that it tended to benefit a “clique of yeoman farmers” (Brown and Korte, 1997, p. 14), but not the village elite. Project management can also make a difference. A study of the impact of agroforestry innovations in Kenya found no relationship between wealth and adoption in the pilot villages that received extra attention for reaching disadvantaged groups, but found a bias toward better-off farmers in villages included in a subsequent round of less intensive promotion (Place et al., 2003). Resources such as soils may differ greatly between and even within farms, and may be related to household livelihood strategies (Tittonell et al., 2010). A review of studies on the system of rice intensification (SRI) concludes that the innovation is most likely to show a response on particular types of weathered, infertile soils (Turmel et al., 2011). A study of uptake of SRI in Timor Leste shows that adopters have somewhat lower yields than nonadopters, but that their initial soil conditions had put them at a disadvantage which the technology helped to ameliorate (Nolze et al., 2013).

The fact that LEIT seems to exhibit many of the diffusion characteristics of other agricultural technologies sounds a note of caution for those who see LEIT as distinct from other technology. At the same time, it indicates that any conclusions we reach about the relevance, organization, and promotion of the technology are likely to be applicable to a wide array of strategies in agricultural development. Our interest is in who is able to take advantage of new technology, and the implications for effectively supporting rural development. The next section looks more closely at the interactions between farm labor and technology adoption, and the following section examines how knowledge about technology is generated and made available.

LABOR

The fact that many examples of LEIT rely on some investment of labor for their implementation (and usually require some additional time for learning and adaptation) has been used by the technology’s supporters as evidence of its relevance for poor households with few resources beyond their own labor, and has been used by the technology’s detractors to characterize LEIT as impractical and labor-intensive. Neither of these extremes represents a particularly useful assessment. This section examines the nature of the labor investment for LEIT, the sources of labor in small-farm agriculture, and the prevalence of off-farm labor.

Labor Requirements

Labor is a fundamental determinant of a technology’s acceptability to farmers. Moreover, the labor component cannot simply be assessed in terms of hours invested per hectare. The timing of labor during the season, the skill requirements (including the possibilities of learning to manage a technology more efficiently), and the difference between one-off investments (e.g., to establish a terrace) and recurrent requirements (e.g., to monitor pest damage) all must be taken into account.

It is inaccurate to characterize LEIT as necessarily labor-intensive. Some examples of LEIT require no more labor than the farmer's present practice, and some types (such as certain variants of conservation tillage, or IPM that reduces the use of insecticides) are attractive precisely because they save labor. But it remains true that the success of LEIT is often dependent on the efficient organization of labor supply. In some cases the crucial factor is an initial investment in labor for the establishment of LEIT (such as a soil conservation measure); once established, the labor requirements then fall, sometimes below those of conventional management. In a number of instances, however, LEIT implies a permanent increase in labor, while in other cases the crucial factor is not necessarily the investment in physical labor but rather the time for learning new skills that can be applied to the farm, or for monitoring performance.

Many studies point to the importance of routine labor demands as a determinant of adoption for LEIT. A number of observers have remarked on the problems that some IPM methods impose on farm labor patterns; for instance, farmers often find they do not have time to devote to the frequent scouting for pests that some IPM techniques require. Some of the debate about SRI revolves around labor requirements, and studies show that higher yields may not be matched by higher returns to labor (Ly et al., 2012; Takahashi and Barrett, 2014). Reviews on the extent to which households continue to use soil conservation techniques show how this is related to their labor requirements (De Graff et al., 2008; Marenya and Barrett, 2007).

There are other aspects of labor that are relevant to the use of LEIT. Even when labor availability per se is not an impediment, there are a number of instances where the new practices require additional skills. The skills may be needed for the one-time application of a particular technique (such as the establishment of contour ridges with an A-frame), but often they are necessary each season in order to make adjustments and adaptations, and to promote further innovation. These skills may require significant time to acquire; Pretty (1995) sees them as part of "transition costs," i.e., investment for transition from conventional to alternative agriculture. "Lack of information and management skills is, therefore, a major barrier to the adoption of sustainable agriculture. During the transition period, farmers must experiment more and so incur the costs of making mistakes, as well as acquiring new knowledge and information" (Pretty, 1995, p. 96).

The time to engage in learning and experimentation is less likely to be available to poorer members of the community, contributing to the patterns of adoption that have been observed. The adoption of conservation farming in Zambia requires advance planning and careful execution of tasks. "It requires a change of thinking about farm management under which the dry season becomes no longer a time primarily reserved for beer parties and

FIGURE 6.3 Farmer experimentation is often catalyzed by participating in on-farm research or extension activities, as illustrated here by an A-frame innovation developed by a Malawi farmer to speed up contour measurements and ridge alignment for soil conservation.

socializing but rather an opportunity for serious land preparation work. Anecdotal evidence from our field interviews suggests that retired school teachers, draftsmen and accountants make good CF farmers" (Haggblade and Tembo, 2003, p. 39). In establishing FFSs for IPM in Zanzibar, it was "necessary to work with groups of farmers who were willing to learn, able to experiment, had enough flexibility to change and were prepared to commit themselves for one or more seasons. This automatically excluded the poorest farmers who had little physical and financial buffer for experimentation" (Bruin and Meerman, 2001, p. 67) (see Fig. 6.3). It also can be a significant barrier to participation by women who are responsible for both household and farm duties, and in particular female-headed households that have high dependency ratios (number of dependents in relationship to economically active adults). Issues of inequities in participation are discussed in more depth in Chapter 10, Gender and Agrarian Inequities.

Hired Labor

The Green Revolution in Asia is a particularly important case of technological change leading to increased labor use. The development of short-stature rice and wheat varieties, in conjunction with increased use of fertilizer and irrigation, made possible significant increases in yield that reversed the trend toward increaing food grain imports. A review of the adoption of modern rice varieties in a number of Asian countries found, with one exception, a significant increase in labor use per hectare (David and Otsuka, 1994).

A very significant part of the increased labor use during the Green Revolution was hired, mostly from landless or near landless households. Indeed, this added employment was one of the most significant contributions of the technology. Despite the fact that LEIT is often envisioned as a way to take advantage of supposedly surplus household labor, a significant proportion of the additional labor for managing these innovations is also hired. In the Honduras case (Box 6.2) for instance, half the labor used to construct the mini-terraces for in-row tillage was hired. On the other hand, a study of SRI adoption in Indonesia points out that the new skills required by the innovation cannot easily be entrusted to hired labor; the minority of farmers who use SRI (and who realize significantly higher rice yields) engage in less off-farm work in order to devote more family labor to their rice fields (Takahashi and Barrett, 2014). The case for seeing LEIT as a distinct strategy is more difficult to maintain when labor is itself increasingly an external input. The growing importance of hired labor for many types of agricultural tasks in communities that are often viewed as composed of static, self-sufficient peasant households is a reminder of the importance of understanding farmers as dynamic actors in a complex economy. The relationship between labor demand and LEIT adoption is illustrated for a case from Kenya in Box 6.3.

The availability and price of hired labor depends to a large extent on the wider economy. The role of wage rates in the uptake of LEIT is illustrated by an analysis of the use of green manures in irrigated rice production in Asia (Ali, 1999). Much of the behavior of rice farmers toward green manure options can be understood by looking at the relationship between labor costs and fertilizer price in individual countries. Green manures and fertilizer are alternative sources of nitrogen, and the cost of green manures is mostly dependent on the labor for their management. When the ratio of labor cost to fertilizer price is above a certain level, farmers abandon the use of green manure.

Off-Farm Labor

Rural economic realities challenge any oversimplified images of the peasant farmer (e.g., Tittonell et al., 2010). Van der Ploeg (1990) provides a striking illustration of these realities in a description of a highland Peruvian farming community, where only 9% of the farmers work solely on their own farms. The poorest group of farmers combines subsistence production with wage labor in order to survive. Other farmers invest part of their time in wholesale trading, and look to this as their principal economic strategy, seeking to reduce labor and other investments in the farm. Another group is involved in enterprises such as petty trade, which offers less scope for expansion, and they channel much of their earnings to further intensifying agricultural production. Although it still may be possible to combine own-farm labor with off-farm migration after the cropping season, the concentration of rural resources is making this less of a possibility. Many farms may simply not be viable, and an absence of external opportunities means that farmers end up seeking day labor with wealthier neighbors, leading to a downward spiral of lower yields, followed by even greater dependence on off-farm income. Such a situation is illustrated by the *ganyu* labor system in Malawi, although a close analysis shows that the deployment of household labor at critical times, such as early-season weeding, responds to a very complex set of considerations involving a range of opportunities for earning the income needed to make up for maize deficits (Orr et al., 2009).

Thus, the labor requirements of any new technology may be interpreted differently by various types of farmers, depending not only on their access to household labor (or ability to hire labor), but also on their alternative employment opportunities. These alternatives can draw them away from the farm, but also may provide extra cash resources to hire local labor. But where agricultural technology does not offer returns to labor that justify a sufficient wage and there are also relatively few outside alternatives, farm labor shortages and rural unemployment may, paradoxically, coexist. The fact that farming is not a full-time occupation does not necessarily make it any less important, or automatically reduce incentives for its improvement. But we must acknowledge that in many situations households' interests in access to more efficient production technology may take second place to their concerns as consumers seeking affordable food prices.

KNOWLEDGE

Most examples of LEIT involve an understanding of the principles of crop management, and the adaptation of innovations to local circumstances, rather than the mere application of standard recommendations. This level of knowledge intensity is sometimes put forward as a distinguishing characteristic of LEIT, although it is debatable whether farmers' successful experience with Green Revolution technology was in fact merely a matter of following instructions, or indeed whether new technologies such as transgenic crops are any less knowledge intensive (Tripp, 2009). Nevertheless, it is certainly true that LEIT relies on building farmer knowledge systems. This section examines the resources available for that purpose.

Local Knowledge

Most efforts at LEIT are based on strengthening local knowledge and supporting farmers' experimental capacities. Both of these arenas have been the subject of considerable study, and occasionally of controversy. A considerable amount has been written about indigenous technical knowledge (ITK), confirming that farmers often have a detailed understanding of their environment. Such traditional knowledge is often overlooked in agricultural development efforts, and farmers may not be encouraged to utilize this resource. For example, Murwira et al. (2000) report how farmers in a rural development project in Zimbabwe were at first reluctant to discuss their use of traditional practices for pest control for fear of ridicule; it was only when the project confirmed that such knowledge could have significant value that farmers were willing to include the information in the project's activities.

Yet these capacities to observe and classify do not always lead to practical knowledge. For instance, Bentley (1989) argues that Honduran farmers' ITK is best developed for describing plants and plant growth, and less adequate for understanding insect behavior or the origins of plant disease. These deficiencies may at times contribute to harmful practices, such as overdependence on pesticides. Thus, ITK cannot always be seen as a basis for further innovation, or used as a certain defense against environmental mismanagement. The need to balance farmers' experience and beliefs with conventional scientific concepts can be a major challenge in the participatory testing and development of technology, as described for a soil fertility project in Kenya (Ramisch, 2014).

Any mistaken image of LEIT as "simple" technology is corrected by appreciating the complex and varied farming environments into which these types of technology must be adapted (Giller et al., 2009). Rigidities in defining the practice of LEIT may be counterproductive. The SRI is usually promoted by eschewing purchased inputs such as herbicide and fertilizer. There are some good reasons for this (manual weeding can improve aeration, and organic fertilizer improves water retention), but absolute restrictions can limit the contribution of SRI practices and their capacity to provide useful innovation for farmers (Krupnik et al., 2012). The generation of LEIT cannot simply rely on providing support to farmer systems of knowledge, but also requires skilled and sustained technical input from extension or other service providers. A number of nongovernmental organizations (NGOs) that originally promoted conservation farming in Zambia later retreated, in part due to a shortage of the management and agronomic skills among their staff required for the promotion of this complex technology (Haggblade and Tembo, 2003).

Another subject of debate is the extent to which farmers experiment. A study of farmer experimentation in Africa (Sumberg and Okali, 1997) identifies two conditions for an "experiment": a farmer's initial observation of conditions or treatments, and the observation or monitoring of subsequent results. They found a wide difference among individuals and sites in the propensity to engage in experimentation (see Fig. 6.4). They also distinguish between "proactive" experimentation, in which there is a conscious effort by

FIGURE 6.4 An informal experiment of a farmer in Central Malawi, where he is testing complex legume mixtures and planting arrangements, including a doubled-up legume system (Snapp et al., 2014).

the farmer to create or control certain conditions for the purposes of observation; and "reactive" experimentation, which has no systematically chosen objectives. Their study found that men are more likely than women to report experimentation, and that these men are likely to have more education and previous involvement with extension. They also found that experimentation was more frequent among people who saw themselves as full-time farmers, frequently (although not exclusively) engaged in commercial production.

A fairly wide variety of strategies have been used to build on farmer knowledge and innovation in the promotion of LEIT. Some of these involve expanding opportunities for farmer interchange, often based on formal group learning methods.

Group Methods

When LEIT involves the introduction of fairly complex technologies that require local adaptation, farmers often profit from "cross visits," opportunities to observe such technologies in practice in other communities, and to discuss techniques and challenges with those farmers that have more experience. The *Campesino a Campesino* movement in Nicaragua aims to help small farmers acquire environmentally sound production techniques, and it makes considerable use of exchange visits, where members of one community visit those in another to learn about innovations. The movement has found that farmers are particularly effective at communicating their experiences to their counterparts (Anderson et al., 2001). Farm tours and visits are important in promoting understanding and farmer experimentation in widely different socioeconomic contexts, as witnessed by their importance in introducing IPM to Texas cotton farmers (Leslie and Cuperus, 1993).

LEIT activities are often organized around group methods, and there is a wide range of examples. Many LEIT projects include opportunities for social learning (the transmission of information in a social context). In addition, there have been advances in developing farmer participation in problem diagnosis and technology development. Several formal methodologies exist. An additional characteristic of many LEIT efforts is an aspiration that once useful principles or techniques are identified and introduced on a small-scale, local farmers can take increasing responsibility for their diffusion, and LEIT projects often make provision for this strategy.

Group methods are of course not the exclusive preserve of LEIT activities; as Pretty (1995) points out, many Asian countries promoted uniform Green Revolution packages through local groups (often formed or mandated for that purpose). But the group approach is particularly relevant to low external input strategies for several reasons (Pretty, 1995). First, resource management often requires more than the efforts of individual farmers; for instance, communities need to agree on common strategies for challenges such as soil erosion control, and some pest management techniques require coordination among neighboring farmers. The effective management of common property resources can play an important role in environmentally sound development strategies. In addition, low external input strategies often go beyond the goal of introducing particular technologies and seek to build, or rebuild, local institutions. Finally, to the extent that LEIT requires the application of principles and the local adaptation of technology, it usually makes sense to organize group activities, not only because they are more efficient, but also because they promote the interchange of ideas and experiences.

An example of group activity for improving common property management is the Landcare Movement which originated in Australia (Prager and Vanclay, 2010). Landcare groups comprise local farmers and other members of the community interested in land management. They meet to discuss common problems, and conduct a range of activities including teaching, training, and trials; engagement with local government is common. Successful interventions have been carried out by Landcare groups in areas such as soil conservation and wetlands management. The strategy has been transferred elsewhere, and is used to promote resource conservation on individual farms. One example is a region of the southern Philippines, where local Landcare groups were formed (Cramb, 2007). The local groups included farmers, community leaders, and extension agents, and they were able to support their activities through a decentralized Philippine government funding initiative related to environmental protection. The groups helped build social capital, although there was considerable heterogeneity in the types of farmers and communities that were best able to take advantage of the opportunity.

One of the most well-known innovations for introducing LEIT is the FFS. The development of an effective IPM strategy for rice in Asia is based on work in Indonesia that led to the emergence of the FFS concept. In order to appreciate the rationale behind lowering pesticide use and allowing ecological processes to reestablish their regulation of pest activity, farmers needed to learn more about pest – plant and pest – predator interactions; the FFS meets this challenge (Kenmore, 1996). The FFS fosters discovery learning by facilitating farmer opportunities to observe and discuss important ecological relationships in the field. An FFS typically includes about 20 farmers and a trained facilitator, and meets once a week during the cropping season. Farmers spend part of each session observing pest and predator behavior, drawing diagrams of the relationships they uncover, and debating their implications. Farmers are encouraged to make "insect zoos" (collecting certain pests to observe their behavior or life cycles), and to conduct simple experiments (such as mechanically cutting a certain proportion of leaves early in the crop cycle, to mimic early insect damage and to observe the recuperative capacity of the plant). Each FFS also includes exercises in group dynamics to promote a group spirit and foster collaboration. The FFS strategy has been applied in a wide range of settings for purposes well beyond the extension of IPM, including livestock health and production, soil fertility, community forestry, gender equity, HIV/AIDS prevention, and other topics (e.g., Davis et al., 2012).

The Sustainability of Groups

Group formation may be useful in the context of a project, but the sustainability of such groups is often in doubt. The rapid spread of conservation tillage in Brazil was due in part to the formation of "Friends of the Land" clubs that facilitated farmer-to-farmer exchange of experience, provided support to farmers experimenting with the technology, and allowed access to outside expertise (see Fig. 6.5). (Many of these clubs were assisted by support from the chemical companies that were selling the herbicides used for conservation tillage.) However, once farmers became familiar with the techniques, interest in the clubs tended to wane, unless other activities were included (Landers, 2001). Winarto (2002) describes how an NGO in Indonesia that successfully introduced IPM to rice farmers helped form an alliance of farmers' associations that campaigned to remove pesticides from the government credit package, and lobbied for lower prices and more timely delivery of fertilizer. However, there is little evidence that the majority of FFS formed in Indonesia for introducing IPM survive beyond the initial season of training.

Although group approaches can promote widespread community involvement in technology generation, they may also be susceptible to capture by local elites. Projects promoting the construction of stone bunds in Burkina Faso relied on the formation of village groups. "Influential village members,

FIGURE 6.5 A farmer-to-farmer exchange visit in Northern Malawi is shown where farmers gain first-hand experience with institutional innovations such as nutrition education through farmer-led recipe days.

such as the better-off, local chiefs, and the so-called enlightened (those allegedly well-versed in modern ways, often returned migrants), tend to dominate these groups. While there is usually an atmosphere of free discussion, it is true that the dominant ones are able to rely on the group to help them develop their own farmland. The less well-off do participate in the activities of the group, although they rarely benefit directly. Quite often, their own farms are neglected" (Atampugre, 1993, p. 106).

The Diffusion of Information

Intensive methodologies such as FFS, which direct considerable facilitation resources toward a small number of communities, are often defended on the basis that once extension services have gained experience with the concepts in an initial period, they can adjust the methodologies to local resources. A complementary expectation is that farmers who have been through this process can serve as catalysts to help neighboring villages initiate their own work. Extension services can make sure that experienced farmers have the resources to offer advice to others. A number of national FFS programs in Asia devoted resources to training and supporting farmer facilitators who could take the place of extension agents in leading FFS, and thus extend the methodology at a lower cost, but the outcome of these efforts has been the subject of critical analysis (Quizon et al., 2001). Beyond these large-scale efforts, many other initiatives in promoting low external input agriculture include farmer-led extension, or farmer promoters in their strategies. In some cases projects pay a small stipend to local farmers who have been identified and trained to play a formal extension role. In other cases, the projects simply try to increase contact between participant farmers and their neighbors, in the hopes that this will facilitate the diffusion of the innovations.

It is important to consider the cost-effectiveness of FFS. Studies in Bangladesh and Ecuador found that although FFS is good for transmitting complex information on pest control, other methods such as field days may be more cost-effective (Ricker-Gilbert et al., 2008; Mauceri et al., 2007). Analysis of alternative communication methods to introduce the "push – pull" system of weed and insect control to Kenyan maize farmers rated field days as superior to FFS (Murage et al., 2011). There are particular questions about the extent to which FFS members are able to share knowledge with other farmers. A meta-analysis of several hundred FFS projects in IPM concludes that there is little evidence of knowledge spreading from participants to their neighbors (Waddington and White, 2014). The participant observation that Winarto (2004) carried out with an FFS group in Java provides insights into the challenges of communicating knowledge gained in FFS. Although there is certainly evidence of social learning, with participants debating, sharing observations, and learning from each other, their desire to communicate this new-found knowledge with other farmers was often thwarted. A farmer's status in the community determined the degree to which others would listen to him (e.g., a young participant had no success in getting his father to modify his practices). New terms (like natural enemy) did not easily find a place in conversation, and the experiences of the FFS were difficult to communicate to others. Despite the persistent proselytizing of some of the IPM farmers, only modest progress was achieved in changing nonparticipants' views on insecticides. Box 6.4 summarizes the successes and failures of FFS in Sri Lanka (see Fig. 6.6).

IMPLICATIONS FOR RURAL DEVELOPMENT STRATEGIES

Many examples of LEIT can make important contributions to improving small-farm productivity, and the innovative methods used to promote the generation and diffusion of this type of technology can strengthen farmers' capacities. But the relatively limited spread of LEIT, and uncertainties about the cost-effectiveness of many of the methods used to support it, challenges any hopes of using this experience as a model for pro-poor technological change. Interactions with farm labor and local knowledge, and the only modest achievements of LEIT projects on the ground, illustrate why it is unwise to hope that rural development strategies based on particular types of

FIGURE 6.6 Social learning at a farmer field school in Sri Lanka.

agricultural technology can bring about fundamental social or political change. More fundamental issues stand in the way of technology-led rural development. This section discusses two of those issues: the incentives that motivate farmers to seek and utilize new technology, and the organization of development projects. The discussion is based on the experiences of promoting LEIT, but should have relevance to a wider range of agricultural development strategies.

Incentives for Technology Generation and Adoption

In order for LEIT to make a significant impact on the countryside, farmers must have appropriate incentives to experiment with, adapt, and gain control of new technology. Our review has shown that the supposedly simple technologies of LEIT do not often reach the poorest farming households. One of the explanations is the nature of income generation for the rural poor. The custom of referring to all landholding rural households as "farmers" masks the complexity of rural livelihood strategies, and often overstates the importance of agriculture to the income streams of these households (see Chapter 3: Farming-Related Livelihoods, for an in-depth discussion of livelihood strategies). For example, less than one-third of the farmers in five sub-Saharan African countries are net sellers of maize, and half of the crop brought to market is produced by only 2% of the farmers (Jayne et al., 2010). Various studies show the exceptional diversity within "farming" communities (Tittonell et al., 2010). The varied deployment of farm household labor is receiving increased attention, although the phenomenon is not of recent origin. A situation where most farmers "were involved in several 'occupations'. . .[and] might take laboring jobs for other people or they might have expertise in a particular craft or skill which they combined with farming" (Overton, 1996, p. 36) is an increasingly common understanding of contemporary rural economies in developing countries, although this description is drawn from 16th century England.

A relatively high proportion of time devoted to nonagricultural activities, and a declining role of farming as a source of cash income are factors that can predispose households to avoid participation in LEIT projects, and can thwart efforts to use this technology for improving the livelihoods of resource-poor farmers. The interactions between off-farm income and agricultural activity can be complex; additional income sources can capture time and attention that might otherwise be devoted to farming; or income earned off the farm can be invested in improving farming capacity (Reardon et al., 2000). The strategies elected depend to a great extent on the resources available to the household, and the opportunities for remunerative agriculture. The role of off-farm income in providing both a pathway out of poverty and a source of potential investment for agriculture is more evident in some Asian examples than in much of Africa, underlining the need for technologies to intensify African farming (Dercon et al., 2013; Headey and Jayne, 2014).

Some difficult choices must be faced, and strategies articulated, regarding the future role of agriculture in rural development. The choices involve both an assessment of the agricultural potential of diverse rural areas, and the capacities of different types of households. Opinions differ regarding the potential of so-called marginal areas for agricultural growth (Renkow, 2000). In addition, there are growing challenges to the "small but efficient" view of farming development. Although some analyses show that increasing agricultural productivity is still the most effective way out of poverty for the poorest sector of the rural population (Christiaensen et al., 2011), there are serious questions about the long-term role of small-scale, labor-intensive farming (Woodhouse, 2010). A move toward somewhat larger farms seems inevitable, and current experience shows how the wider economy influences the equity of such a transition (Jayne et al., 2010; Deininger et al., 2009).

Policy makers need to recognize the differences among rural households. De Janvry and Sadoulet (2000) have proposed that we should recognize four types of paths leading away from rural poverty: households may "exit" agriculture through migration or the development of rural employment opportunities; some may follow an "agricultural path" that connects them with agricultural markets; others can follow a "pluriactive path" that combines off-farm income with subsistence farming; and finally some households must be provided an "assistance path" through income or food transfers that allows immediate survival, and eventual opportunities to follow other paths.

This topic is discussed in detail in Chapter 4, Farming Systems for Sustainable Intensification, including trajectories of agricultural development for different resource groups of farmers.

Households that are leaving farming will not be major targets for agricultural technology generation, and should instead be eligible for assistance that improves their skills and capacities as urban migrants or participants in a diversifying rural economy. Those who have a commitment to agriculture as a major source of income will have increasing participation in markets, and are in many respects the most logical targets for technologies such as LEIT. Those who balance income sources are perhaps the most problematic. Their relative lack of attention to farming may make them more likely to misuse inputs such as pesticides, and less likely to invest in resource conservation, hence making them particularly important candidates for LEIT. On the other hand, their diverse income strategies lower their incentives for participation in technology generation activities, and often restrict their capacities to invest in new technology; they may require different approaches if LEIT is to make a contribution to their farming.

Strategies for Demand-Driven Research

The different motivations and pathways of rural households add complexity to the already difficult challenge of promoting LEIT. The way forward is not clear, but there is growing evidence that the strategy of many independent, short-lived projects is not productive. The problem extends beyond LEIT, and calls into question the common strategy of donors in funding small pilot projects focused on specific technological innovations with the attendant demonstrations, group formation, participatory exercises, and assumptions that somehow there will be a spontaneous diffusion of results.

Many LEIT projects are limited in breadth and focus. They typically concentrate on a few specific technologies, and cover a relatively limited number of communities. There is nothing wrong with working with a restricted technology set, as long as it responds to farmers' priorities rather than project mandates, and as long as there is a capacity for evolution. There is also nothing intrinsically wrong with starting on a small-scale, as long as there is some conception of the next steps that are necessary and a willingness to collaborate with similar efforts. The latter is a particular problem with LEIT, and it is not uncommon to find several separate projects working on similar issues (e.g., soil fertility) in the same region with little or no communication, coordination, or joint learning. In addition, technology themes proliferate, and farmers may come into contact (simultaneously or serially) with efforts in, e.g., participatory plant breeding, group formation for fodder crop nurseries, and an FFS for IPM.

When there is evidence of at least modest success at the pilot stage, the next step is often to call for "scaling-up." This is a particularly imprecise term which usually does not define exactly what is expected (policy change, project replication, investment in an extension effort, developing new organizations), and is instead a symptom of poor planning in agricultural development assistance. There is also the problem of basing projects on attractive slogans or fads, rather than supporting long-term, pragmatic efforts that take advantage of a wide range of technology and approaches (Tittonell and Giller, 2013; Krupnik et al., 2012). It is crucial that governments and development agencies move away from piecemeal strategies. In addition, the exceptionally spotty record on actual outcomes of LEIT projects is related to a more general lack of attention to monitoring and evaluation by agricultural development organizations (Haddad et al., 2010). Increased investment in data collection and analysis would contribute to more realistic and efficient management of agricultural development projects.

There is a need to think about institutions that allow more effective farmer demand, and mechanisms that are more efficient in facilitating access to information and advice. Although LEIT projects pride themselves on promoting "demand-driven" technology development, most are short-term expressions of particular donor priorities. More truly demand-driven activity will only come in response to effective political pressure from well-organized farmers. We have seen that most farmer groups promoted by LEIT projects are too narrowly focused to have any chance of a sustainable existence or widespread support. Developing strong, broad-based farmer organizations that can exert pressure for more effective public research and extension will have higher payoffs than small-group activity in response to a brief donor-driven project. There is a growing consensus that farmer organizations are a vital element for rural development (Markelova et al., 2009), but heightened expectations and donors' desire to provide external assistance should be tempered by a realistic assessment of the challenges of sustainable farmer organization

Farmer organizations will only be viable if they address major issues of concern to their members. It is important to recognize that although access to technology may be one of these, it is unlikely that technology generation, on its own, will be the basis of a significant growth in viable organizations. Most successful farmer organizations address the economic or political priorities of their members. For households with less participation in agricultural markets, other types of rural organization may be called for, but institutions that promote farmers' voices and interaction can provide incentives that direct participants' attention to agricultural innovation. Organizations need to offer as many advantages to farmers as possible, in order to elicit commitment and offer opportunities for varying levels of participation.

It is easy to overestimate the importance of technology generation as a basis for the development of farmer organizations. Such organizations are only likely to invest in technological innovation when there are good returns to farming. Rural diversity can be an additional impediment; members of peasant organizations in highland Ecuador were sometimes divided by political considerations and economic realities between strategies that emphasized traditional practices and those that promoted external inputs (Bebbington et al., 1993). In addition, we must recognize that political organization in support of agriculture does not necessarily come from the grassroots; many of India's most prominent farmers' organizations represent an elite of larger farmers interested in access to subsidized technology (Brass, 1995).

Despite these limitations, strong farmers' organizations and other robust examples of rural civil society are necessary to generate sufficient demand for technology development. On the other side of the equation, public agricultural research and extension must be guided by clear policies on rural development, and must have the skills and resources to respond to farmers' requirements. Rural organizations will provide many opportunities for social learning and the development and transmission of information about new technology, but this is not sufficient. Other sources of information and debate such as newspapers and FM radio offer opportunities for discussion of the breadth of issues affecting rural residents. Media at its best can enlist the interest and attention of the diversity of households that should be able to take advantage of agricultural innovations. Finally, efficient and transparent input and output markets must be able to provide the information that farmers require.

CONCLUSIONS

This review of the experience of promoting LEIT, which is sometimes seen as a radically alternative path for agricultural development, has found patterns of success and failure that are remarkably similar to those of other technology-based development efforts. This analysis is not designed to debate the philosophical or political roots of some of the strategies that favor LEIT, but there is little evidence that this class of technology, on its own, is sufficient to improve productivity or to address rural inequality. A more integrative approach is preferable that takes full advantage of the contributions of LEIT, but recognizes a much wider range of technologies and methods that can contribute to sustainable agricultural development. Regardless of orientation, many of our efforts at improving the welfare of resource-poor farmers face similar challenges, and are presumably amenable to similar improvements of focus and purpose to make them more effective.

The adoption of agricultural technology often depends to a considerable extent on labor resources. Farmers deploy additional labor when they see that the returns are sufficient, although increasingly, even on very small holdings, much of that labor is hired, indicating that labor is now often an external resource purchased on the market. The use of hired labor is an indication of the diverse livelihoods of many rural households; some of these can balance on- and off-farm labor, while others may end in an exit from farming. This diversity of income sources also helps explain the diversity of interest in new technology in supposedly homogeneous farming communities. The adoption of new technology also requires knowledge, and farmers' incentives for developing that knowledge are varied. Methods such as social learning are often quite effective for introducing new technology, but farmers require time, and hence adequate incentives, to participate. Project-led group formation may help develop new knowledge, but there is rarely motivation for maintaining narrowly focused groups. There must be ways of diffusing new knowledge to a larger audience of farmers.

The reorientation of development strategies suggested by this review includes: (1) a careful examination of the heterogeneity of the countryside and the attendant diversity of incentives for acquiring new technology, and (2) reconsideration of development assistance strategies based on pilot projects and vaguely defined scaling-up strategies.

There is not one type of "resource-poor farmer," but many, requiring a differentiated strategy. Some are already participating in agricultural markets or have the potential to do so, and often have strong motivation to acquire new farming techniques. Others are balancing several, often insecure, sources of income with subsistence farming, and although their environmental footprint and household food insecurity argues for the provision of low-input technology, these households' attention is more difficult to capture. Many other rural households have so few agricultural resources that assistance should be directed toward the development of alternative sources of livelihood. A substitution of realism for romanticism in agricultural development must be accompanied by more responsible and coordinated programs, integrated with policy. An endless number of small donor-funded or government projects, even if based on imaginative techniques that involve farmers in technology generation, is not going to promote meaningful technological change. More investment is required in modalities such as broad-based rural organizations and other means of rural communication that allow farmers to exert more political pressure on both public and private technology providers.

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Chapter 7

Ecologically Based Nutrient Management

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NUTRIENT MANAGEMENT AS APPLIED ECOLOGY

Ecologically based nutrient management is an integrated approach that applies ecological knowledge to optimize soil fertility, crop production, ecosystem services, and long-term sustainability. In particular, ecological nutrient management applies concepts from community and ecosystem ecology. An *ecosystem* is a dynamic complex of organisms, and the physical environment with which they interact. An *agroecosystem* is simply an ecosystem which is managed to achieve agricultural outcomes, including the production of food, fodder, and fiber. Application of an ecosystem framework provides agriculturalists with a flexible systems approach that can be used to organize the complex, dynamic interactions between organisms and their environment that ultimately govern nutrient dynamics and crop yields. *Ecosystem functions* are processes such as nutrient cycling, water and energy flows, soil retention, and primary production or crop yield that result from complex interactions among living and nonliving ecosystem components (i.e., plants, decomposers, climate, soil environment, etc.). When we are considering ecosystem functions and their benefits to human wellbeing, we refer to them as *ecosystem services*, in order to emphasize their value to humans.

In applying principles and concepts from ecology, the scope of nutrient management is expanded to include a wide range of soil nutrient reservoirs, soil organisms, and biogeochemical processes. For example, rather than focusing solely on soluble, inorganic plant-available pools, ecologically based nutrient management seeks to optimize organic and mineral soil reservoirs that are more efficiently retained in the soil, such as organic matter (OM) and sparingly soluble forms of phosphorus. This framework also expands the scope of management beyond the normal focus which is limited to crop nutrient uptake. Instead, efforts are directed toward managing

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organisms and nutrient cycling processes occurring at a variety of spatial and temporal scales, from the rhizosphere, to field and landscape scales. Integrated management of the full array of ecosystem processes that regulate the cycling of nutrients and carbon in soil can improve productivity, while also increasing nutrient use efficiency (NUE) and ecosystem services over the long-term.

In this chapter we will explain ecologically based nutrient management, and emphasize strategies that integrate management of nitrogen, phosphorus, and carbon. Nitrogen and phosphorus are the two nutrients that most commonly limit crop production in agroecosystems. Biological processes play major roles in regulating the cycling of N and P, and, for this reason, the fate of these nutrients is strongly linked to the flow of carbon. We will discuss strategies for managing N, P, and C cycling processes, giving particular attention to the role of C in influencing the fate of N and P. Although we emphasize these major nutrients, many of the concepts we discuss are widely applicable to the other macro and micronutrients important for plant growth. Because a basic understanding of these cycles is fundamental to ecological nutrient management, we will first briefly review the key features of these elemental cycles.

THE BASICS OF NUTRIENT CYCLING

To understand nutrient cycling we must consider distribution, fluxes, and the regulatory mechanisms that make up an elemental cycle. Nutrients move from one *compartment* or *pool* to another. *Reservoir* is another term commonly used to refer to stores of nutrients in the soil. A compartment is usually defined by physical boundaries, while distinct pools can exist within a single compartment. For example, the soil compartment has several distinct pools of N. Plant uptake of NO_3^- results in the movement of N from the soil compartment (or more specifically, from the inorganic soil pool) to plant biomass. The distribution of nutrients among compartments and pools in agroecosystems varies in terms of the absolute amounts, depending on soil, climate, biotic, and management factors.

We refer to the rate of transfer from one pool to another as a *flux*. The flux of nutrients is often framed in terms of *source/sink* transfers when we want to emphasize the role of a particular process in regulating nutrient flows. *Source* simply refers to the pool where the nutrient came from, whereas a *sink* is the pool actively taking up the nutrient. All fluxes are regulated by a process, which can be either *biotic* (controlled by living organisms, i.e., mineralization) or *abiotic* (controlled by chemical and/or physical mechanisms, i.e., precipitation). The flux from one pool to another often entails a chemical modification of the nutrient. The most common chemical modifications are organic/inorganic and oxidation/reduction reactions.

We use models to depict relationships between location, form, and transfer of nutrient cycles. These models can be adapted to represent nutrient cycling at any scale, with varying degrees of detail. An ecosystem can be divided up into very few compartments, i.e., the simplest nutrient cycle might only distinguish between plant and soil compartments. As more compartments and pools are added, the cycling model becomes more complex. To address nutrient flows at the landscape level, individual fields or farms and adjacent waterways would be the designated compartments. A very simple depiction of N flows is shown in Fig. 7.1A.

Only three compartments are shown, with two biologically mediated processes that control the flux of N from soil organic matter (SOM) into the inorganic pool (Flux A, mainly controlled by microorganisms), and then from the inorganic N pool to plant biomass (Flux B, regulated by the plant). If mineralization and plant assimilation are equal (N moving in and out of the inorganic N pool is the same), and if these two processes are the dominant fluxes regulating this pool, then the size of the inorganic N pool will remain a constant, even though NO_3^- is actually moving in and out. This situation is called a *steady state*. You can see that if we collected monthly soil samples and extracted inorganic N under steady state conditions, the NO_3^- pool will appear static since the concentration remains constant through time. We would miss the dynamics that are actually taking place, i.e., N is moving in and out of this pool. This is one of the difficulties in using static measurements of pool size as indicators of nutrient availability. The limitation of static measurements is particularly prominent when standing pools of

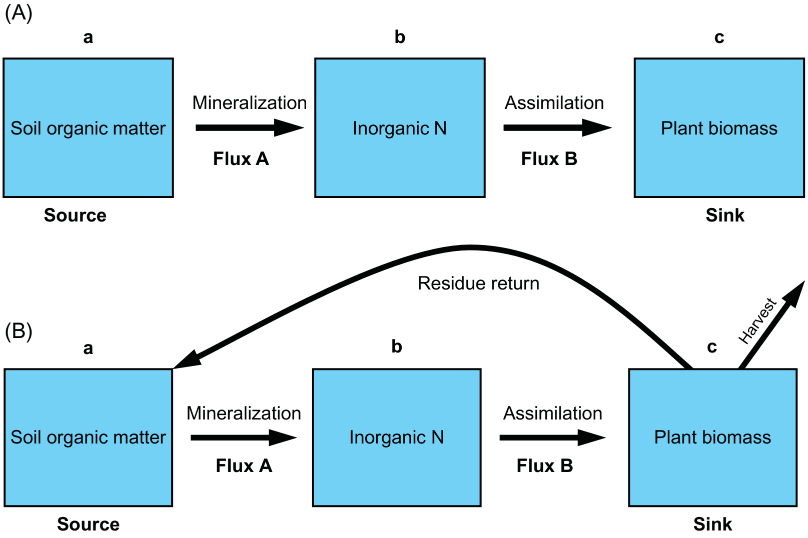


FIGURE 7.1 A simple model demonstrating the use of compartments and fluxes to depict nutrient flows. (A) Three compartments (a, b, and c) are shown with two biologically mediated fluxes. (B) The cycle is closed when plant residues are returned to the soil. Net export of N occurs through harvest.

inorganic N are very small. Small standing pools of NO_3^- are usually interpreted as an indicator of low N fertility. However, if plant assimilation is keeping up with mineralization, you can have a very large flux in a very small inorganic N pool. This is often the case in fields where organic residues have been used as nutrient sources for many years.

We can close the cycle in this simple model by adding two more fluxes (Fig. 7.1B). These two new processes are the result of human management. In this model, harvest removes the N from our agroecosystem, and we do not consider the fate of the harvested N which could be going to animals, and/or humans, and the N remaining in crop residues is left in the field to become part of the SOM. In this case, harvest is considered to be an *export*, since the harvested N leaves our system while the other three fluxes are part of the *internal* N cycle.

When developing nutrient management strategies, it is important to remember that the rates of different processes can vary by orders of magnitude. This impacts the distribution of nutrients among pools, and results in compartments with widely varying turnover times. Turnover time is defined as the time it will take to empty a reservoir if the source is cut off, and if sinks remain constant. In other words, fluxes out of the compartment continue but the influx is shut off. Understanding turnover time, and how to manipulate different pools of nutrients and OM over space and time, is at the foundation of ecologically based nutrient management, and will be the topic of this next section.

A useful way to compare the dynamics of different compartments is mean residence time, or the average amount of time a nutrient spends in the compartment before being transferred out. Mean residence time is calculated as the pool size/flux, assuming the pool is close to steady state conditions (i.e., in $\approx$ out). For example, to estimate the mean residence time of nitrous oxide in the atmosphere on a global basis we calculate the total size of the pool and then divide by the estimated global rate of production:

$[N_2O] = 300$ ppb, Total $N_2O = 2.3 \times 10^{15}$ g
Rate of production: 20×10^{12} g/year
MRT $= 2.3 \times 10^{15}$ g$/20 \times 10^{12}$ g/year $= 110$ years.

Both turnover time and mean residence time require detailed knowledge of fluxes and pool size that can be difficult to accurately measure in soils without the use of expensive tracer experiments. However, the mean residence time for important soil nutrient pools varies widely. For example, mean residence time for NO_3^- is about a day, while stabilized components of SOM have a mean residence time of hundreds to thousands of years (Tan, 2003). Given the huge difference in the temporal dynamics of these pools, it is not necessary to make measurements in your agroecosystems to apply these useful concepts. Estimates from the literature can be very helpful as a starting point.

Nitrogen Cycling

In unmanaged terrestrial ecosystems, the soil N cycle is driven by SOM, which contains approximately 50% C and 5% N, of which typically <5% is in labile forms. Available N normally enters ecosystems through biological N fixation, although during the past two centuries many unmanaged ecosystems also received anthropogenic N derived from fossil fuel burning and other human activities, through wet and dry deposition. In agroecosystems, large quantities of N are added as inorganic fertilizer or organic residues from biological N fixation and various soil amendments, such as compost or animal manure, also playing a major role in driving the N cycle. The breakdown, or depolymerization, of the large, complex molecules that make up organic residues is facilitated by extracellular enzymes secreted mainly by soil fungi and prokaryotes. With the exception of a few enzymes targeting phosphorus, such as phosphatase, plants do not release exoenzymes into the soil. As a result, plants are largely dependent on the primary decomposers to release nutrients from complex organic residues. Exoenzymes catalyze the release monomers, such as amino acids and sugars, which are small enough to be transported into cells by microbes and plants. These labile compounds are recycled and reused through microbial metabolism, faunal grazing of microbes, as well as the microbial death and damage that are caused by stress, such as wet−dry or freeze−thaw cycles (Schimel and Bennett, 2004; Fig. 7.2). Plants also contribute to internal cycling via root exudation of a diverse array of organic compounds which are decomposed, but can serve as signals to soil organisms (Bais et al., 2006).

Soil microorganisms play a dominant role in regulating soil N cycling. Mineralization occurs when heterotrophic microbes break down the nutrient rich organic monomers freed by exoenzymes and obtain energy, NH_4^+, and other nutrients. Ammonia can be assimilated by heterotrophs, or used as an energy source by ammonia-oxidizing microbes to produce nitrite (NO_2^-) that is quickly converted to NO_3^- (nitrification). During nitrification, some nitric oxide (NO) and nitrous oxide (N_2O) are also produced and lost from the soil (Godde and Conrad, 2000; Fig. 7.2). Alternatively, NH_4^+ can be lost from the soil through the emission of ammonia (NH_3) gas if soil pH is greater than 8. Nitrate can be lost from the system through several processes. Denitrification is a metabolic process which takes place when heterotrophic bacteria under oxygen limitation use NO_3^- as an alternative electron acceptor to produce N_2O and N_2. The leaching of NO_3^-, which contaminates groundwater, occurs when rainfall exceeds evapotranspiration, especially in coarse-textured soils. Runoff also carries N in various forms to surface waters. A second anaerobic pathway that helps to retain NO_3^- in the soil involves the conversion of NO_3^- to NH_4^+ (dissimilatory nitrate reduction to ammonium or DNRA). This pathway can compete with denitrification, and can be the dominant dissimilatory reduction pathway in some tropical soils (Silver et al., 2001).

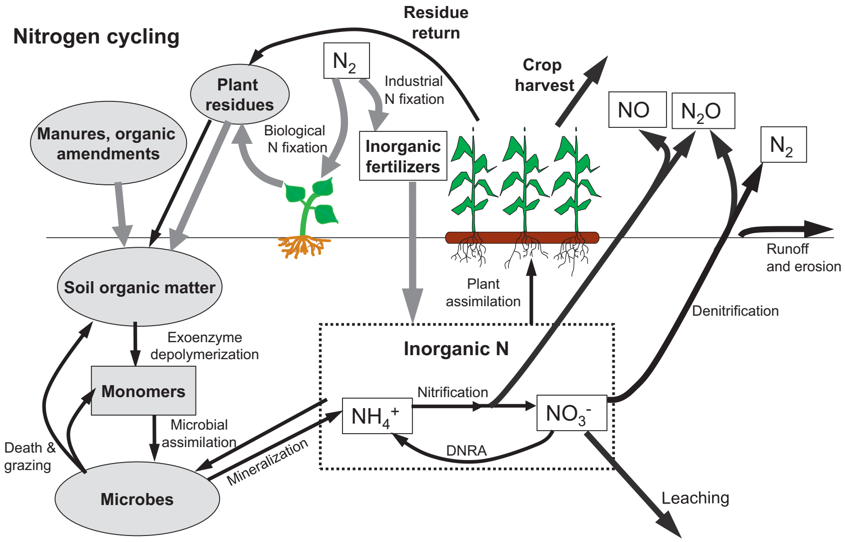


FIGURE 7.2 Nitrogen cycling in agroecosystems. See text for full discussion of cycling processes. New N is added through biological N fixation, synthetic fertilizers or organic amendments such as manure or compost (*gray arrows*). The main pathways of removal are through harvested exports, leaching, and denitrification (*thick black arrows*). Some gaseous losses also result from nitrification during the conversion of ammonium to nitrate (*thick black arrows*). Internal cycling processes occur through human management of residues, plant assimilation, and microbially-mediated transformations (*thin black arrows*).

Phosphorus Cycling

While N transformations are primarily controlled by microbially mediated processes, the soil P cycle is regulated by both biological and geochemical processes that compete with one another for the small amounts of soluble, inorganic P which are typically present in the soil solution (Cross and Schlesinger, 1995). A second major distinction shaping the P cycle is that it cannot be converted into gaseous forms that can be lost from the system. For convenience, the P cycle is portrayed as consisting of two subcycles reflecting the abiotic and biotic mechanisms (Fig. 7.3). The geochemical and biological subcycles are composed of processes that are distinct from one another, with the exception of the weathering of primary minerals, which is mediated by both biological and geochemical mechanisms (Schlesinger, 2005). Biological weathering occurs at rates many times faster compared to abiotic weathering processes. The biological transformations involving P are fewer compared to N, and begin with reactions mediated by exoenzymes that release P. Phosphorus mineralization is the microbial conversion of organic P to orthophosphates ($H_2PO_4^-$ or $H_2PO_4^{-2}$, depending on soil pH) which can, in turn, be assimilated by either plants or microorganisms.

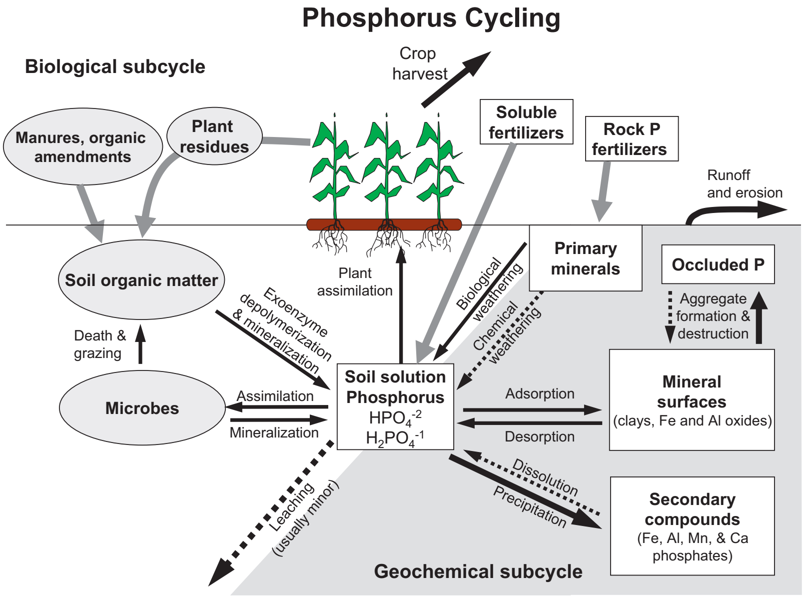


FIGURE 7.3 The phosphorus cycle consists of biological and geochemical subcycles. See text for full discussion of cycling processes. New P is added through soluble synthetic fertilizers, sparingly soluble amendments, such as rock P, or organic amendments such as manure or compost (*gray arrows*). The main pathways of removal are through harvested exports, erosion, occlusion, precipitation, with small losses occurring through leaching in some systems (*thick black arrows*). Internal cycling processes occur through human management of residues, plant assimilation, microbially-mediated transformations, and geochemical processes (*thin black arrows*). Dotted arrows indicate processes with smaller fluxes.

The microbial P will become available over time as the microbes die or are grazed. As with N, SOM and newly added organic residues can serve as an important source of P.

The geochemically mediated sinks for orthophosphates compete with biological assimilation and include two types of inorganic reactions; these are precipitation–dissolution and sorption–desorption processes. Precipitation–dissolution reactions involve the formation and dissolving of precipitates. Precipitation reactions occur with dissolved iron, aluminum, manganese (acid soils), or calcium (alkaline soils) to form phosphate minerals. The rate of dissolution is negligible for these precipitates, with the exception of the calcium phosphates. Calcium phosphates, such as apatite, account for 95% of P found in primary minerals of the earth's crust, and are commonly referred to as *sparingly soluble P*, since these minerals can be dissolved by chemical and biological weathering. Apatite is the primary constituent of rock P, which can be added to infertile soils as a slow source of P. Sorption–desorption reactions involve sorption and desorption of ions and molecules at the surfaces of mineral particles. Adsorption is a reversible chemical binding of P to soil particles. In some soils, adsorbed phosphate may become trapped on the surface of soil minerals when a Fe or Al oxide coating is formed on the mineral. The trapped phosphate is then described as being occluded. For all practical purposes, P that becomes occluded is no longer agronomically relevant.

Carbon Cycling

All biologically mediated cycling processes are dependent on C, either for energy or as the backbone of biomolecules that must be synthesized for life to exist. SOM is defined as all carbon-containing soil constituents, and is therefore the major biologically relevant soil reservoir for N and P in most arable soils. Because SOM is the result of all life, the biochemistry of SOM constituents is complex, reflecting the diverse array of compounds produced by plants, microbes, and larger soil organisms. The chemical composition and the accessibility of SOM to decomposing organisms (i.e., the actual size of the SOM and whether or not it is protected by soil minerals through occlusion or surface interactions) regulate the rate of decomposition with the former, being more important in the early stages of decomposition, and the latter, exerting more influence later in the process (von Lutzow et al., 2006). For practical purposes, SOM is conceptualized as a series of pools with varying flux rates that reflect differences in chemical composition and the degree of physical accessibility to microorganisms (Fig. 7.4). Decomposition of SOM is mediated primarily by bacteria and fungi, who release the majority of the C as CO_2 via respiration while incorporating a small portion of the C into cellular structures through biosynthesis (growth and reproduction). Growth, reproduction, and death, combined with interactions among soil organisms as part of the soil food web such as grazing, predation, and parasitism, regulate the flow of C and accompanying nutrients such as N, P, and other elements present in living organisms.

The bulk of SOM has rather long mean residence times, ranging from 250 to 1900 years; clearly beyond the time frame of planning for most agricultural settings. This SOM, referred to as the “stabilized fraction,” has long been the source of much controversy in terms of the actual chemical constituents and the mechanism of stabilization. Recently, extraction methods involving stepwise digestion which were used to study SOM composition for the past 100 years have been replaced by technologies which can discern the molecular structure of organic residues in situ. These approaches have revealed that humic substances (i.e., humic and fulvic acids), which were once thought to dominate the stable fraction, are actually present in soils in very limited quantities. This work, along with studies using ^{13}C labeling to trace turnover times of various SOM constituents, has resulted in significant changes in our understanding of the mechanisms than enable organic resides to persist in soils, as well as the chemical composition of this stable fraction

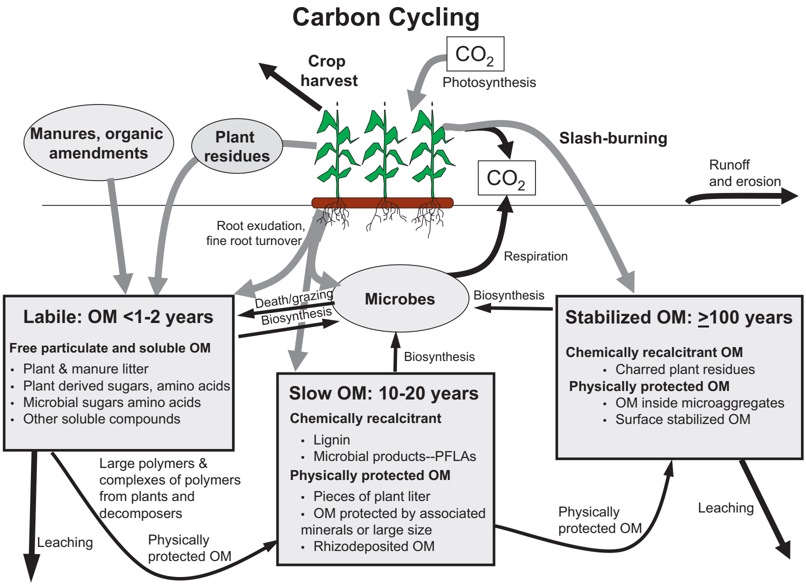
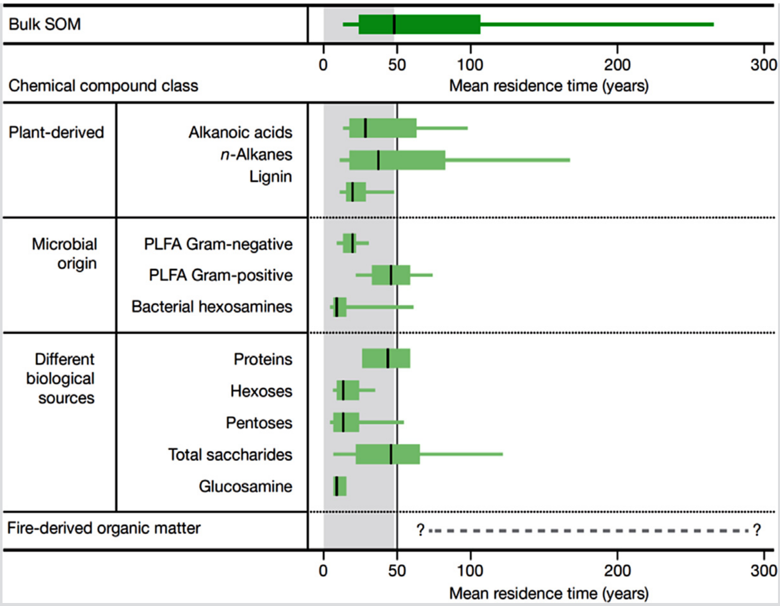


FIGURE 7.4 Carbon cycling in agroecosystems. See text for full discussion of cycling processes. The level of soil organic matter (OM) is determined by the balance between photosynthesis or new OM additions and decomposition. Decomposition encompasses two distinct processes that reflect the dual function of C: (1) respiration (energy), and (2) biosynthesis (growth and reproduction). Biosynthesis results in C from the various substrates actually being incorporated into microbial biomass, while respiration results in the release of CO_2 into the atmosphere. In this diagram we separate out OM pools based on their approximate rates of turnover. The stable OM pool is by far the largest, usually accounting for $>80\%$ of soil OM. The only route to stabilized OM that is directly under management control is through charcoal production. The vast majority of OM in the stabilized pool has undergone some form of microbial processing, and some of it has cycled through other trophic levels of the soil food web (i.e., grazers that feed on bacteria). In addition to the biological processes of respiration/biosynthesis, there are abiotic mechanisms which contribute to the stabilization of OM including adsorption, adventitious chemical reactions, and physiochemical interactions between clay particles and organic compounds that end up physically protecting these compounds making them inaccessible to decomposers or exoenzymes (von Lutzow et al., 2006; Schmidt et al., 2011). Thus, initially the rate of OM composition is controlled by the lability/recalcitrance of the compound. Some form of physical protection is required for OM to become stabilized in the soil for 100 years or more. Aggregate formation, which results in occluded OM, is mediated by both soil organisms and abiotic processes.

(Schmidt et al., 2011). During decomposition of plant biomass in incubation experiments, some plant-derived compounds (classically, long-chain alkanoic acids, *n*-alkanes, lignin, and other structural tissues) often persist longer than others. This led to the idea that chemically recalcitrant compounds such as these would persist in soils, while decomposers rapidly consumed labile compounds such as proteins and sugars. However, the newer methods show that in mineral soil the importance of chemical composition decreases over time, so that the initially fast-cycling compounds are just as likely to persist as the slower cycling molecules (Table 7.1; Schmidt et al., 2011). Thus, we now understand that physical protection is the primary driving force in stabilizing organic compounds in soil over the long-term. This is contrary to the long held view that chemical recalcitrance is a key factor in determining how long organic substrates persist in soils. Instead, mechanisms such as aggregate formation and adsorption to mineral particles play a key role in OM stabilization. Furthermore, due to this shift in mechanisms leading to longevity, it is clear that the stable fraction is composed of smaller organic compounds that persist simply because they cannot be accessed by decomposers. Lignin is relatively short-lived in soil compared to polysaccharides, which are "sticky" and are intimately associated with mineral soil particles, and most soils do not have a significant "humus" fraction. This stabilized

TABLE 7.1 Molecular Structure Does Not Control Long-Term Decomposition of Soil Organic Matter (SOM)



This table compiles data from surface horizons of 20 long-term field experiments (up to 23 years) in a temperate climate, using ^{13}C labeling to trace the residence time of bulk SOM and of individual molecular compounds. The variation in turnover time is also seen in the compounds of microbial origin, including phospholipid fatty acids (PLFA) produced by Gram-negative and Gram-positive bacteria and amino sugars (hexosamines).
Source: Schmidt et al. (2011). Used with permission

pool represents a sizable N reservoir, and the elemental composition of stable SOM is fairly consistent across soil types and climatic zones, with C and N contents of 50–60% and 2–4%, respectively (Tan, 2003).

A smaller, but more active SOM fraction that responds to agricultural management within shorter time durations (1–10 years) is particulate OM. Particulate OM refers to pieces of plant residues, including roots and shoots, that are the size of sand (53 um to 2 mm) and have mean residence times ranging from a single growing season to 10–20 years. Particulate OM can serve as a significant source of nutrients, and also plays a key role in aggregation in some soils. Lastly, the soil microbial biomass is not only important for its decomposing function, but also serves as a labile pool of nutrients. The amount of N and P in soil prokaryotes is nearly equal to the amount in terrestrial plants (Whitman et al., 1998). For cultivated systems, the estimated N and P in soil bacteria amounts to an average of 630 and 60 kg/ha, respectively, in the first meter of soil (Whitman et al., 1998).

APPLYING AN ECOLOGICAL NUTRIENT MANAGEMENT STRATEGY

The plethora of processes controlling the cycling of nutrients in agroecosystems presents ample opportunities for enhancing the flows of N, P, and C. The over-arching strategy guiding ecosystem-based nutrient management is distinct from the conventional approach that has focused primarily on fertilizer management for the past 50 years. Table 7.2 compares the two management schemes. The underlying theory guiding conventional nutrient management emphasizes developing optimum delivery systems for soluble inorganic fertilizers, and managing the crop to create a strong sink for fertilizer by removing all other growth limiting factors. The primary difficulty with this strategy is that soluble inorganic forms of N and P are fast cycling and are subject to multiple pathways of loss. As you might predict, based on the nutrient cycling diagrams, when the pool of soluble inorganic N or P is greatly increased, undesirable fluxes also increase, and a proportion of these added nutrients is lost. So, while this approach has resulted in greater yields, it has also resulted in poor NUE, and major losses of fertilizers to the environment are widespread (Drinkwater and Snapp, 2007a). Soil degradation is also a secondary consequence of these intensive, fertilizer-driven cropping systems, mainly due to the use of intensive tillage combined with reduced inputs of organic residues and bare fallows.

Ecological nutrient management seeks to harness soil processes that foster internal cycling and retention of nutrients, while reducing those that contribute to nutrient loss and soil degradation. Ecological nutrient management is a multifaceted approach that aims to achieve optimal yields, balance nutrient exports with additions, maintain soil nutrient reservoirs, and minimize losses of nutrients and soil to the environment. In agroecosystems with

TABLE 7.2 Characteristics of the Conventional Agronomic Approach (Balasubramanian et al., 2004; Cassman et al., 2002) Compared to an Ecosystem-Based Approach to Nutrient Management

	Agronomic Framework	Ecological Framework
Goals	Maximize crop uptake of applied N, P to achieve yield goal and reduce environmental losses	Achieve optimal yields and maintain soil reservoirs while balancing nutrient additions and exports as much as possible
Nutrient management strategy	Manage crop to create a strong sink for fertilizer by removing all growth limiting factors and by providing an optimum delivery system (Balasubramanian et al., 2004)	Manage agroecosystem to increase internal cycling capacity to: (1) maintain nutrient pools that can be accessed through plant- and microbially mediated processes; and (2) conserve N and P by creating multiple sinks in time and space
Nutrient pools actively managed	Inorganic N and P	All N and P pools, organic, and inorganic
Processes targeted by nutrient management	Crop uptake of N and P	Plant and microbial assimilation of N and P, C cycling, N, P, and C storage, other desirable processes that conserve nutrients
Strategy toward microbially-mediated N transformations	Eliminate or inhibit as much as possible	Promote processes that conserve N, reduce processes that lead to losses (i.e., denitrification) by maintaining small inorganic N and P pools
Strategies for reducing NO_3 leaching, P occlusion/ precipitation	Increase crop uptake of added N, use chemicals that inhibit nitrification	Minimize inorganic pool sizes through management of multiple processes: cover cropping, additions of N and P with organic residues
Assessment of NUE	Based on fertilizer uptake of the crop in one growing season	Based in budgeting framework, reflect agroecosystem level retention, multiyear
Typical experimental approaches	Short-term, small-plot, empirical, factorial experiments dominate	Participatory, systems approaches, on-farm research is important, spatial and temporal scales of experiments are determined by the processes of interest

Modified from Drinkwater and Snapp, 2007b.

poor or degraded soils, an additional goal is to restore soil fertility and agroecosystem functions.

To implement this comprehensive set of goals, ecological nutrient management must target a variety of nutrient reservoirs and cycling processes. The basic strategy is to conserve or even enhance nutrient pools that can be accessed through plant- and microbially mediated processes by creating sinks for inorganic N and P that will promote nutrient retention and internal cycling of nutrients. The nutrient reservoirs that are targeted include labile and stabilized SOM, microbial biomass, and sparingly soluble P. Management aims to promote processes that conserve these pools, while minimizing those that lead to nutrient losses. For example, practices that encourage plant and microbial assimilation of N and P, and other processes leading to N and P storage such as aggregate formation, are favored. While flux through the inorganic N and P pools may be very large in these systems, a central objective of this strategy is to reduce the size of these pools that are the most susceptible to loss. Examples of management practices that contribute to these outcomes include diversifying crop rotations and nutrient sources, cover cropping and intercropping, and legume intensification. The particular suite of cropping practices used are site specific, and reflect the environmental characteristics of the agroecosystem (climate and soils), the crops that are being grown, resources available to the farmer, and the livelihood goals of the household.

THE ROLE OF PLANTS AND MICROORGANISMS IN CYCLING NUTRIENTS

Cycling Processes Influenced by Plants

Effective use of plant diversity in agroecosystems requires some understanding of the roles played by different crop species in nutrient cycling. Plants and their associated microbes regulate ecosystem processes which ultimately control C, N, and P cycling (Hooper and Vitousek, 1997). Intentional use of plant diversity based on the capacity of a species to enhance particular ecosystem processes is an important strategy in ecological nutrient management. Agroecosystem plant species diversity can be increased, either by introducing additional cash crops or noncash crops (i.e., cover crops, intercrops) selected to serve specific ecosystem functions.

The most easily defined plant functional roles are those relating to phenology, productive potential, and above- and below-ground architecture. *Phenology* refers to plant life-cycle characteristics such as germination, growth, flowering, and reproduction, that are controlled by climatic conditions and seasons. For example, the functional role of legumes varies with phenology (Fig. 7.5). Many legume species used for grain production are short duration annuals, with determinant flowering, and a high harvest index

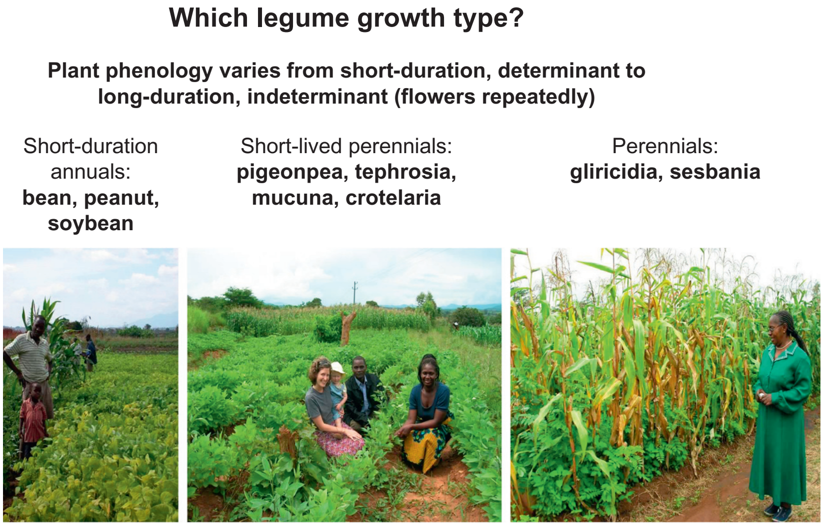


FIGURE 7.5 Examples of legumes with differing phenology. Legumes can be integrated into cropping systems using a number of different strategies, depending on their life-cycle.

(proportion of above-ground biomass that is harvestable product). Green manure legume species are at the other end of the spectrum. They provide large amounts of nutrient-rich residues, and are generally short or long-lived perennials, with indeterminant flowering and low-to-zero harvest index. Differences in the seasonal niche of plants can be used to expand the amount of time a field is covered with actively growing plants, increasing nutrient uptake in space and time, and reducing nutrient losses (McCracken et al., 1994; Snapp and Silim, 2002). Increased plant growth has cascading effects on internal cycling processes in agroecosystems. For example, if bare fallow periods are replaced with a cover crop, rhizodeposition provides C to the soil microbial community for a greater part of the year, increasing the potential for assimilation of nutrients into the microbial biomass (Drinkwater et al., 1998). The tremendous variation among plant genotypes in root/shoot partitioning and root architecture can be exploited to complement cash crop characteristics and optimize plant-mediated processes below-ground. For example, root biomass makes greater contributions to SOM than shoots, which tend to decompose more rapidly (Puget et al., 2000).

Plant species characteristics, such as biochemical composition of litter and root exudates, fine root turnover, and the characteristics of the rhizosphere environment, influence ecosystem function through their impact on processes related to decomposition, such as net mineralization of nutrients, aggregate formation, and stabilization of OM. Striking plant species effects have been documented for decomposition dynamics and net mineralization of N and P (Wedin and Tilman, 1990; Fierer et al., 2001), aggregate formation (Tisdall and Oades, 1979; Angers and Mehuys, 1989; Haynes and Beare, 1997), availability of nutrients such as Ca, Mg, and P from mineral sources (Marschner and Dell, 1994; Johnson et al., 1997; Neumann and Roemheld, 1999; Kamh et al., 1999), and microbial community composition (Kennedy, 1999). Many of these observed plant species impacts on nutrient cycling processes are actually mediated by microorganisms associated with the roots.

Beyond the particular impacts associated with particular plant functional groups or species, there is evidence that increasing plant diversity, intercropping, or diverse rotations (those adding one or more crops in rotation to a monoculture) increases total soil C and N (Gardner and Drinkwater, 2009; McDaniel et al., 2014; Cong et al., 2015). When rotations were diversified by adding cover crops, total C increased by 8.5%, and total N 12.8% (McDaniel et al., 2014; 122 publications). In addition to these impacts on nutrient cycling, plant biodiversity can also enhance disease suppression (Abawi and Widmer, 2000), reduce weed competition and herbicide requirements (Gallandt et al., 1999), and foster beneficial arthropod communities (Lewis et al., 1997). Inclusion of all of these functions is integral to agroecological management of crop production. One useful approach is to compile information on the functional traits of potential cover crops (Table 7.3). Decisions about rotation and intercropping that impact plant species composition can contribute to reducing the need for agrochemical inputs (Drinkwater and Snapp, 2007a,b).

Plant–microbial Interactions

While plants themselves can directly impact biogeochemical processes through nutrient assimilation and the quantity and quality of litter and root exudates, many influences on nutrient cycling are the result of plant–microbial interactions. The *rhizosphere* is the region of soil that is immediately adjacent to the plant root, and is the site of plant–microbial interactions (Fig. 7.6). The importance and extent of plant–microbial interactions that take place in this microenvironment has not been fully appreciated in the past (Drinkwater and Snapp, 2007b).

Mycorrhizal Fungi

Arbuscular mycorrhizae (AM) fungi, which are endosymbionts, are the most important fungal symbiont in agroecosystems. Plant–mycorrhizal associations are the major mechanism for phosphorus uptake in over 80% of plant species. Colonization of roots by mycorrhizal fungi provides the plant with a well-distributed and extensive absorbing system in soil, and a greater chance of encountering fertile microsites not available to roots alone. The ability of mycorrhizal fungi to access small soil pores (Drew et al., 2003), and their

TABLE 7.3 Example of Cover Crop Functions That Can Be Evaluated.

Forbs		Legumes					Grasses			
	Brassicas	**Bell Beans**	**Medics**	**Rose Clover**	**Strawberry Clover**	**Vetches**	**Barley**	**Oats**	**Orchard Grass**	**Tall Fescue**
Function										
Adds N to soil		X	X	X	X	X				
N retention	**X**						**X**	**X**	**X**	**X**
Erosion control	**X**			**X**			**X**	**X**	**X**	**X**
Weed suppression			**X**						**X**	**X**
Improves soil structure and water infiltration							**X**	**X**	**X**	**X**
Inhibits nematodes	**X**			**X**						
Attracts beneficial insects	**X**					**X**	**X**	**X**	**X**	**X**
Opens up heavy soils	**X**	**X**								

Note that the legumes supply new soil N while Brassicas and grasses excel at N retention. This is a simple yes (X) or no (blank) assessment, however, a more detailed evaluation could provide a ranking or some other more quantitative information.
Source: Modified from Eviner, V.T., Chapin, F.S., 2001. Plant species provide vital ecosystem functions for sustainable agriculture, rangeland management and restoration. California Agr. 55, 54–59 (Eviner and Chapin, 2001).

ability to quickly respond to localized nutrient patches (Tibbett, 2000; Cavagnaro et al., 2005), increases the plant's access to these nutrients. This is of particular significance in soils of low nutrient status, and for immobile nutrients, such as NH_4^+ and PO_4 (Ames et al., 1983; Menge, 1983; Hetrick, 1991). Also, under drought stress, the role of mycorrhizal uptake of NO_3^- becomes more important since the NO_3^- supply to the roots via mass flow is reduced (Nichols et al., 1985). The N uptake mechanisms are largely unknown, but NH_4^+ is preferentially used. For example, corn plants colonized by *Glomus aggregatum* took up to 10 times more N from a $^{15}NH_4^+$ patch than from a $^{15}NO_3^-$ patch (Tanaka and Yano, 2005). While AM fungi increase the recovery of ^{15}N from decomposing plant residues in soil, it is unclear how much they rely on organic N, or if they accelerate OM decomposition (Hodge, 2004).

Background soil fertility and species diversity can influence the role of mycorrhizal contribution to nutrient cycling in agroecosystems. The species type and extent of mycorrhizal diversity can greatly influence nutrient uptake efficiency, ecosystem function, and NPP (van der Heijden et al., 1998). Under the nutrient-rich conditions that occur in industrialized agricultural systems, formation of mycorrhizal associations may become a cost to the plant, as the plant is able to satisfy its own nutrient requirements (Johnson et al., 1997). Agricultural production practices appear to have inadvertently reduced diversity, function, and efficiency in plant – mycorrhizal symbiosis (Daniell et al., 2001). In a meta-analysis of AM and ectomycorrhizal studies, colonization generally declined in response to N and P fertilization, although N effects on AM abundance were less strong than those for P (Treseder, 2004). One explanation is that mycorrhizae may be less important in

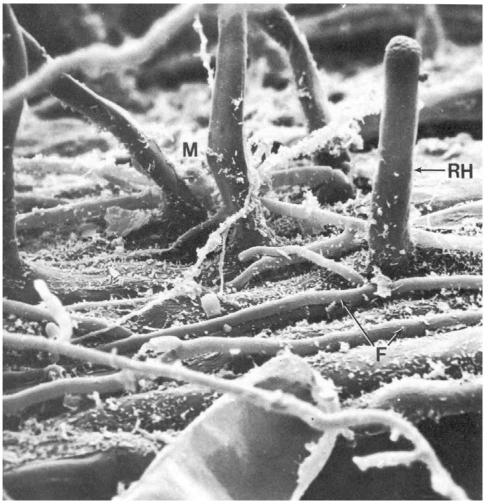


FIGURE 7.6 Electron micrograph of the root surface. Dense bacterial colonization can be seen on the root surface as well as fungal hyphae (F), root hairs (RH), and mucigel (M) from root exudates. *From Foster, R.C., Rovira, A. D., Cook, T.W., 1983. Ultrastructure of the Root-Soil Interface. American Phytopathological Society St. Paul, MN, 157 p Foster et al. (1983).*

facilitating plant uptake of NO_3^-, due its availability via mass flow, except in very N-limited ecosystems. In an organic farming system, a mycorrhiza-defective tomato mutant had 12% lower N content than the mycorrhizal wild-type, and there was more soil NO_3^- as well (Cavagnaro et al., 2006), indicating that AM are important in farming systems where fungicides and P fertilizers are not used. Manipulation of mycorrhizal populations to develop more efficient plant–symbiont combinations is in its infancy, but strategies that can be pursued include use of sparingly soluble rock P, reduced tillage, and integration of auxiliary plants that are highly mycorrhizal.

Biological N Fixation

Plants lack enzymes that can convert N_2 gas into a usable form and, as a result, most plants in natural ecosystems rely on the N released via microbial decomposition of SOM. Some bacteria, known as *diazotrophs*, do produce the enzyme nitrogenase that catalyzes the reduction of N_2 into NH_3, a plant available form of N. This microbially mediated process is referred to as biological nitrogen fixation (BNF). Because N_2 is a stable molecule with a strong triple bond, BNF is an energy intensive process. Carbon is the primary energy source for the range of different types of bacteria, called diazotrophs, which carry out BNF. The high energy demand of BNF may explain why it is not more universally found in plant–microbe associations, and why N cycling in natural ecosystems is driven primarily by the recycling of previously fixed N through mineralization and immobilization of N from OM pools. Globally, BNF in unmanaged ecosystems is estimated to convert about 150 Tg of N_2 gas into plant-available N every year (Vitousek et al., 1997). In managed ecosystems, only an estimated 33 Tg N/year of nitrogen is fixed by cultivated legumes, while more than 100 Tg N/year is fixed nonbiologically through the fossil-fuel based production of synthetic nitrogen fertilizers (Galloway et al., 2003).

Diazotrophs and plants have evolved different degrees of association that facilitate the transfer of photosynthetically derived carbon from plant to bacteria to support BNF. Most diazotrophs are heterotrophic, and rely on plant-derived carbon to support BNF. Symbiotic diazotrophs that fix nitrogen within nodules of leguminous plants are the most familiar example of BNF, and are typically referred to collectively as rhizobia (Fig. 7.7). In most cases, the legume–rhizobia symbiosis is highly specific. Complex chemical signaling has evolved between legume species and specific rhizobial strains to initiate nodule formation. Symbiotic rhizobia in the nodule receive a direct supply of C in exchange for N-fixation for plant growth. The nodule provides physical protection for the rhizobia, while increasing the capture of the fixed N by the plant.

More recent work has identified numerous other diazotrophs that are associated with plant roots, either externally or internally within intracellular root

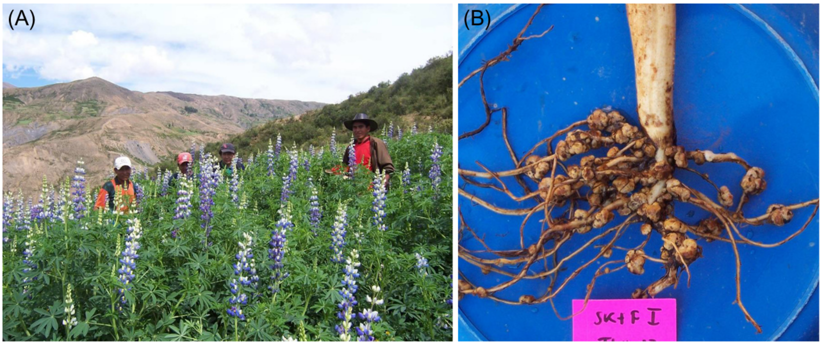


FIGURE 7.7 Leguminous plants are important in cropping systems worldwide. (A) In the Potosi region of Bolivia, Tarwi (*Lupinus mutabilis* Sweet) is a multipurpose legume that serves as a fertility source and grain crop. (B) The root nodules on Tarwi are large and numerous.

spaces. These associative diazotrophs utilize labile carbon root exudates as an energy source to support BNF. The plant has less control over the fate of the fixed N in this situation, compared with the N fixed within a root nodule. The N fixed by associative diazotrophs is incorporated into the bacterial biomass. This N becomes available for plant uptake when grazers feed on these bacteria, and trophic interactions in the rhizosphere food web result in a net N release (Clarholm, 1985). Due to the rapid turnover of microbial biomass in comparison with the much longer life-cycle of the plant, significant quantities of associatively fixed N end up in the associated plant (Ladha and Reddy, 2003). Some free-living diazotrophs, such as cyanobacteria, are autotrophs, and they are capable of both fixing carbon via photosynthesis and fixing N via BNF. Many cyanobacteria, in spite of their relative self-sufficiency, form symbiotic partnerships with plants, and the plants again are eventually the beneficiaries of the fixed N (Yoneyama et al., 1987).

The ecology of BNF is complex, and many things must be considered to optimize this valuable process. For example, at the field scale BNF is regulated by interactions between plant species, climate, and soil type. Similarly, at microscales, BNF is regulated by plant−microbe−microsite environmental interactions. The complexity of the ecology of BNF is reflected in the high variability found in BNF rates in natural and agroecosystems (Ojiem et al., 2007; Walley et al., 2001). The soil environment exerts influence on BNF through direct and indirect effects on the plants and microorganisms involved in N fixation. High soil temperatures (>27−40°C), water stress, soil acidity ($\text{pH} < 5$), low soil P availability, and Al toxicity—all common conditions in certain tropical systems with highly weathered soils—can limit rhizobial growth and nitrogenase activity (Hungria and Vargas, 2000; Graham and Vance, 2003). The availability of molybdenum (Mo), a key component of the nitrogenase enzyme, can also be an important limiting factor in BNF in some soils (O'Hara, 2001). Because BNF only supplies new N to agroecosystems while recycling other nutrients, integration with other soil amendments is critical to both the ability of the system to support the nutritional demands of BNF, and to maintain longer-term nutrient balances.

Nonsymbiotic N Fixation

Associative and free-living diazotrophs are commonly found in the rhizosphere of graminaceous species, such as rice, maize, sugar cane, and tropical pasture grasses. Field measurements of the contributions from associative and free-living diazotrophs reveal extreme variability, with contributions of 0–80 kg N/ha to crop growth (Bremer et al., 1995; Peoples et al., 2001; Table 7.3). With the rapid development of improved molecular methods, we are only beginning to scratch the surface of identifying the variety of diazotrophs responsible for fixing nitrogen in soils, and we still do not have methods that provide accurate measures of how much N free-living and associative diazotrophs are fixing in different agroecosystems (Buckley et al., 2007).

A promising area of biological N fixation research is in understanding the ecology and importance of associative N fixation with cereal species such as rice, maize, and sorghum. Watanabe et al. (1979) found that 80% of bacteria in rice roots are capable of fixing N. *Acetobacter*, a nonobligate diazotroph commonly found in sugar cane roots, can fix up to 150 kg N/ha per year (Boddey and Dobereiner, 1995). *Azospirillum* and *Herbaspirillum* are examples of diazotrophs commonly found associated with rice, sugar cane, maize, and sorghum roots. The amount of N fixed by these associative N-fixers has been highly debated, from a maximum of 5 kg N/ha (Giller, 2001) to a range of 1–25 kg N/ha for semiarid Australian cereals (Gupta et al., 2006). A recent study found that even in the presence of mineral N fertilizer, multiple tropical maize lines derived 12–33% of their N from associative N fixers (Montañez et al., 2009); however, evidence that associative BNF contributes significant N to maize in temperate grain production systems is lacking. It is important to note that much research remains to be done, and a further challenge is the nonspecificity of diazatroph–plant interactions that makes it more difficult to select and inoculate highly effective N-fixing strains compared to the more specific legume–rhizobial symbioses.

Partnerships With the Rhizosphere Community

Because the rhizosphere is the site of increased C availability, there are numerous other kinds of interactions that involve free-living or rhizosphere microorganisms that are not obligate symbionts. Rhizosphere microbial communities, referred to as rhizobiomes, vary between plant species, and even between different crop cultivars (Grayston et al., 1998; Peiffer et al., 2013; Turner et al., 2013). For example, the abundance of disease suppressing bacteria in the rhizosphere of wheat varies among wheat cultivars, resulting in differences in resistance to this pathogen across cultivars. Differences in the rhizosphere community are most commonly detected when there is either significant genetic variation between plants (Bouffaud et al., 2014) or when closely related plants have distinct phenotypical differences relating to the rhizosphere (Briones et al., 2002, 2003; da Mota et al., 2002). Some evidence suggests that crop breeding under nutrient rich conditions has disrupted these plant–microbial interactions. In soybean, breeding history has altered the ability of modern cultivars to suppress rhizobia that are not fixing N for the plant, and as a result, these cultivars are vulnerable to parasitic Rhizobia strains (Kiers et al., 2007). Altered composition of nitrifying bacteria in the rice rhizosphere associated with differences in plant anatomy and physiology between cultivars resulted in different nitrification rates and N use efficiency (Briones et al., 2002). Another study of invasive grass species found that community compositions of nitrifying bacteria varied across grass species, giving rise to variations in the nitrification potential. These linkages between plant genotype–phenotype, rhizobiome composition, and nutrient assimilation suggest that cultivars which can access soil nutrient reservoirs and improve nutrient retention can be developed by targeting these plant–microbial interactions in the rhizosphere.

Since crop plants mainly take up NH_4^+ and NO_3^- rather than large polymer organic forms of N, mineralization is important for the N supply to plants in the absence of inorganic N fertilizer additions. The role of these microbial–plant interactions in stimulating N mineralization has been studied intensively. Plants can stimulate mineralization of organic substrates by supplying labile C to decomposers in the rhizosphere (Clarholm, 1985; Cheng et al., 2003; Hamilton and Frank, 2001; Kuzyakov and Xu, 2013). The rate of decomposition and N-mineralization varies with plant species (Cheng et al., 2003), rhizosphere community composition (Clarholm, 1985; Ferris et al., 1998; Chen and Ferris, 1999), and nutrient availability (Tate et al., 1991; Liljeroth et al., 1994). The release of nutrients for plant uptake appears to be enhanced by the involvement of secondary consumers feeding on the primary decomposers due to differences in the stoichiometry (the ratio of elements to one another e.g., N:P or C:N) between the two trophic levels (Clarholm, 1985; Ferris et al., 1998; Chen and Ferris, 1999; Fig. 7.8). This trophic cascade provides a mechanism for the primary producers to influence nutrient mineralization, similar to the so-called microbial loop in aquatic ecosystems where primary producers have been shown to increase excretion of soluble C under nutrient limiting conditions (Elser and Urabe, 1999). There is some evidence suggesting that terrestrial plants can influence the rate of net N mineralization through this mechanism, based on their need for nutrients by modifying the amount of soluble C excreted into the rhizosphere (Hamilton and Frank, 2001; Fig. 7.9).

Greater reliance on SOM as a nutrient source increases the importance of microbially mediated processes such as decomposition and mineralization. The tight coupling that occurs in the rhizosphere between net mineralization of N and P and plant assimilation reduces the potential for nutrient losses. Inorganic nutrient pools can be extremely small in ecosystems, while high rates of plant growth are maintained if N mineralization and plant assimilation are spatially and temporally connected in this manner (cf. Jackson et al., 1988). The

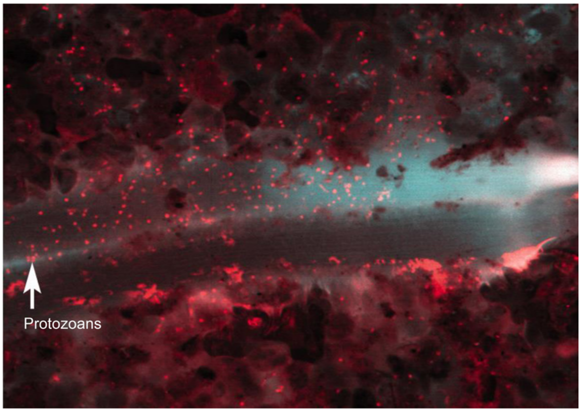


FIGURE 7.8 A swarm of protozoa grazing on red fluorescent bacteria in the rhizosphere. The rhizosphere is the home of numerous organisms that influence nutrient cycling and plant access to nutrient through food web interactions. *From Bringhurst, R.M., Cardon, Z.G., Gage, D.J., 2001. Galactosides in the rhizosphere: utilization by Sinorhizobium meliloti and development of a biosensor. Proc. Natl. Acad. Sci. U.S.A. 98, 4540–4545. With permission copyright (2001) National Academy of Sciences, U.S.A.*

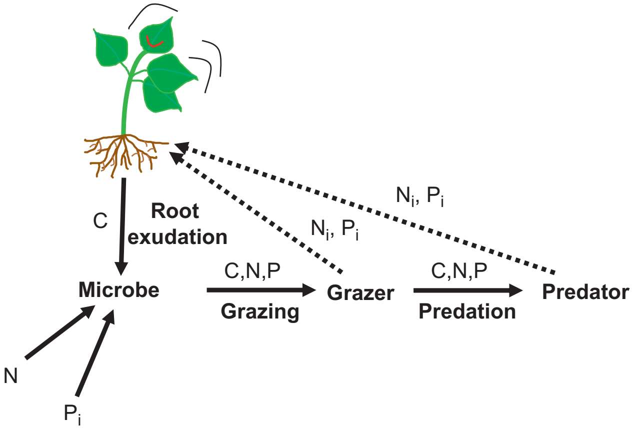


FIGURE 7.9 Feeding interactions across trophic levels increase net mineralization of N and P in the rhizosphere. Plants supply C to microbes who take up N and P from sources that are not available to plants, grazing of these microbes increases the rate of mineralization.

identity of the soil OM pools that are accessed through this mechanism remains unknown; however, phytoremediation studies show that decomposition of chemically recalcitrant substrates is accelerated in the rhizosphere compared to bulk soil (Reilley et al., 1996; Siciliano et al., 2003). This evokes the intriguing possibility that plants may be able to promote access to stabilized SOM pools through partnerships with rhizosphere microorganisms.

Microbial Mediation of Nutrient Cycling

Microorganisms represent a substantial portion of the standing biomass in agricultural ecosystems and contribute to the regulation of C sequestration, N availability and losses, and P dynamics. The size and physiological state of the standing microbial biomass is influenced by management practices, including rotational diversity (Anderson and Domsch, 1990), tillage (Holland and Coleman, 1987), and the quality and quantity of C inputs to the soil (Kirchner et al., 1993; Wander and Traina, 1996; Lundquist et al., 1999; Fliessbach and Mader, 2000). The mechanisms that control community structure and functional characteristics of below-ground ecosystem processes remain largely unknown, however, this is an area of active research and much progress has been made in the last decade.

While some plants are able to produce and secrete enzymes required for P mineralization (Vance et al., 2003) release of nutrients from organic compounds is largely carried out by heterotrophic microorganisms (Paul and Clark, 1996). Microbial production of extracellular enzymes that can attack polymers and release small, soluble molecules is an important mechanism contributing to the internal cycling of N, P, and S (McGill and Cole, 1981; Paul and Clark, 1996). Microbial community composition and metabolic status determine the balance between C released through respiration, and C assimilation into biomass during decomposition, as well as the biochemical composition of that biomass and the net release of plant available nutrients. Decomposers in soils with greater plant species diversity or greater abundance of C relative to N have reduced energy requirements for maintenance, and therefore convert a greater proportion of metabolized C to biomass (Anderson and Domsch, 1990; Fliessbach et al., 2000; Aoyama et al., 2000). Changes in microbial community structure can lead to increased C retention if the management practices result in fungal-dominated decomposer communities (Holland and Coleman, 1987).

Microbial Control of N Cycling

The relative abundance of C and N strongly influences the rates of competing microbial processes, and offers opportunities for farmers to optimize N cycling though manipulating microbial metabolism. For example, plant litter with a high C:N ratio initially increases microbial N immobilization, and decreases NH_4^+ and NO_3^- availability to plants. As microbial decomposition of these residues continues, and cascading effects on grazers and other trophic levels increase, net N release increases (Booth et al., 2005). When large amounts of inorganic N are added, as in industrialized cropping systems, inorganic N pools expand beyond the capacity of crop and microbial uptake, so that pathways of loss such as denitrification and leaching are increased. Soluble fertilizer additions appear to stimulate preferential decomposition of some soil OM pools, including particulate OM (Neff et al., 2002).

In agroecosystems with low N fertility, plants and soil microbes compete for NH_4^+ and NO_3^-. In short-term studies, i.e., one to several days, microbes take up more inorganic ^{15}N than plants, presumably because they have higher substrate affinities, larger surface area to volume ratios, and faster growth rates than plants (Hodge, 2004; Schimel and Bennett, 2004). But after a month or so, plants contain an increasing proportion of the added ^{15}N, because the gradual release of microbial ^{15}N into the soil becomes available for root uptake, and plants hold on to N longer than microbes (Harrison et al., 2007).

Increased soil stocks of labile C substrates contribute to N conservation through both aerobic and anaerobic pathways (Silver et al., 2001; Burger and Jackson, 2003). Studies in agricultural soils simulating conditions in bulk soil indicate that the major fate of NH_4^+ is nitrification (Shi and Norton, 2000; Burger and Jackson, 2003). Competition between heterotrophs and nitrifiers for NH_4^+ is strong, resulting in very small NH_4^+ pools, and nitrification rates can be two- to threefold greater than NH_4^+ immobilization (Burger and Jackson, 2003). Nevertheless, soils receiving greater C additions supported a larger, more active microbial biomass, resulting in a greater proportion of NO_3^- assimilation and reduction of standing NO_3^- pools (Burger and Jackson, 2003).

Carbon abundance also influences dissimilatory NO_3^- reduction pathways in ways that support N conservation and reduce environmental impacts. In one study, denitrification in soils receiving organic N amendments reduced the proportion of N lost as N_2O (Kramer et al., 2006). Carbon abundance can also favor a second anaerobic pathway, DNRA (Silver et al., 2001). This process was thought to be limited to extremely anaerobic, C-rich environments such as sewage sludge and estuarine or lake sediments (Giles et al., 2012), but has recently been detected in a broad range of unmanaged terrestrial ecosystems (Giles et al., 2012), and in agricultural soils (Yin et al., 2002). Silver et al. (2001) reported average rates of DNRA were threefold greater than denitrification in humid tropical forest soils. The resulting reduction in NO_3^- availability to denitrifiers and leaching may contribute to N conservation in these ecosystems (Silver et al., 2001). In rice paddies, soils with greater levels of SOC due to additions of straw mulch had threefold greater DNRA compared to soils where straw was removed and endogenous SOC was reduced (Yin et al., 2002).

As with N, soil OM levels and C abundance influence microbially-mediated processes that control the uptake of P by microbes, as well as mineralization and biological weathering. For example, microorganisms solubilize sparingly soluble inorganic P through several mechanisms if they have adequate C substrates for growth and reproduction but are lacking P (Illmer et al., 1995; Oberson et al., 2001). Direct excretion of phosphatase enzymes is one mechanism of phosphate-solubilization. Another is local acidification through organic acid excretion, such as occurs in the soil fungus *Penicillium radicum* isolated from a low-P rhizosphere of unfertilized wheat (Whitelaw et al., 1999). In this system, phosphate-solubilization from insoluble or sparingly soluble complexes with calcium, colloidal aluminum, and iron was related to titratable acidity and gluconic acid concentration. Organic acid excretion not only alters pH, but also may chelate Al_3^+ or other cations, directly further enhancing the solubilization of phosphate (Erich et al., 2002).

The assimilation of inorganic phosphorus by microbes may protect phosphorus from geochemical adsorption reactions with soil particles, through microbial turnover and OM mineralization processes which are synchronized with plant and further microbial uptake. Indirect evidence for this is the enhanced levels of microbial P and cycling of P from inorganic to organic and plant forms associated with managed systems that had enhanced soil biological activity and legumes present (Oberson et al., 2001). Labeled glucose and residue studies have recently shown that biomass P turnover is rapid, approximately twice as fast as C (Kouno et al., 2002). This indicates that the potential for microbial P pools to support plant P requirements may have been markedly underestimated.

CONCEPTS AND STRATEGIES TO OPTIMIZE ECOLOGICAL NUTRIENT MANAGEMENT

Using Spatial and Temporal Scales to Organize Management Decisions

The use of both temporal and spatial scales to organize nutrient flows into a logical structure is fundamental to developing a coherent set of management strategies that act together to achieve the goals of ecological nutrient management. The spatial scales we must consider range from microns to the plant, field, and farming community, or regional scales. We can think of these spatial scales as nested within one another, so that at any level, we are able to identify the location of the processes we are aiming to manage. For example, the use of rock phosphate as a source of P involves processes occurring at the micron, plant, and field scales (Fig. 7.10).

In using a sparingly soluble P source, the farmer is aiming to modify the solubilization of P, a microscale process which is mediated by microorganisms and the rhizosphere of some plant species. The background soil environment and climate affect processes occurring at every level, including the farmer's decisions. Assuming that P is a limiting factor in this field, plant productivity will be impacted by field-scale management decisions and the resulting rate of P-solubilization. The field-scale decisions that will directly influence this process are: (1) choice of amendments at the field scale, (2) selection of plant species, and (3) inoculation of P-solubilizing microbes (may be an option in the future!). Interactions across these scales impact one

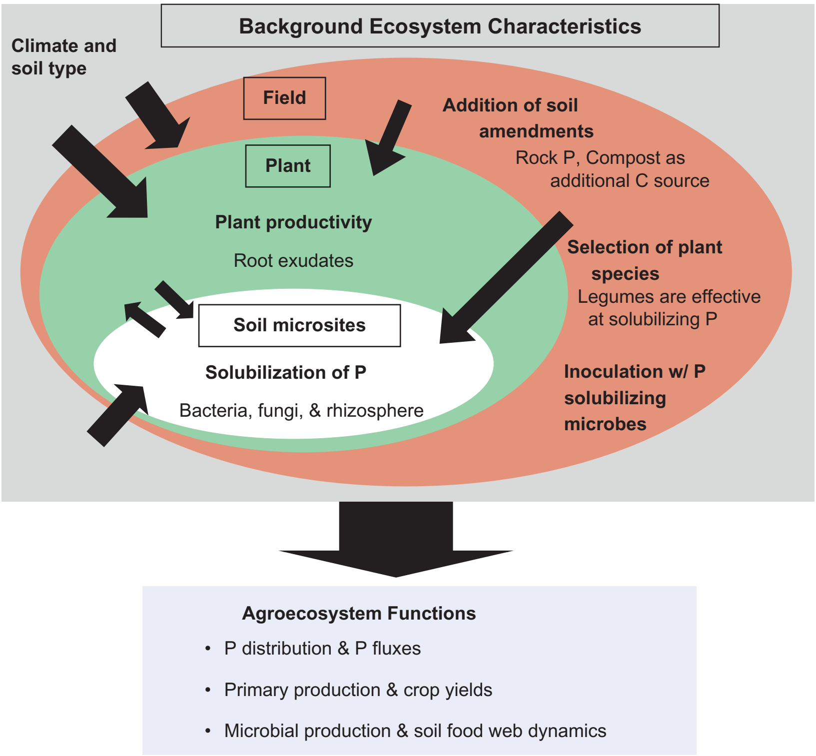


FIGURE 7.10 Processes occurring at multiple scales must be considered in nutrient management decision-making. Here the processes that impact the decision to use rock P and the ultimate outcomes are illustrated. See text for full discussion.

another, i.e., field management impacts the plant and soil microbes, P solubilization influences plant productivity and creates feedback, because increased productive capacity increases the ability of the plant to stimulate P solubilization through direct and indirect means. Adding rock P in conjunction with planting a legume can be particularly effective, because legumes are able to access sparingly soluble P. If rock P was added without consideration of plant species, or use of an additional C source (such as compost or manure) to support microbial P-solubilization, then it is possible that there may not be a detectable improvement in crop yields in the first growing season because microbial activity is limited by access to C (energy), not P. The inclusion of a supplemental C-source is particularly important if a nonmycorrhizal crop is to be planted. This example illustrates how systematic analysis of processes occurring at different scales can help in planning management interventions.

Just as interactions across spatial scales were important in conceptualizing the key processes in the rock P example, interactions among processes occurring at different rates is also a useful organizing principle. This is particularly important when a major change in an agroecosystem's management regime is implemented, such as increased inputs of organic residues or a change in tillage regime. There are major differences in the process rates and the flux through various pools. As a result, the MRTs of relevant nutrient pools range from minutes for transient inorganic N forms, such as nitrite, to centuries for stabilized pools of SOM. Generally speaking, the spatial and temporal scales of ecological processes are commonly linked. Small-scale or local processes are often ephemeral and rapid. Examples are nutrient transformations controlled by microorganisms, such as nitrification or mineralization, and nutrient uptake by a single fine root. These rapid, small-scale processes and interactions can be highly variable in space and time, but in aggregate, they determine agroecosystem functions at the field scale. For example, two competing biological processes that occur very rapidly yet play a significant role in regulating the amount of N lost from a field on an annual basis are the flux of NH_4^+ into fine roots versus the conversion of NH_4^+ to NO_3^- by nitrifying microorganisms. If the former predominates, then the NH_4^+ available to nitrifiers is reduced and NO_3^- pools remain small. On the other hand, when nitrifiers have access to ample NH_4^+, then NO_3^- production is elevated resulting in larger NO_3^- pools and increased losses of N.

Managing agroecosystems to modify reservoirs in support of longer mean residence times requires planning for management that occurs over longer time frames compared to small-scale processes and pools that are fast cycling. For example, soil degradation and restoration results from slow changes that accrue over decades rather than years, and that represent the sum of many shorter-term processes and events. Yet it is these longer-term processes that are critical to the long-term sustainability of agroecosystem production.

One approach that has been used in the case of soil OM is to focus efforts on OM pools that can be influenced by management in shorter time frames. Because of the different mean residence times of the soil organic pools that are impacted by management changes, the shift to new steady state conditions will occur over multiyear, decades, and even longer time-scales. Agroecosystems that are undergoing changes in ecological processes are considered to be "in transition" (Liebhardt et al., 1989). During this transition period, there are clear signs of directional change. For instance, when soluble fertilizers are replaced with organic nutrient sources, subsequent shifts in C and N cycling impact crop yields and the distribution of SOM pools (Wander et al., 1994; Liebhardt et al., 1989). In the short-term, organic inputs will have a greater impact on faster cycling processes. To impact slower cycling SOM reservoirs requires that nutrient management strategies consider time frames of 5–10 years. Fig. 7.11 illustrates how a green manure incorporation impacts SOM pools with differing mean residence times and their contribution to crop N supply.

While many ecological processes that govern nutrient availability fall somewhere along the continuum from small-scale and fast to large-scale and

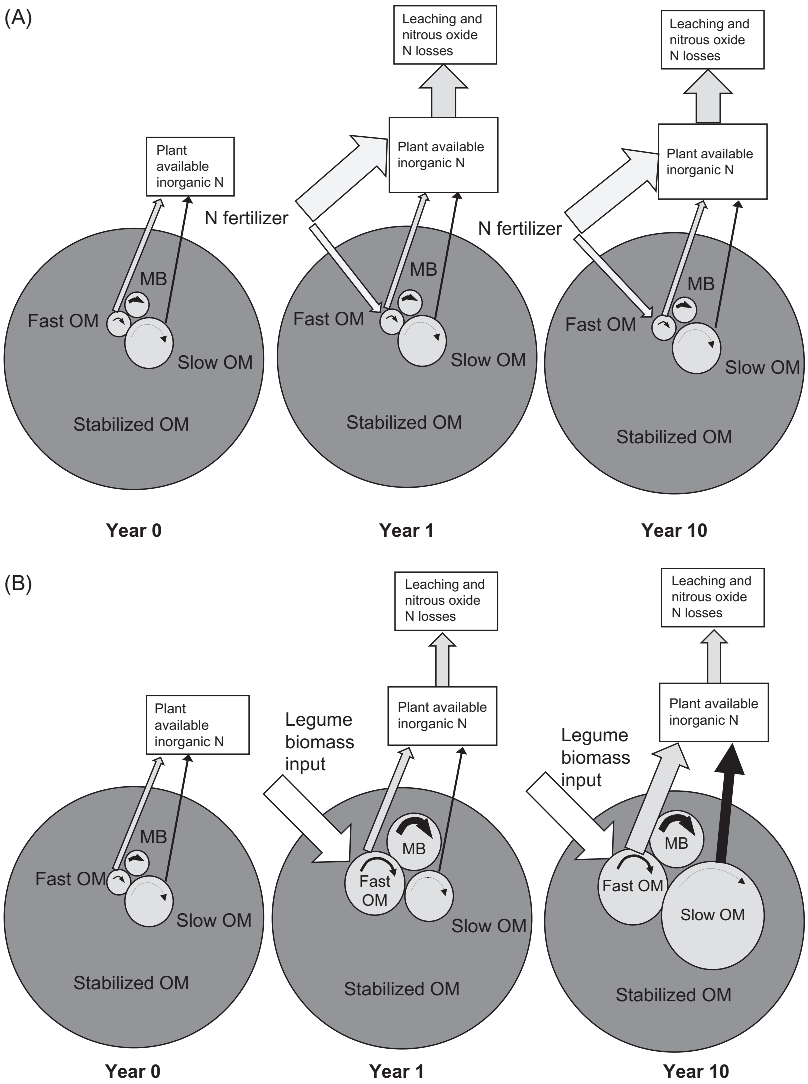


FIGURE 7.11 The effect of sole use of N fertilizer compared to legume additions on soil organic matter pools and N availability over time. Four soil organic matter pools are represented in each diagram: microbial biomass (MB), fast-cycling organic matter pool primarily composed of recent litter additions (Fast OM), slow-cycling organic matter pool primarily composed of partially decomposed litter (Slow OM), and the much larger stabilized SOM pool which is unavailable for microbial decomposition and plant N uptake. In both A and B, year 0 represents a relatively degraded soil with low soil organic matter levels and low N supplying capacity from decomposition of fast OM with small contributions from slow OM. (A) Uncoupled nutrient management using N fertilizer without any added C sources. Fertilizer applied alone without carbon sources (residues, compost, manure, and legume vegetation and roots) is taken up by crop plants, but very little is retained as soil OM. About 40% or more of N fertilizer applied is lost through leaching and gaseous loss pathways. Even after 10 years of management with N fertilizer, soil organic N reserves have not increased. (B) Integrated management using legumes as an N source resulting in carbon-mediated retention of

(*Continued*)

slow, there are exceptions. In agricultural systems, it is not uncommon to have large-scale processes that occur very rapidly. Management interventions such as crop harvest, burning, and tillage are examples. These events cause rapid, large-scale changes, and result in dramatic shifts in virtually all the smaller-scale ecosystem processes from one moment to the next. A well-known example is the pulse in soil respiration that occurs after tillage.

Evaluating Management Impacts on Agroecosystem-Scale Nutrient Flows

To efficiently gauge the impact of farm management on longer-term soil fertility and sustainability, it is crucial to consider the flow of nutrients across boundaries of management units, as well as the larger landscape in which they are embedded. To analyze the movement of nutrients across field and farm boundaries, net flows of nutrients can be estimated by constructing nutrient budgets. This approach is used in ecosystem ecology to compare fluxes into and out of a defined compartment, which can be as small as a patch of organic residue in the soil (Hodge, 2004), or as large as the entire atmosphere (Schlesinger, 2005), in order to find out whether the balance of these fluxes are positive or negative. Over the last 10 years, the value of nutrient budgeting as a tool for analyzing nutrient flows in agroecosystems and agricultural landscapes has become apparent, and the approach has been widely applied at a variety of scales. Depending on the questions that are being addressed, the scale of land unit used can be individual fields, farms, watersheds, or even whole regions and countries.

To conceptualize how management is affecting the nutrient status of a field or other management unit, we treat the field as a compartment, and focus on inputs and exports across the field boundary. The simplest nutrient budgets emphasize the flow of nutrients that are controlled by the manager, such as fertility inputs and harvested exports (Fig. 7.12). These fluxes are usually the dominant flows that regulate the transfer of nutrients into and out of a field or farm. These simple mass balances provide a starting point for managing smaller-scale processes that are regulating the fate of nutrients in agroecosystems. While this balance does not quantify internal nutrient

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◀ N though increased coupling of N and C cycles. In year 1, legume biomass is incorporated into the cropping system. Biomass enters the fast OM pool and drives a rapid increase in the size and cycling rate of MB. Labile carbon and nitrogen compounds are decomposed rapidly by microbes, resulting in a quick burst of N availability. The slow OM pool is not immediately impacted by the legume addition. Carbon and N from the legume biomass flows through the food web to eventually become part of the slow OM pool on a decadal time scale. By year 10, the size of MB and fast OM pools are maintained, and a larger slow OM pool also contributes to the N supplying capacity of the soil. The net effect is greater N availability from these soil reserves for crop uptake, along with small gains in total soil OM to support longer-term nutrient supplying capacity.

FIGURE 7.12 Major nutrient flows in a smallholder cropping system in the Potosi region of Bolivia where animals are an integral part of fertility management. Farmers harvest nutrients from rangeland through grazing their animals on marginal lands and manure is deposited in corrals (*dotted arrows*). Internal transfers of P also occur when harvested crop residues serve as forages for animals (*thin solid arrow*). Manure is used primarily on fields that are closest to the homestead, although some is transported to farther fields (*thick black arrows*). The manure contains nutrients that have been captured from communal rangelands as well as recycled from cropping fields. Nutrients leave the agroecosystem as harvested crops and through losses to the environment (*gray arrows*). Erosion is the major environmental nutrient loss pathway in these systems.

cycling processes or environmental losses resulting from these internal processes, it provides useful information for assessing whether surplus or inadequate nutrients are being added, and thus is useful in developing nutrient management strategies. All things being equal, environmental losses are directly related to the level of N and P availability. Soils with excess applications will lose more through microbially mediated processes compared to soils that do not have surplus nutrients (Aber et al., 1989).

Construction of a field-scale mass balance entails calculating the difference between inputs and harvested exports over the course of a rotation cycle (Drinkwater et al., 1998). All fertilizers, soil amendments, and N-fixing crops must be accounted for as inputs. One of the most challenging aspects of using this budgeting approach is the determination of N inputs from leguminous cover crops. A common practice for legumes is to measure N in standing biomass for green manures as an estimate of N from BNF, and to consider no net gain or loss of N for leguminous grain crops (Drinkwater et al., 1998). The exports are all harvested crops or animals, including grains,

BOX 7.1 How Do Different Nutrient Management Strategies Affect N Mass Balance in Grain Systems?

Fifteen-year N balances for three distinct grain production systems: (1) MNR—integrated system with grains, forages, and legumes, with animal manure returned to the field. (2) Cash grain systems with leguminous green manures as the only N source. (3) Cash grain system based on soluble N fertilizer inputs (modified from Drinkwater et al., 1998). All systems include maize and soybean, while only the MNR and LEG also grow wheat and leguminous green manures.

Nitrogen Balance	**MNR (kg/ha)**	**LEG (kg/ha)**	**CNV (kg/ha)**
Nitrogen inputs	1365	740	1310
Nitrogen in grain exports	−825	−745	−790
Surplus or deficit: (Total inputs—Exports)	540	−5	520
Net change in soil nitrogen	415	110	−495
N not accounted for (Total inputs—Exports)—Soil N change	125	−115	1015

These simple input − output balances show that the LEG system is running close to steady state, i.e., inputs are roughly equal to harvested exports, while the MRN and CNV have accrued comparable surpluses of N over this 15-year period. These differences in N balance are driven mainly by the inputs rather than yields, since the harvested N in these three cropping systems is similar. If we include data on soil N using samples conducted at the beginning of the experiment and then 15 years' later, we can detect a significant increase in soil N for the MNR, while the CNV system shows a significant decline in soil N for the same time period. The small increase shown for the LEG system is not statistically significant.

forages or crop residues removed, manure or animal biomass removed. This simple budgeting method can be very useful as an indicator of directional change and the relative efficiency of divergent nutrient management strategies (Box 7.1). Negative balances indicate that deficits are accruing, and that nutrients are being extracted from the soil (Box 7.2). In this case, if nutrient management practices are not modified, soil fertility will continue to be depleted and production will decline. Chronic surpluses may indicate that over-application is a problem, however, to fully determine whether or not these surpluses are being retained in the field, additional analysis of soil stocks (i.e., Box 7.1) and potential loss pathways such as erosion (Box 7.2) will need to be evaluated.

BOX 7.2 Intercropping of Pigeon Pea Reduces Erosion and Increases Grain Yields and P Recycled Through Active Soil OM Pool.

In the table below, net exports of P in yields and through erosion at two sites with differing erosion rates in Songani, Southern Malawi. Erosion P losses were estimated after Stoorvogel et al., 1993 where erosion rates were estimated as follows: (1) site 1 (2% slope) erosion was estimated at 5 ton ha year; and (2) site 2 (30% slope) at 20 t/ha per year (Snapp et al., 1998). Based on percentage ground cover, we estimated that erosion, and the resulting P loss, was reduced by 25% when maize was intercropped with pigeon pea intercrop, compared to monoculture maize. Long-duration pigeon pea extends the period of soil cover over a 4-month period of intermittent rains.

	Yield Maize	**Yield P'pea**	**P Harvested in Grain**	**Erosion P Loss**	**Net P Balance**	**P Recycled in Crop Residues (Internal P Cycle)**
	t ha^{-1}	**t ha^{-1}**	**kg/ha^{-1}**	**kg/ha^{-1} per year^{-1}**	**kg/ha^{-1} per year^{-1}**	**kg/ha^{-1} per year^{-1}**
Maize, low erosion site 1	1	0	2	2.3	− 4.3	7.7
Maize, high erosion site 2	0.5	0	1	9	− 10.0	3.8
Maize + P'pea,site 1	1.1	0.4	3.4	1.7	− 5.1	17.4
Maize + P'pea,site 2	0.5	0.3	1.9	7.8	− 11.7	9.8

Because there are no inputs of P for this maize crop, all P balances at the end of the season are negative, indicating that a net export of P has occurred. Phosphorus lost through erosion is threefold greater in the steeper field. The addition of pigeon pea into this system increases the export of harvested P while also reducing P lost through erosion. However, because of the increase in harvested yields, overall P removal is accelerated with pigeon pea + maize. As a result, although erosion losses are reduced at each site, the need to add P through soil amendments is increased by intercropping. The last column reports the P content of crop residues from maize or maize + pigeon pea, and shows how the inclusion of the legume more than doubles the amount of P that will be recycled back into labile OM pools.

Integrating Background Soil Fertility Into Nutrient Management Planning

Nutrient cycling in agroecosystems reflects interactions between the environment, management, and the organisms present in the system. While management practices can exert a strong influence on shorter-term outcomes such as crop nutrient uptake and yields, the particular effect of identical management strategies will vary across farms, depending on climate, soil type, and the legacy of past management decisions. These inherent characteristics of the agroecosystem need to be considered in developing overall nutrient management strategies. Fig. 7.13 illustrates how management practices can have different results, depending on the initial fertility status of a site. In this diagram, we have laid out three different management scenarios for two fields that differ in terms of the initial fertility status. The cause this difference in soil fertility is inconsequential, it could be due to either soil type difference, or past management history.

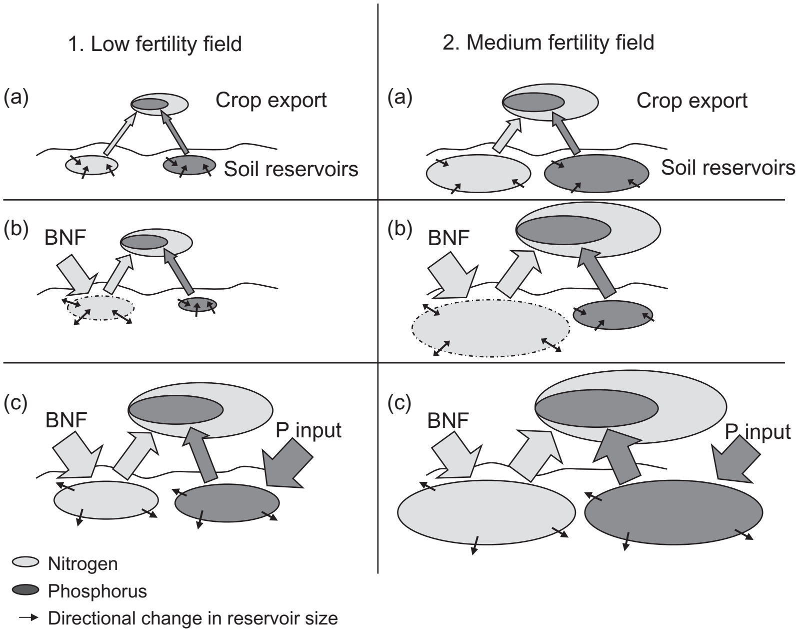

FIGURE 7.13 Management practices will have differing consequences depending on background soil fertility. A low fertility (1) and medium fertility (2) background are compared for three management options: (a) absence of any fertility additions, (b) inclusion of N-fixing crop in the system where at least part of the N-fixed is retained in the system, and (c) N-fixing crop combined with modest addition of rock P. The effect of these three management regimes is illustrated in terms of relative flows of N and P into soil pools and crop harvest, changes in soil pools, and crop N and P content. See text for full discussion.

For a low fertility field (Fig. 7.13 (1a)), small soil N, P, and OM reservoirs support low productivity. With crop exports, small soil reservoirs continue to shrink, leading to a downward spiral of soil degradation. If legumes alone are incorporated into a cropping system in this field (Fig. 7.13 (1b)), BNF will only provide a small benefit as legume growth will be limited by a small and increasingly shrinking soil P reservoir. The presence of legumes in the system can increase the availability of soil P (Bah et al., 2006), but this will only increase the rate of P depletion over the long-term. In this scenario, legumes are not likely to increase productivity, but they may help maintain soil N reservoirs and SOM status. If incorporation of legumes is paired with modest P fertilizer additions (Fig. 7.13 (1c)), BNF can make much larger contributions to overall productivity. If the P fertilizer is in organic form, such as manure, SOM reservoirs can also be increased. It is at higher levels of productivity that retaining crop residues becomes more economically feasible for farmers, reinforcing the maintenance of the SOM reservoir. As the OM reservoir increases, the capacity of the soil to retain N and P in relatively available forms increases.

For a medium fertility field (Fig. 7.13 (2a)), modest crop production can be sustained over the short-term by the mining of existing soil N and P reservoirs. With the incorporation of legumes into this field (Fig. 7.13 (2b)), BNF can provide substantial benefits because biomass production is not limited by P and other nutrient availability. Legumes can improve the P status of the soil by moving P from less to more available soil pools (Bah et al., 2006). Long-term dependence on just legume BNF input will eventually lead to P depletion, and this medium fertility soil could shift to a low fertility status as in Fig. 7.1B. Again, if incorporation of legumes is paired with modest additions of P fertilizer (Fig. 7.13 (2c)), BNF can make much larger contributions to productivity over the long-term. As in Fig. 7.13 (1c), the form of P fertilizer and the quantity of crop residues retained affects the longer-term SOM reservoir.

Synthetic N fertilizers, as an alternative to BNF, could help boost productivity in any of the non-P limiting scenarios. However, inorganic N fertilizers can exacerbate soil P depletion (Lupwayi et al., 1999), and do not contribute to longer-term nutrient cycling capacity of the system if they are not coupled with C inputs.

The size of nutrient exports relative to crop residues retained in the field determines the directional change in soil reservoir size. Legume grain crops, e.g., tend to export almost as much N as they fix (Alves et al., 2003). As yields increase with increasing soil fertility, grain crops can export more N than they fix (Ojiem et al., 2007). Incorporation of green manures as intercrops or relay crops can help balance N exported in a cash crop with N fixed by the legume (Lupwayi et al., 1999).

Strategic Use of Soil Amendments and Cover Cropping to Enhance Linkages Between Cycles

We have discussed the role of plants and microbes in connecting N and P cycling with C flows, and emphasized how these linkages support internal cycling capacity and promote nutrient retention. Here we provide specific examples of how use of various nutrient sources can either promote or impair these linkages. For example, while the initial crop uptake of inorganic, soluble fertilizers is greater than crop uptake from other forms of amendments such as organic residues or rock phosphate, retention of these soluble forms in the ecosystem through conversion to soil OM is reduced, resulting in greater environmental losses (Bundy et al., 2001; Ladd and Amato, 1986; Drinkwater et al., 1998). This greater loss of soluble fertilizers occurs because the processes that sequester soluble nutrients are saturated (Azam et al., 1985; Ladd and Amato, 1986; Hodge et al., 2000) leaving NO_3^- vulnerable to leaching/denitrification. In contrast, microbial assimilation of N from organic sources is two- to fourfold greater than for N from inorganic fertilizer, leading to increased storage of legume-derived N in SOM pools. Likewise, soluble, surplus P sources push P cycling into absorbed, precipitation, and occluded pools.

In cropping systems where soluble fertilizers are part of the overall nutrient management strategy, fertilizer additions should be managed to enhance assimilation in biologically regulated sinks. In rotations, inorganic sources can be preferentially applied to those crops with higher NUE. Improving the spatial/temporal connections between fertilizers and senescent crop residues appears to increase the retention of older SOM fractions (Clapp et al., 2000), suggesting it may be advantageous to add small portions of fertilizer when high C crop residues are being incorporated. A review of three long-term trials from temperate countries suggests that the fate of soluble P from fertilizers depends on whether P was added primarily as an organic or inorganic source, as well as soil characteristics (Blake et al., 2000). In these studies, P-use by plants was much more efficient if applied in balance with C.

Targeted use of animal manures facilitates plant and microbial uptake of P, through a range of mechanisms. These include direct competition for adsorption sites by manure-compounds, enhanced release of P from sparingly soluble pools through altered pH and soluble C addition, and enhanced microbial activity (Erich et al., 2002; Laboski and Lamb, 2003). Where manure is utilized at sustainable, moderate levels, and livestock are distributed extensively across the landscape, organic-P sources appear to be inherently less vulnerable than inorganic fertilizer sources to loss from occlusion, erosion, or leaching (Powell et al., 1999). While manure additions also contribute to N fertility and SOM pools, in the long-term, soil nitrogen status will depend in large part of the proportion of land devoted to symbiotically-fixing plant species. Use of animal manures serves as a mechanism to recycle N and P back to cropping fields where forages were produced.

Likewise, use of sparingly soluble inorganic P inputs should be combined with strategies to link P solubilization with C flows. Application of sparingly-soluble sources of P to crops (e.g., most legumes) that can assimilate P into biological pools is an efficient strategy to bypass desorption, precipitation, and occlusion of P (Oberson et al., 1999). In degraded soils, additions of rock P may be need to be combined with the use of shrubby, short-lived, mycorrhizal plants that have been shown to reduce erosion, build OM, and assimilate N and P into plant accessible N and P pools. Two legumes species, pigeon pea and lupin, are notable for providing these multiple ecosystem services, and have also been shown to access sparingly soluble phosphorus pools. Interestingly, these crops are commonly integrated with nutrient-demanding crops in indigenous cropping systems. For example, pigeon pea is grown as an intercrop with maize in India, and lupin as a rotational crop just before potato in the Andes. The use of legumes to transfer P from mineral forms to labile OM pools increases the amount of P that is actively cycling via biological processes and can contribute to increased P uptake by subsequent crops that may not have the ability to access sparingly soluble P. An example is provided in Box 7.2, where the amount of P recycled in crop residues increased nearly threefold when pigeon pea was intercropped with maize.

The consistent theme uniting all of these strategies is to evaluate the possible fates of various nutrient sources, and to also consider how to link use of these sources with enhanced C cycling. Furthermore, the greatest potential for effective nutrient cycling is realized when soil amendments are combined with use of biological N fixation.

Biological N-Fixation: A Key Source of Nitrogen

Effective management of biological N fixation is central to ecologically based nutrient management. The most familiar example of symbiotic nitrogen fixation is the close association between legumes and rhizobial bacteria (*Rhizobium*, *Mesorhizobium*, *Sinorhizobium*, and *Bradyrhizobium*) although associative and free-living diazotrophs are potentially important in several monocot crops.

Legumes can be incorporated into crop rotations either intercropped with nonlegumes or in sequential (relay) rotations. A disadvantage of relay cropping is that mineralization of N may not coincide with the subsequent crop N demand. Beneficial effects of relay cropping systems include the addition of OM and mineralization of N from residual legume biomass that can support the growth of subsequent, nonlegume crops. Grain legumes, such as soybeans, are typically grown as monocultures in rotation with nonlegume grain crops, such as maize. Grain legumes are the most common type of legume in cropping systems, because they provide essential human and livestock protein sources in a form that is easily stored and transported. Grain legumes, such as soybeans, can fix up to 200 kg N/ha per year (Table 7.4). However, most of this N is exported off the farm in the protein-rich seeds, resulting in low or negative net soil N balance. Most estimates of N fixation, however, do not include root biomass, which can be 16–77% of total plant N (Table 7.5). Root biomass is difficult to measure; however, from the limited data available, it is clear that legume species can vary greatly in root-to-shoot ratios. Perennial species tend to have a higher root:shoot ratios than annual species (Antos and Halpern, 1997). This is generally supported by recent below-ground N results (Table 7.5), where perennial legumes tend to

TABLE 7.4 Average and Upper Range of Biological N-Fixation Contributions to Tropical Cropping Systems

Associated Crop	Average N Fixed (kg N/ha per year)	Upper Range of N Fixed (kg N/ha per year)
Rice: *Cyanobacteria*[b]	30	Up to 80
Azolla: *Anabaena* in rice[a]	32	–
Sugarcane: *Acetobacter* [c]	–	Up to 150
Grain legumes[a]	77	Up to 200
Green manure legumes[a]	85	Up to 300
Pasture legumes[a]	78	Up to 250
Leguminous trees and shrubs[a]	150	Up to 275

[a] *From Giller (2001). Legume nitrogen fixation values do not include below-ground biomass and are, therefore, underestimates.*
[b] *From Roger and Ladha (1992) As cited in Reis (2000).*
[c] *From Boddey et al. (1995).*

TABLE 7.5 Measured Legume Below-Ground N Biomass as a Percentage of Total Plant N

Legume	Primary Use	BGN as % of Total Plant N	Sources
Chick pea (*Cicer arietinum*)	Grain	29	Turpin et al. (2002)
Fava bean (*Vicia faba*)	Grain	25	Khan et al. (2003)
Fava bean (*Vicia faba*)	Grain	17	Mayer et al. (2003)
Field pea (*Pisum sativum*)	Grain	17	Mayer et al. (2003)
Jack bean (*Canavalia ensiformis*)	Green manure/ forage	39	Ramos et al. (2001)
Mucuna (*Mucuna aterrima*)	Green manure	49	Ramos et al. (2001)

have a higher below-ground N as a percentage of total plant N (average of 43%) than the annual grain legumes (average of 32%). Environmental conditions can also influence root biomass and root architecture. Generally, plant allocation to roots increases under drought conditions. If estimates of root biomass are included, grain legumes can provide modest positive N balances, even with high grain N exports.

Intercropping systems incorporate legumes into agroecosystems by planting legumes and nonlegumes together in close proximity in the same field. Examples of an annual intercropping system include maize–pigeon pea mixtures (Snapp et al., 2003). Legume intercrops can supply a slow, but steady supply of N for the nonlegume crop. Furthermore, intercropping can also reduce soil erosion and nutrient leaching, contribute to suppression of weeds and pathogens, and provide food and shelter for beneficial insects. To provide these benefits while increasing yields, intercrops must combine crop species that maximize complementarity and minimize competition for light, nutrients, and water. One of the major constraints to the adoption of legumes in cropping systems is the opportunity cost of taking land out of production in either space, as part of an intercrop, or in time as part of a legume relay cropping rotation. For this reason, successful adoptions are more likely when legumes serve multiple purposes of producing a net positive N balance, while still producing consumable products or livestock forage. Pigeon pea is one such example of a green manure crop that produces a high-protein vegetable product while maintaining a positive N balance (Ghosh et al., 2007).

In contrast with grain legumes, green manures are grown for the primary purpose of improving soil N fertility, and are typically incorporated into the soil at a maximal stage of biomass production. Tropical green manures, such as *Canavalia*, *Crotalaria*, and *Mucuna*, commonly fix over 100 kg N/ha per year, all of which is retained in the system, resulting in more positive N balances than grain legumes. Green manures as relay crops are more commonly used in temperate systems, because of lower land pressures and because they can be grown during the colder winter months when crop production is not possible. In tropical systems, relay green manures are less common due to high land pressures, limited labor supply, the ability to produce crops year-round in some regions, or the lack of water to support green manure growth during the dry seasons between cropping seasons. Intercropping of green manure crops to supply N to a simultaneously growing cash crop have been adopted in some systems. The aquatic fern, *Azolla*, and its symbiotic association with the cyanobacteria *Anabaena* provides an example of a green manure that is used exclusively as an N source when intercropped in lowland rice systems. With 80–95% of *Azolla* N derived from fixation, rice–*Azolla* intercrops can fix approximately 30 kg N/ha (Yoneyama et al., 1987; Choudhury and Kennedy, 2004). Some constraints to more widespread adoption of *Azolla* are pest pressures, P limitation, and limited irrigation availability in some regions (Giller, 2001).

Farmers that have limited land, labor, and other resources are interested in "dual purpose" legumes, which have an intermediate phenology. That is,

FIGURE 7.14 A Bolivian farmer shows off his fava bean crop. The previous potato crop failed due to unfavorable climatic conditions, leaving behind P from the manure application that is normally applied to potatoes but not to bean crops. As a result, the fava beans produced a very large biomass.

they provide a product, such as leaf, vegetable, or grain, while at the same time providing long-term benefits through residues that suppress weeds and build soil fertility (Fig. 7.14). There is a trade-off, as carbohydrate and nutrient invested in residues provides less resources for yield potential, thus residue biomass is inversely related to harvest index across legume species (see Fig. 3.12). Examples of dual purpose, low harvest index legumes include long-duration pigeon pea, forage soybean, and mucuna. Such species provide returns to farmers in the short-term—and thus the economic feasibility of adoption—while simultaneously contributing to ecosystem services.

Over the long-term, dual purpose plant types contribute to resilient cropping systems. This is both through the soil building properties of high quality residues, and the inherent ability of indeterminant growth types to recover from pest epidemics. Plant breeding efforts have historically focused on producing high yield potential phenotypes. Examples include the development of new varieties of pigeon pea and cowpea that are extra-early, and extra short duration. These crops often incorporate high harvest index traits, which has had the unintended consequence of reducing biomass available for fodder, weed suppression, and soil fertility enrichment. Producing a wider range of dual purpose genotypes with intermediate phenology, and experimenting with intercrops of short and long-duration crops are approaches that require careful consideration in the future.

Alley cropping involves the use of woody or shrub perennial legumes between "alleys" of nonlegume crops. Prunings from the legumes are used as livestock forage, and/or added to the soil as a N source for the nonlegume.

Inclusion of perennials in cropping systems provides important ecological benefits due to their extensive rooting systems that persist across multiple cropping seasons. Perennials can reduce soil erosion, access deeper soil pools of nutrients and water, provide critical microbial habitat between annual cropping seasons, and increase SOM. *Leucaena* and *Gliricidia* are two common leguminous alley crop species. *Leucaena* intercropped with sorghum increased sorghum yields by 73%, as compared to sorghum grown without N fertilizer, and yields were 43% greater than with a low rate N fertilizer application (Ghosh et al., 2007). Alley cropped legumes can fix between 200 and 300 kg N/ha per year (Giller, 2001). Some of the challenges in the adoption of alley cropping systems include the competition of the legume with the cash crop for moisture in dry years, the pruning labor required, and the use of land for a noncash crop. Selection of species that have complementary rooting systems with cash crops (i.e., a deep-rooted perennial legume cropped with a shallow-rooted annual), and species that grow at a manageable pace to supply N while not requiring excessive pruning inputs, are important considerations in the selection of legume species for alley cropping.

Lastly, while reliable data on the contributions of nonsymbiotic diazotrophs (free-living and those found in the rhizosphere) is limited, there are circumstances where it may be possible to increase N fixed by these microbes. Management practices that affect the availability of soil carbon should significantly impact the potential for BNF. For example, the retention of the carbon in straw from a wheat crop with a yield of 2 t/ha could theoretically fuel the production of 50–150 kg N/ha if utilized by diazotrophs to drive N fixation (Kennedy and Islam, 2001). In addition, crop selection and breeding can affect BNF potential, because plant species differ greatly in the quantity and quality of root exudates produced.

Agroecosystem-Scale Nutrient Use Efficiency

A central theme of any fertility management regime is the idea of evaluating the efficiency of nutrient inputs. In our experience, understanding and promoting nutrient efficiency is the key concern of resource-constrained farmers. It is much more important than determining the rate of nutrient application that will maximize agronomic return. This is because smallholder farmers with very limited assets need to optimize returns to their modest investments, rather than optimizing profitability per se. An efficiency approach is a different way to think about nutrient management compared to the majority of soil fertility management research and fertilizer recommendations developed around the globe, which focus on optimizing plant yields. When NUE is considered within industrial agriculture management regimes, it is usually measured as yield per nutrient input from fertilizer, i.e., kg maize/kg fertilizer N. In other words, the efficiency of a nutrient source is evaluated based on the estimated contribution to yield for a single growing season.

There are several drawbacks to this approach. First and foremost, the focus on the single process of plant assimilation of the nutrient input leaves out many processes that retain nutrients for crop use in subsequent years and are beneficial for long-term improvement of soil fertility. Furthermore, this metric is limited to a single growing season, so the fate of these fertilizer inputs over longer time frames is not factored into the assessments of NUE. You can see that reliance on this metric as an indicator of NUE leads to management decisions that are driven solely by consideration of immediate yield outcomes while more complex outcomes such as longer-term benefits to soil fertility or retention of nutrients in SOM do not factor into nutrient management strategies. An additional consequence is that organic amendments such as green manures or composts that contribute to building SOM are judged to be inefficient nutrient sources, and therefore inferior to inorganic, soluble fertilizers. One consequence of the wide application of this single NUE metric to drive nutrient management decisions is that farmers find themselves on a "fertilizer treadmill," where their farming systems have become dependent on high inputs of soluble fertilizers simply to maintain acceptable yields (Drinkwater and Snapp, 2007a,b).

A more comprehensive, ecologically based model for NUE assessment takes into account diverse nutrient fates over a longer time scale than a single growing season. From this holistic perspective, NUE is defined in terms of the retention of nutrients within the agroecosystem, usually at either the field or farm-scale, in conjunction with plant production related outcomes. Therefore, we distinguish between crop-scale NUE and agroecosystem-scale NUE. Crop-scale NUE, or yield/fertilizer input, is certainly one useful measure to consider in the context of nutrient management decisions, however, use of this metric cannot support integrated management. Agroecosystem-scale NUE can be estimated using the simple inpu—output mass balance approach we discussed earlier. This requires information on rotation, fertility inputs, and crop yields for at least one rotation cycle. Clearly, there are many sources of error in these simple budgets, however, we have found them to be a useful starting point for developing strategies to improve nutrient management in a variety of agroecosystems. In the future, it may be possible to use natural isotopic ratios of $^{15}N/^{14}N$ as an indicator of agroecosystem-scale NUE. While NUE is a useful concept, it should only be used as one of the many factors that contribute to the development of field-specific nutrient management planning.

Integrating Nutrient Management With Other Farming System Decisions

In addition to the processes which are directly linked to nutrient cycling, nutrient management practices have cascading effects on other agroecosystem processes, making it advantageous to integrate nutrient management

BOX 7.3 The Goat Dilemma: How Should Revenues From the Sale of a Goat Be Used?

A farmer sells her goat at the start of the planting season. Should she: (1) use the proceeds to buy fertilizer to apply at the recommended rate of 45 or more kg N/ha, which has been shown to be profitably applied to a maize crop? Or (2) should she use the proceeds to apply a moderate dose such as 17 kg N fertilizer per ha, and apply this over a larger area? She also needs to consider if she can afford to apply fertilizer and hire extra labor to weed the crop intensively. Her decisions need to take into consideration the value of concentrating the fertilizer in fields where she usually obtains high yields, versus a strategy that includes application of the fertilizer to low yield potential fields that might help enhance the yield output from the entire farm.

planning with tillage, pest management, marketing, and livelihood goals. A farmer perspective on the decision of how to best manage a fertilizer source use is illustrated by the "what to do with a goat's worth of proceeds" dilemma described in text Box 7.3. The question facing many smallholder farmers is how to optimize returns from the modest proceeds raised by selling one goat. Should this be invested in fertilizer, in improved seed, in hiring labor to carry out extra weeding, or in some combination of these strategies? Trade-offs need to be considered. Is it worthwhile to invest in fertilizer for parts of the farm where an extra weeding operation cannot be undertaken, due to labor or financial constraints? Integrated nutrient management occurs within the context of investment decisions such as these, which are made on a whole farm basis. This further complicates farmer decision-making, as an investment in fertilizer or compost at high rates in one field may preclude nutrient investment in other fields. An on-going question is the extent to which returns can be enhanced through targeting fertilizer to the highest performing fields, or through spreading fertilizer throughout a farm to obtain the high efficiency possible at low rates of fertilizer.

The interaction among these allocation decisions was studied using simulation modeling and on-farm research in southern Africa to evaluate combinations of weeding intensity and N fertilizer rates (Dimes et al., 2001). In these systems, N was the limiting nutrient, and therefore N fertilizer additions should have increased maize yields. However, yield increases were not achieved unless an extra weeding was carried out in fields receiving N fertilizer. For these site-specific management decisions, the most promising strategy is expected to vary, depending on the heterogeneity of resources across a farm, and the background rate of fertility, e.g., what production is obtainable without fertilizer, based on a minimal investment in planting, weeding, and harvest. To illustrate how allocation of resources to fertilizer applications

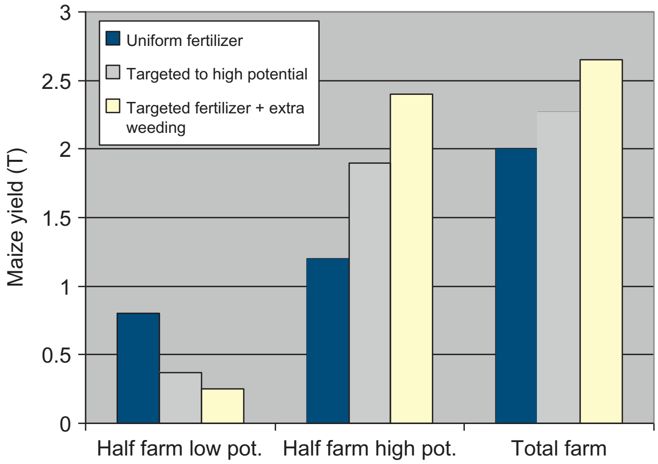

FIGURE 7.15 Effect of fertilizer and weed management decisions on total farm maize yield. Three possible scenarios are presented for investment in inputs by a smallholder farmer across a hypothetical farm, where half of the maize production area has low potential productivity (0.5 ha of 0.5 T/ha potential maize grain yield without inputs), and the other half has high potential productivity (fourfold higher yield potential without inputs: 0.5 ha with 2.0 T/ha yields). Maize production outcomes are presented for the two halves of the farm and on a total farm basis, for scenario (1) N fertilizer applied uniformly (solid blue bars), (2) N fertilizer targeted to the field with greater yield potential, and (3) a reduced amount of fertilizer combined with extra weeding, both targeted to the field with greater yield potential. The overall financial investment remains the same for all three scenarios.

and labor for weeding interacts with the inherent productivity at the farm-scale, we have compared the impact of three different management scenarios on maize yields (Fig. 7.15). Scenarios of targeted and homogenous application are explored for a farm with two maize production fields that vary in yield potential, one being low (0.5 t/ha without fertilizer), and the other high (2.0 t/ha without fertilizer). Uniform application of a 25 kg of fertilizer per ha rate across the farm lead to the lowest yield potential overall, although the poor yield potential site had a higher yield than in other scenarios. Scenario two targeted a higher dose of fertilizer to the high yield potential site, combined with a lower rate at the low yield potential site, and had a significant positive effect on the overall production of maize grain from the farm. Trading-off some fertilizer for an extra weeding, which is again targeted to the higher potential site, produced the largest maize yield overall for the same level of investment across the farm. Notice that, in this third scenario where fertilizer resources and weeding efforts are directed toward the more productive half of the farm, yields in the other half with poorer soils are exceedingly low.

The take home message from this example is that trade-offs occur across a farm, and the outcomes of management decisions will vary, depending on the particular situation on that farm. Yield from the low potential fields on a smallholder farm may be at such a low level that the grain produced and response to input is minimal, and is not able to significantly influence overall productivity of the farm. Abandoning part of the farm as a minimal investment site, and intensifying production on higher potential sites, may be a useful strategy in some circumstances. If input resources are limited, e.g., farmers may not be in a position to apply all of the inputs that economic returns would justify. It is important to take into consideration the background level of fertility, the interactions of fertility and other inputs at different sites across the farm, and overall, the response of staple grains to complementary investments over the short and long-term, including weeding and SOM building practices.

DEVELOPING SITE-SPECIFIC ECOLOGICAL NUTRIENT MANAGEMENT SYSTEMS

Clarify Goals of Nutrient Management

A first step in managing the nutrient cycling to support agricultural goals is to identify nutrient management goals for your agroecosystem. What are the yield and fertility objectives? What is the relative balance between fertility and food or nutritional goals? Is there a perceived problem that needs to be addressed? Initially, the goals do not need to be prioritized or evaluated for whether or not they can be reasonably achieved. Refinement of goals will be easier after a concept map is developed.

Concept Map of Nutrient Flows

Drawing a conceptual diagram of nutrient flows, compartments, and processes regulating those flows, similar to some of the diagrams we have used in this chapter, can be a useful exercise. The use of conceptual models as communication and planning tools has proven to be a useful tool for facilitating communication and planning in groups with diverse perspectives (Heemskerk et al., 2003). A conceptual model is a visual representation of the system to be studied. Conceptual models are particularly useful in planning interdisciplinary agricultural systems research, because they require the team to graphically represent the problem to be addressed within a larger, systems context. Ideally, to be useful as a planning tool, a conceptual model should:

- Describe a system that encompasses the research questions/management issues, but has clear boundaries;
- Explicitly define the components of the system and how they interact with one another. For example, it should identify the factors that directly or indirectly contribute to production, environmental outcomes, or nutrient flows;

- Provide a logical framework for the problems or questions to be addressed;
- Be simple enough to be understood by scientists from a variety of disciplines and stakeholders;
- Be developed and agreed upon by all stakeholders and researchers.

Diagrams of agroecosystem nutrient flows can serve as an vehicle for achieving several outcomes which are prerequisites for successful implementation of ecologically based nutrient management. This process is important for:

1. *Facilitating information exchange*: Ensures that farmers and researchers have an agreed-upon understanding of nutrient management practices, while also helping scientists to share information about important soil processes that control nutrient availability with farmers.
2. *Organizing a complex system*: By laying out the relationships among the interacting processes that are occurring at different spatial and temporal scales, trade-offs and linkages between management strategies become apparent.
3. *Moving the local nutrient cycling knowledge system forward*: The process of agreeing upon a diagram that represents diverse perspectives helps to identify knowledge gaps, while also promoting the incorporation of innovations and new knowledge into the shared knowledge structure.

Resource Inventory

As part of the information gathering stage, it is important to define the agroecosystem characteristics that provide the backdrop for nutrient management decisions. These include:

1. *Background environment*: Soil types, soil fertility status, climate;
2. *Cropping system characteristics*: Crops that are grown, rotation, and proportion of land that is usually in each crop, relationship between crops, forage, and animal production, field sizes, locations, management intensity;
3. *Nutrient input sources*: Identify the sources of nutrients that are locally available, and constraints which impact their use by farmers;
4. *Relationship to other management practices*: How do other management issues such as weed control, and tillage systems impact nutrient management?
5. *Fate of crops*: Important to distinguish between crops grown for family consumption and those aimed at markets, identity of markets, relative value of cash crops.

There are numerous resources available outlining methods that can be used in characterizing agroecosystems and in problem diagnosis (i.e., Gonsalves et al., 2005).

Revisit and Refine Goals

With the above information in hand, it will be possible to prioritize, evaluate trade-offs, and identify which goals are easily achievable. At this point, a useful step might be to distinguish between long-term and short-term goals. If a farmer-identified problem is the catalyst for this evaluation, then the range of possible solutions should be evaluated using the conceptual diagram and information that has been gathered.

Quick Assessment of Consequences of Current Nutrient Management Practices

Before moving forward to develop nutrient management strategies to achieve the goals (or solve the problems) which have been identified, prioritized, and analyzed, construction of simple input−output balances is a further step that can be used to analyze the current management. This approach has proven useful in pin-pointing the most important weaknesses in nutrient management systems which are currently being used by farmers. In the United States, application of this tool indicated that organic vegetable growers were over-applying compost, leading to environmentally unsound levels of soil P. In Andean systems, this approach demonstrated that P management practices in fields closer to the community provided sufficient P, and were compatible with increased use of legumes for N fixation, while fields that were farther from communities did not receive adequate P to benefit from legume intensification (Vanek and Drinkwater, 2013). Further study of these systems revealed that potassium was being extracted at rates that far exceeded inputs, indicating that over the long-term, potassium limitations may reduce yields. An additional example is the resource allocation maps (RAMS) which are specifically designed to track nutrient flows at the farm or community scale, where transfers across fields, rangeland, and corrals are important (Box 7.4, Defoer, 2002). Readers should visit the website for this textbook for updates on tools which are being developed to facilitate the use of nutrient budgeting in developing management strategies.

Selecting and Testing Promising Nutrient Management Practices

Using this iterative process, a collaborative team can colearn with farmers regarding which management strategies are worthy of further testing and research. There is no single process that should be used in making these decisions, however, if a number of competing practices are identified, a simple method for comparing and contrasting these practices is to list the strengths and weaknesses of each. Also, the relationships between practices should be considered. Once you have agreement from farmers and other

BOX 7.4 Mapping Farm and Community Scale Nutrient Flows

Participatory research approaches have illustrated that farmer resource management can be improved through maps of agroecosystem nutrient resource flow, also called RAMS (Defoer, 2002). Farmers and researchers together develop the maps and use them to record, monitor, and analyze data and decision-making, which enhances understanding of soil fertility status, nutrient transfers, and degree of recycling associated with management options. Information gathered in this way is of value at different levels. This includes local participants who may be able to better assess where losses are potentially high on their farm, and thus where opportunities to recycle should be concentrated to improve overall nutrient efficiency. The RAMS approach illustrates the exciting potential of approaches that act as an interface between a "hard system" of knowledge (resource flow budgeting which can be used for modeling and comparisons with other systems), and a "soft system," integrating knowledge gained from collaborating with farmers and improving understanding of farmer perception of losses, gains, and transformations within and across a farm. Participatory research that integrates qualitative and quantitative approaches may provide new insights into designing sustainable agricultural systems that are not only efficient from a bioengineering perspective, but also are relevant to real world farmers.

At a community or small watershed scale, resource mapping is also being pursued as a means to enhance understanding and recycling of resources on a larger scale than the farm. In Nicaragua, e.g., participatory microwatershed studies were initiated through community meetings of stakeholders, where resource mapping, transect analysis, and indicator-based assessment was used to evaluate current status and opportunities for improvement.

Livestock-crop integrated systems are ideal ways to concentrate and transfer nutrients, as animal manure is collected by corraling animals at night, and during the day pasturing them over a wide area. A cow pastured on four hectares can provide sufficient nutrients to support half a hectare of nutrient-demanding crops such as maize. Thus, livestock transforms a widely spread, relatively unavailable nutrient source from wild or semiimproved pastures, or even urban streets, and concentrates these nutrients as manure, which can be targeted to specific crops. Transhumerace, nomadic livestock systems that move through field crop areas and trade residue grazing for transient manure deposition, were once one of the most common land use systems in the world.

stakeholders about which practices are of the most interest, you can design research trials to evaluate and optimize these practices. This research should be conducted in farmer's fields as much as possible, using participatory experimental designs such as the mother–baby scheme (Snapp et al., 2002). To succeed, research aimed at supporting ecological nutrient management must be conducted within a systems-context, and must apply participatory methodologies.

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Chapter 8

Participatory Breeding: Developing Improved and Relevant Crop Varieties With Farmers

Eva Weltzien and Anja Christinck

INTRODUCTION

Plants and animals are part of agroecological systems; their genetic and phenotypic properties are intimately related with the natural environment in which they occur, and multiple relationships exist with other components of these systems. However, cultivated plants and domesticated animals have a special position within the agroecological system; directly or indirectly, they serve the livelihood needs of people. Their evolution has been closely linked to the rich diversity of human social, cultural, and economic activities under specific environmental conditions; they are thus simultaneously a natural resource and a cultural asset (Padmanabhan et al., 2013).

Since the very beginning of agriculture, people have tried to alter plants and animals in such a way that they are better adapted to their felt needs. Adapting plants and animals to human needs could be described as the most general goal of breeding. Until quite recently in our history, breeding was done only by farmers.

Today, farmer-selected and farmer-produced seed continues to be the primary source of seed in many parts of the world. Plant breeding activities of farmers usually form part of their general agricultural practices and include operations such as mixing, exchanging, selecting, and storing seed. Selection by farmers is usually based on their observation and understanding of environmental adaptation and quality requirements, and is thus closely related to local knowledge and cultural traditions. Farmer breeding is thus an activity that reveals clearly how agroecological systems and their

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components are shaped by human management decisions, and depend on them (Kaufmann et al., 2013).

Since plant breeding emerged as a scientific discipline, a new system of variety development, testing, and release was established. This “formal” system coexists with the “informal” farmer system of crop management and enhancement. Most farmers in the world currently use both formal and informal systems for sourcing seed of crop varieties. However, many local crops, even if economically important, as well as locally adapted landraces of staple food crops, continue to be mainly available from the informal system.

The rich diversity of adapted crops and varieties for specific agroecological “niches” has allowed people to settle and survive in diverse environments, and even under harsh climatic conditions, on steep slopes, poor soils, or under conditions such as recurrent droughts, floods, or storms. Many such farming systems are presently undergoing rapid change, which leads to growing demand for new crop varieties. For example, the sizes of landholdings are continuously declining in some areas, resulting in a reduction of fallow periods, and a need for agricultural intensification. Climate change can lead to rising temperatures, altered rainfall patterns, or increased incidence of pests and diseases. Furthermore, new options may emerge for marketing, processing, innovative products, fair trade, and so on, which also require new varieties. Hence, many traditional crops or crop varieties that were ideally adapted to certain farming practices and site-specific conditions tend to disappear, because of technological or climate change, economic pressure, changed food habits, or loss of traditional knowledge. Plant breeding could make an important contribution to safeguarding such varieties by readapting them to present conditions, technologies, and needs.

Formal plant breeding programs have clearly made major contributions to cropping system productivity around the world. However, the farmers’ adoption of varieties from the formal system remains limited under certain conditions, particularly under marginal agroecological conditions, or if access to resources is limited. Under such circumstances, “high-yielding” varieties may not be superior to traditional varieties, as they lack important adaptive or quality traits. Thus, awareness is rising that plant breeding is not a user-neutral technology: various groups of farmers may need different types of varieties, depending on the farmers’ access to resources, and the intended use (Harwood, 2012). However, even in better-off regions, there is rising awareness that formal plant breeding does not always address the farmers’ preferences and needs, or that the diversity and stability of farming systems could be better supported by applying new types of breeding strategies that are based on collaboration between researchers and potential users of new varieties.

In the last decades, the application of concepts from participatory research in general to plant breeding has evolved rapidly. This has opened new options for project and program design, especially in view of addressing a wider range of development goals. Many international and national plant breeding institutions oriented their programs toward the United Nations' Millennium Development Goals (UNDP, 2014), and the International Treaty for Plant Genetic Resources (FAO, 2009), and will adapt them to meet the recently announced Sustainable Development Goals for the period 2015–30 (UN, 2015). The Human Right to Food is another highly relevant international policy instrument that gained importance after the "Voluntary guidelines to support the progressive realization of the right to adequate food in the context of national food security" were adopted by the FAO Council in 2004 (FAO, 2005).

As a result, publicly funded plant breeding has progressively been targeted to address the needs of specific users, particularly poor farmers and people affected by food insecurity, and closely related to this, to commitments regarding the sustainable use of crop genetic resources (e.g., ICRISAT, 2006).

Examples are regional frameworks for agricultural research, such as the Integrated Agricultural Research for Development (IAR4D) framework of the West and Central Africa Council for Agricultural Research and Development (CORAF/WECARD), that increasingly build on process-related criteria and use multistakeholder platforms as instruments to institutionalize user-orientation at different levels and scales (CORAF/WECARD, 2011).

THEORY OF PARTICIPATORY PLANT BREEDING

Definitions and Terminology

Participatory plant breeding (PPB) includes various approaches of close farmer–researcher collaboration to bring about plant genetic improvement within a species. The basic idea is that farmers and researchers have different knowledge and practical skills, as well as divergent approaches to problem diagnosis and solving (Weltzien et al., 2003). The strengths and weaknesses of both groups tend to be complementary, so that better research results can be achieved through cooperation (Hoffmann et al., 2007).

All the different phases or stages of a plant breeding program are concerned, and options for farmer participation exist for all of them: setting objectives, creating variability, selecting experimental varieties and testing them, as well as producing and diffusing seed of new varieties (Fig. 8.1).

Collaboration between farmers and scientists can take many forms, and roles and responsibilities can be shared in many diverse ways. Some researchers have tried to classify PPB approaches according to the form of collaboration or the locus of decision-making (Farnworth and Jiggins, 2003; Lilja and Ashby, 1999). In any PPB program, farmers contribute knowledge and information to the joint program, and in some cases also genetic material. For example, farmers can contribute their own check or control varieties to trials, or farmer varieties can also be used as breeding parents in crossing programs. In addition, farmers may be directly involved in the breeding process by

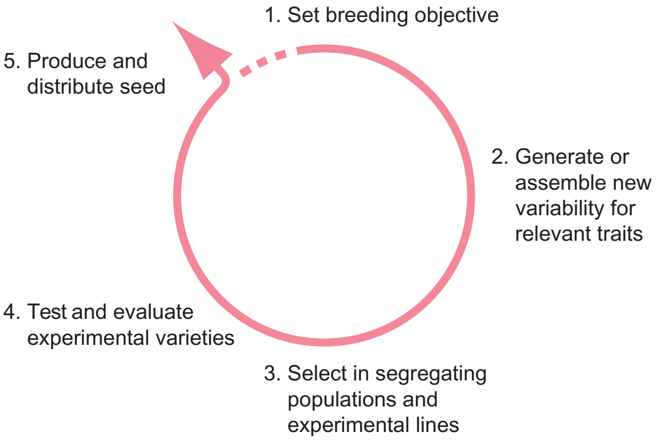

FIGURE 8.1 Stages of a plant breeding program. *From Christinck, A., Dhamotharan, M., Weltzien, E., 2005a. Characterizing the production system and its anticipated changes with farmers. In: Christinck, A., Weltzien, E., Hoffmann, V. (Eds.), Setting Breeding Objectives and Developing Seed Systems with Farmers. Margraf Verlag, Weikersheim, Germany, and CTA, Wageningen, The Netherlands, pp. 41–62, p. 11.*

conducting and managing trials on their own land, and making selection decisions in various ways. Thus, in addition to knowledge and genetic material, other major contributions of farmers in PPB programs are labor and practical skills regarding the evaluation and selection of test entries.

As with any developing field of research, the terminology for PPB has not been fully standardized, and is used differently by different groups of researchers. Some of the more commonly used terms are explained in the following paragraphs to assist the reader with interpretation of the growing PPB literature.

As in this chapter, PPB is used as an overarching term that includes all approaches to plant breeding, with close collaboration between farmers and researchers (Weltzien et al., 2003). However, some authors focus on the stage of the breeding program in which the collaboration takes place, and on the status of the germplasm under consideration. In this context, one of the most commonly used terms is *participatory variety selection* (PVS). It is used to describe farmer participation in the process of evaluating finished, stable varieties. Accordingly, the term *participatory plant breeding* (PPB) is then used only when the project involves farmers' contributions in the earlier phase of variety development; i.e., making crosses or selections in the early (segregating) generations. It is thus important to verify in which way the term PPB is being used in specific publications. Publications that use PPB in a "narrow" way tend to use *farmer participatory crop improvement* or *collaborative plant breeding* as overarching terms, which include then both PVS and PPB (Cleveland and Soleri, 2002; Witcombe et al., 1996). These terms are, however, used only rarely.

The term *decentralized plant breeding* puts emphasis on the importance of selection in the target environment, i.e., farmers' fields, based on considerations regarding the interaction between plant genotypes and the environment. This approach may, however, also imply farmer participation in the selection and diffusion of varieties (Ceccarelli et al., 1996, 2000). Lastly, the term *client-oriented plant breeding* (COB) has been proposed with the aim to avoid an artificial dichotomy between "participatory" and "nonparticipatory" breeding approaches (Witcombe et al., 2005). The essential strength of participatory methods is seen here in improving the client-orientation of formal breeding programs, with productivity gains and research efficiency as the main goals.

In recent years, involvement of other stakeholders (besides farmers) has gained importance in PPB projects, particularly when biodiversity conservation and breeding activities are tied to value chain development. Such projects tend to involve a variety of actors along food supply chains, and use multistakeholder approaches to achieve their goals. Stakeholders can include, e.g., traders, food processors, restaurant chefs, and urban consumers (Padulosi et al., 2014; Jäger et al., in prep.). In view of this rather confusing terminology, we use PPB in its most generalized meaning throughout this chapter, with a focus on describing the broad range of goals pursued by PPB programs, and the various ways for achieving them.

Typical Elements of Participatory Plant Breeding Approaches

Even though various groups of researchers emphasize different aspects and potentials of PPB, all the approaches developed under the aforementioned terms have some essentials in common:

- New forms of cooperation;
- Detailed assessment of agroecological conditions and farmers' needs;
- Use of local germplasm;
- Decentralized organization and selection in target environments;
- Innovative strategies for seed production and distribution.

In addition, there may be other elements that are important for some but not all PPB projects, such as strengthening indigenous knowledge and culture, conserving traditional crop varieties, improving nutrition and consumer health, developing innovative products and markets, or empowering farmers or specific groups, e.g., women and their organizations.

In the following sections, we will outline certain theoretical considerations behind these elements, which have led various groups of researchers to depart from the ways how things used to be done "normally" in formal plant breeding programs.

New Forms of Cooperation

A variety of goals of very different nature tend to be addressed by PPB programs, some of which may be quite general goals, which cannot be met by plant breeding alone, such as poverty alleviation or empowerment of farmers. However, PPB could be an important building block for addressing such goals, particularly if it would become part of a more far-reaching development strategy. In such a setting, PPB cannot be planned by one institution alone; very typically, PPB projects rely on various partners, including national or international research institutions, farmer organizations, nongovernmental organizations (NGOs), and local state authorities. In some cases, the private sector is also involved, e.g., if industrial food processing and marketing are part of the intended strategy.

The process of setting priorities is extremely important for any plant breeding program, but even more so for a PPB program: a shared vision about the goals needs to be achieved among all partners involved (Fig. 8.2). It is, therefore, important that discussions about the goals are held regularly to ensure that the goals remain relevant, and that they are evident and important to all partners involved in the program. These identified goals are then the guiding principles for priority setting, and should be formulated in a way that facilitates regular adjustments and refinements as the program and the partnerships evolve. Furthermore, indicators that could help monitor the progress should be identified, and a process of monitoring and evaluation installed (Germann et al., 1996).

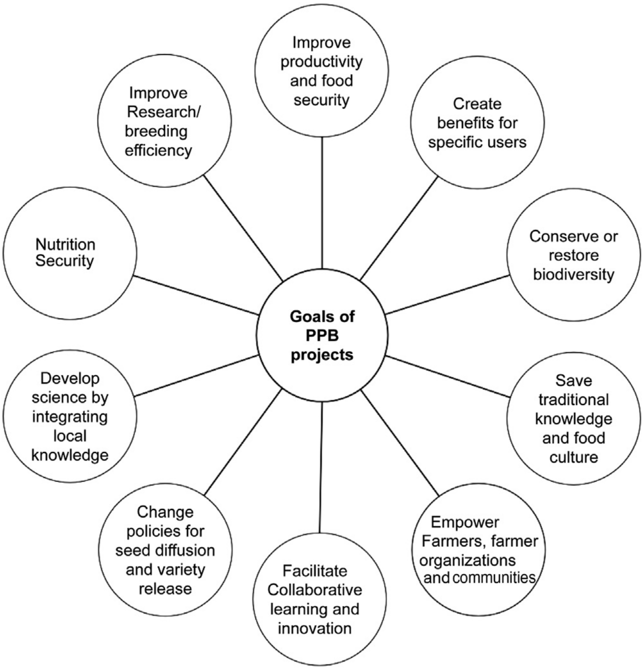

FIGURE 8.2 Possible goals of participatory plant breeding projects.

BOX 8.1 Key Issues for Priority Setting in a Participatory Plant Breeding Program

1. Define the *target group* and the *environment*, i.e., production conditions in which the newly identified varieties should perform better than existing cultivars, and the specific needs of the target group of farmers.
2. Closely linked to this are priority traits to be used as *selection criteria*.
3. To achieve good progress from selection, the *germplasm base* must be chosen appropriately.
4. It is also important to discuss what *type of variety* might be the most appropriate for achieving the goals, e.g., open pollinated, rather diverse varieties may better achieve goals of diversity conservation than single-cross hybrids.
5. An issue that is often left until activities are planned is the identification of key *roles and responsibilities of partners*. Since, however, different options for sharing responsibilities have a major impact on some of the goals, it is important to consider roles and responsibilities of different partners from the outset of the breeding program.

The priority setting process requires detailed information on a variety of key issues (see Box 8.1). This information is seldom “available”’ before the project starts, and studies should be designed in such a way that the points of view of each partner group (particularly the farmers) will possibly be expressed and documented for the further planning process.

Experience gained in a number of PPB projects has shown that participatory communication tools, such as semistructured or informal interviews, focus group discussions, wealth ranking, transect walks, time lines, mapping, classification, and ranking exercises, can be extremely useful for reaching a good base for further planning. The particular strength of such communication tools is that they facilitate direct dialogue between farmers and researchers, and can help develop a common understanding of the situation, as well as of main constraints and needs. Practical guidelines for conducting such a situation analysis, particularly for plant breeding projects, have been suggested by Christinck et al. (2005c). Furthermore, many inspirations can be extracted from general guides and publications on participatory research (see Box 8.2).

Detailed Assessment of Agroecological Conditions and Farmers’ Needs

In general, it is impossible to successfully develop a highly specialized and adapted technology if the conditions under which it is going to be operated are only vaguely known. This was the situation of many formal breeding programs in developing countries; often, it was simply presupposed that farmers would need a particular variety type, or that increasing the yield potential of certain major crops would per se be attractive for farmers; however, low adoption

BOX 8.2 Participatory Research Methods

Sources of information and training materials on participatory research methods are listed below. We concentrate on selected publications that are available via the internet, usually free of cost.

The websites of the Food and Agriculture Organization of the United Nations (FAO) (www.fao.org) and the World Bank (www.worldbank.org) contain sections on publications (→ e-library) for download and/or purchase (search for participation or PRA methods).

Guides on participatory methods and gender analysis can be downloaded from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) homepage (some available in various languages, including Spanish or French) http://www.giz.de/en/mediacenter/publications.html

A more in-depth reflection on specific aspects of the application and use of these communication tools is offered by a journal called Participatory Learning and Action (PLA) Notes, published by the International Institute for Environment and Development (IIED) in London (visit http://pubs.iied.org/search.php?c=part for free download).

rates and no or insignificant yield increases under farmers' production conditions teach us that these assumptions were not generally true.

Under marginal conditions, farming is usually part of a complex livelihood strategy. It may interact with many other activities pursued by the members of a farm household, including animal husbandry, handicrafts, food processing and marketing, labor work, and seasonal migration. Therefore, understanding the general production goals and the importance of farming and certain crops within the people's livelihood strategy, as well as cultivation practices, uses, and the main constraints to yield increase or income generation, will be general preconditions for successfully developing plant varieties that meet farmers' requirements.

A crop can fulfill many different functions in the farming system. Farmers often use different products from one plant, and the value of these "by-products" can even exceed that of the main product, or be of great use in certain situations. The importance of multipurpose uses can vary largely from crop to crop, and for different groups of farmers. Fig. 8.3 summarizes various functions of a crop for rural people's livelihoods, and shows how different the situation can be for different crops or crop varieties.

However, a situation analysis should also focus on the typical constraints of the system, in view of both agroecological and socioeconomic considerations. This could also be an opportunity to recheck whether PPB is really the solution to the constraints and problems identified together with the farmers, before starting the actual breeding work. Other options, such as the reintroduction of landraces, improved seed production, or market development and training, should be weighed and considered carefully as alternatives or

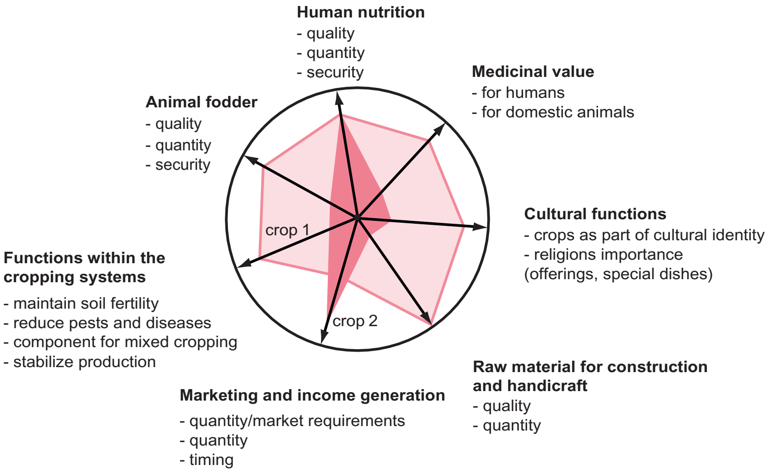

FIGURE 8.3 Functions of crops within a farming system; crop 1 is a typical multipurpose crop with high importance for most functions (except marketing), whereas crop 2 is a food crop important for nutrition and marketing, but not for other functions mentioned. *From Christinck, A., Dhamotharan, M., Weltzien, E., 2005a. Characterizing the production system and its anticipated changes with farmers. In: Christinck, A., Weltzien, E., Hoffmann, V. (Eds.), Setting Breeding Objectives and Developing Seed Systems with Farmers. Margraf Verlag, Weikersheim, Germany, and CTA, Wageningen, The Netherlands, pp. 41–62, p. 43).*

complementary options. Quite often, PPB may be only a part of the solution; strategic partnerships with NGOs, farmer organizations or commercial enterprises, starting from the early stages of the project, can help increase the impact and sustainability of the PPB work.

Farming systems in many parts of the world are presently undergoing processes of gradual or rapid change. It is usually complex in nature because agroecological, sociocultural, political, and economic factors interact, causing very specific sets of conditions at the local level.

Change is an important motivation for farmers to search for new varieties. Generally, we should be aware that farming systems have not been static in the past and that adapting to variable conditions and allocating resources accordingly are key capacities of farmer families all over the world. However, the ability to adapt specifically to rapid change depends much on the natural, technological, economic, and human/social resources that are available to individuals or groups of people, and whether these resources are useful to tackle the new situation. Change can be a slow and constant process that develops over decades—or it can be associated with catastrophic events, such as wars, political and economic crises, floods, and earthquakes. Accordingly, people may or may not have useful resources at their disposal, and various groups of people may be affected differently or need different solutions to solve problems associated with change.

Interest in new crop varieties can emerge from such dynamics, thus being an important motivation for farmers to participate in a PPB project. That is why taking a deeper look into the processes of change, as well as causes and effects leading to change at a local level, is a major point of interest in setting objectives for a PPB program (Table 8.1). Even if it is not always possible to anticipate future developments, it could at least be possible to identify major trends and their effects on the farming systems and people's livelihood strategies, and collaboratively agree on them with the project partners; furthermore, approaches to adjusting the program as the understanding of the situation develops should be considered.

Use of Local Germplasm

In many PPB programs, local germplasm, such as traditional landraces, seed mixtures, or individual farmers' populations, is being used as breeding material. It represents a key source of variability, especially for local adaptation, and for meeting grain quality requirements, whereas breeders' lines tend to contribute specific traits that may help overcome existing weaknesses of local germplasm, such as resistance to diseases, pests or drought.

Choosing and creating genetic variability for selection are of key importance in plant breeding programs. All the desired traits need to be present in the breeding material, and the genetic variation with regard to important traits determines the level of improvement that can be achieved during the selection phase. Identifying and creating variability for selection can involve direct selection in suitable landrace populations, identifying appropriate parents for crossing, or creating new base populations. Various possibilities exist to ensure that important adaptive traits will be present in appropriate frequency and variability in the base populations (see Box 8.3).

In cross-pollinated crops (such as maize or pearl millet), crosses between different varieties and populations occur naturally, if the parental material grows in close vicinity and flowers at the same time. Farmers can thus easily produce crosses between local and exotic germplasm by growing them in the same field, possibly as a mixture. In situations where it is a normal practice of farmers to select seed, providing interesting, useful new germplasm for crossing may be a key input from researchers who wish to strengthen the farmers' capacity to create their own new varieties.

Farmers can also learn to make targeted crosses, both in cross-pollinating and self-pollinating crops, and some farmer-managed PPB projects have asked researchers for this type of training. However, in most PPB projects, targeted crossing has been done by professional plant breeders because of efficiency considerations.

When planning a participatory hybrid breeding program, decisions have to be taken about the type of germplasm to target for use as seed parent, and which to use as pollinator parent. In situations where farmers themselves are

TABLE 8.1 Changes of Various Types of Conditions and Possible Effects on Cropping System and Variety Use

Type of Change	Possible Effect on Cropping System and Variety Use
Agroecological Conditions	
Reduced soil fertility due to erosion, reduced fallow periods, lower number of farm animals (manure)	Lower yield, increased intensity or greater variety of pests, diseases, or parasitic weeds
Amount of rainfall reduced or increased, onset of rainy season earlier or delayed, different rainfall distribution patterns	Reduced yield stability, higher risk of crop failures, higher or different pest and disease incidence, shift to other crops
Increased temperatures	Crops negatively affected by drought and heat
Higher frequency of adverse conditions, such as frost, thunderstorms, sandstorms, etc.	Higher risk of crop failure (due to damage)
Newly introduced pests and diseases	Lower yield, risk of crop failure
Access to irrigation or changes in the quality/availability of irrigation water	Shift to crops or varieties with higher yield potential or specific adaptation (to water lodging, salinity, etc.)
Socioeconomic Conditions	
New marketing opportunities due to food processing factories, new infrastructure, exports, etc.	Crops/varieties with special characteristics required (to meet market demand)
Introduction of new farming technology (such as animal traction, tractor plowing, harvesting machines)	Need for adapted crops/varieties
Reduced availability of farm labor due to other economic activities	Crops/varieties, which require less labor, required
Access to agricultural inputs (such as seed, fertilizer, pesticides)	New options to grow crops/varieties with higher yield potential, able to respond to improved soil fertility
Failure of agricultural input supply (due to crises, wars, or disasters)	Low-input varieties required
Culture and Knowledge	
Erosion of traditional knowledge and skills	Traditional varieties are abandoned or may need to be adapted to present knowledge and technologies
Shift of food preferences	Traditional crops/varieties may be less (or more) preferred than before

BOX 8.3 Possibilities for Improving Chances of Success by Creating Variability for a Specific Breeding Program

- All traits required for a successful variety need to be present: good local adaptation, grain quality for primary uses, and resistance to common pests and diseases;
- Genetic diversity for the traits under improvement to ensure rapid progress from selection;
- Provide for ample recombination between different parents used in crossing, e.g., large populations for bi-parental crosses, several random matings, and large population sizes while building base populations;
- Use large parent population sizes when creating new population crosses or new bulks to avoid genetic drift and inbreeding;
- Conduct evaluation of parents and base populations under target conditions to avoid loss of key adaptation traits;
- Increase frequency of well-adapted genotypes in the base population(s);
- Use well-adapted, farmer-preferred parent as recurrent parent for one backcross, especially if "donor" parents are very different from farmer-preferred varieties, or if adaptation and use requirements are very complex.

going to produce the hybrid seed, it is important that the pollinator parent meets the requirements for a farmer-preferred variety, as the grain produced on this variety will be used for local consumption, and may contribute to the food security of the seed producers in highly decentralized systems. In addition, in most crops it may need to carry genes for restoring pollen fertility in its offspring, produced on a male-sterile seed parent. The seed parent germplasm, on the other hand, needs to fulfill the biological requirements for useable male-sterility in most crops and provide interesting hybrid combinations with the targeted male parent. Ideally, it should be shorter in height than the male parent, so that the pollen can fall down onto it, and it should have desirable grain quality, so that seed that will be sold is attractive. Furthermore, it should be high yielding itself, so that seed production is profitable.

Decentralized Organization and Selection in Target Environments

The most general aim of selection during early generations of breeding populations in the target environment is to ensure adaptation to specific (often marginal) agroecological conditions, which cannot easily be "simulated" in research stations. These agroecological conditions include, in addition to location-specific factors (such as soil or water quality, climate), management practices that may affect the performance of a variety, e.g., mixed cropping or local practices for soil preparation, sowing, weeding, or harvesting.

Plant breeders call the issue that certain plant types or varieties may perform differently in different environments "genotype by environment interaction" (or G × E). In general, most plant breeders tend to give preference to those populations that perform well under a wide range of conditions: "broad adaptation" is an important feature of new varieties, particularly with regard to breeding economics, e.g., the size of the potential market. However, these varieties may fail under specific growing conditions, often those of poor farmers working with limited resources, and under marginal agroclimatic or soil fertility conditions. Ceccarelli et al. (1996, 2000) have shown theoretically and practically that plant breeding programs need to address specific target environments when interactions between genotype and environment exceed certain limits, or show patterns with incompatible adaptation requirements. Breeding for adaptation to specific site conditions ("narrow adaptation") is often regarded as an advantage of the PPB approach. If planned and implemented in a consistent manner, such an approach will lead to the development and release of a range of new varieties, each adapted to specific niches, conditions or requirements, and may enhance the overall level of agrobiodiversity in farmers' fields (Haussmann et al., 2012; Joshi and Witcombe, 2001; Sperling et al., 1993).

The involvement of farmers in selecting among early generation breeding material has various other advantages beyond ensuring environmental adaptation. Witcombe et al. (2006) listed the following circumstances under which farmer collaboration in the early selection phase is particularly beneficial:

1. If empowerment of farmers is a main objective of the breeding program, strengthening their knowledge and skills regarding crop improvement and utilization of genetic diversity are important for reaching this goal.
2. If farmer-preferred traits and selection criteria are not (yet) well known and/or joint learning is one of the objectives of the PPB program.
3. If consumer preferences for grain qualities are important and complex, it is difficult to do selection for such traits on the basis of laboratory tests.
4. If farmers have complex selection criteria with trade-offs among traits being very specific.
5. If it is economically reasonable to do the selection on farm (rather than on research stations) because farmers are able and willing to contribute important resources and skills to the breeding program without receiving payment, or at lower cost compared with research stations.
6. If the size of the market is too small for private or public sector investment (i.e., because of very specific site conditions or market preferences to be addressed), or if the needs of the farmers are not adequately considered in existing breeding programs because of lack of communication, lack of knowledge, or other priorities set.

Options for farmer participation in a decentralized breeding program are highly diverse. Many farmers have strong skills and profound experience in

BOX 8.4 Improving Chances of Success for Decentralized Selection in Early Generations

- High selection intensity, i.e., selection of only a few clearly superior plants or lines out of a large number of individuals;
- Homogeneous field conditions so that differences among plants are not masked by differences in soil conditions;
- Selection criteria that can be evaluated on single plants/rows with reasonable heritability;
- Clear vision or understanding of the selection target(s);
- Good knowledge of parental material, inheritance of selection criteria, and methodological options.

selecting individual plants from larger populations. In such cases, it is feasible to give them population bulks of diverse material that harbor all the necessary traits for improvement. Some interested farmers can manage the entire population for a number of generations using the selection technique she or he is familiar with, but applying it to material more diverse than is normally available locally. There are cases were farmers have developed new open-pollinated varieties using this procedure. These varieties can later on be tested in a multilocation testing scheme to compare their yielding ability and range of adaptation to other varieties. Various factors for success are listed in Box 8.4.

Working with relatively few, but highly interested farmers ("expert farmers") appears to be most effective during this stage of a breeding program (Witcombe et al., 2006)—if the goal is developing one or several new varieties. Otherwise, if training and empowerment of farmers or biodiversity considerations are the focus of the PPB activities, more farmers may need be involved. In some projects, farmers visited research stations and selected from early generation material for further testing and evaluation on their farms (Sperling et al., 1993). Also, early generation trials were entirely grown on farm, and the farmers of the village made their own selections from such trials (Rattunde et al., 2016; Ceccarelli et al., 2000). Such practices can lead to a great number of selected and further propagated "varieties" and to the rapid spread of innovative material with preferred traits, but not necessarily to the development of stable varieties for release and diffusion through the formal seed system.

Besides capturing the advantages of selection in target environments and farmer participation during selection in early generations, a decentralized organization is also useful for the variety testing phase—the final stage of variety development. It requires a number of experimental varieties to exist, which are stable and reproducible; furthermore, sufficient quantity of seed should be available for testing on a larger scale. Chances for success during

BOX 8.5 Improving Chances of Success During the Variety Testing Phase

- Genetic diversity expressed among experimental varieties for key selection criteria;
- Experimental varieties do not have major weaknesses that hamper acceptability;
- High selection intensity;
- Testing environment reflects well the conditions in the target environment for the new varieties;
- Trial management that maximizes heritability for key selection criteria, e.g., sufficient replication, appropriate trial design, and sufficient number of locations for testing.

this phase of a breeding program are determined by the diversity and the trait combinations expressed in the new materials, as well as by the quality of testing (Box 8.5).

One key advantage of farmer participation during this phase is the evaluation of new varieties in farmers' own fields, under their own management. Thus, the varieties are tested directly in the target environment (see earlier discussion). Participatory evaluation trials are usually grown by a larger number of farmers, thus covering a wide range of possible growing conditions in the target environment. This gives farmers and breeders a chance to observe the varieties' responses to different, locally prevalent stress factors. Farmer-managed trials are often exposed to severe types of stress, e.g., poor soil fertility, delayed weeding, or temporary flooding. In such cases, particular adaptation characteristics or weaknesses of the new varieties may be discovered during the testing phase. On research stations, such extreme stress conditions occur very rarely. However, farmers tend to choose new varieties primarily if they perform better than their local varieties under extreme stress conditions: "Harvesting something in a difficult year is more important than having more surplus in a good year" is a common and plausible reasoning by subsistence farmers.

The form of cooperation between farmers and plant breeders in a decentralized variety-testing scheme may vary: sometimes farmers and breeders evaluate separately so that mainly the results of it "counts"; in other cases, there is more intensive dialogue on relevant criteria and the underlying concepts. Learning from each other and integrating farmers' and "scientific" knowledge would then be part of the project outcomes.

Farmers benefit from exposure to a large number of new varieties to choose from; they can identify varieties for different types of conditions, uses, and market opportunities. PPB practitioners regularly observe that different farmers prefer different varieties, for very specific reasons. Therefore, the participating farmers should ideally represent various groups and conditions. For example, subsistence farmers or people selling on local markets often prefer different varieties than farmers who grow the same crop for national or international markets. In addition, if animal husbandry is an important part of the agricultural activities, varieties with a higher total biomass yield or better fodder quality may be preferred. Furthermore, access to resources and agricultural inputs, such as irrigation water or fertilizer, availability of labor, or technical equipment, as well as cultural traditions and individual preferences, tend to influence the varietal preferences of farmers.

A further advantage of farmer participation in the advanced stage of variety development is that seed of preferred varieties can be harvested and multiplied immediately. Very often, breeders observe that "adoption" of really promising varieties happens long before they are officially released. Neighbors and relatives can see the new varieties under "real" conditions, and may ask the owner for seed. Therefore, the benefits from newly developed varieties reach the farmers much earlier than through the formal system (even though on a limited scale), and such informal seed diffusion in the variety testing phase should be observed and monitored carefully. This information could give important indications regarding the size of the future market and the potential customers of the new varieties. However, restrictive seed laws can impede this early adoption, a fact that should be considered and addressed when planning the trials (see also next section).

Innovative Strategies for Seed Production and Distribution

For a plant breeder, the "normal" way of organizing the diffusion of seed of a newly developed variety is through the formal seed system. Private or parastatal companies organize the production and sell the seed ("certified seed") to farmers, and depending on the legislation of the country, the seed has to fulfill certain legal requirements. Farmers, however, would usually use their own seed, or informal networks, for accessing and distributing seed. Fig. 8.4 shows formal and informal seed systems, and the ways in which they may interact.

Both formal and informal seed systems have their specific strengths and weaknesses (see Table 8.2). This is why many PPB projects have tried out innovative strategies, such as decentralized on-farm multiplication schemes (McGuire et al., 2003); or special communication strategies using mass media (Joshi and Witcombe, personal communication, documented in Sperling and Christinck, 2005); or targeted support to farmer seed cooperatives (Christinck et al., 2014).

Table 8.2 shows that the informal seed system has various strong advantages regarding the diffusion of PPB varieties: since seed production forms part of the normal crop production, and the diffusion takes place mainly along social networks (among relatives, friends, and neighbors, at local markets, or through local traders), the cost for production and distribution is generally much lower compared to the formal system. This is particularly

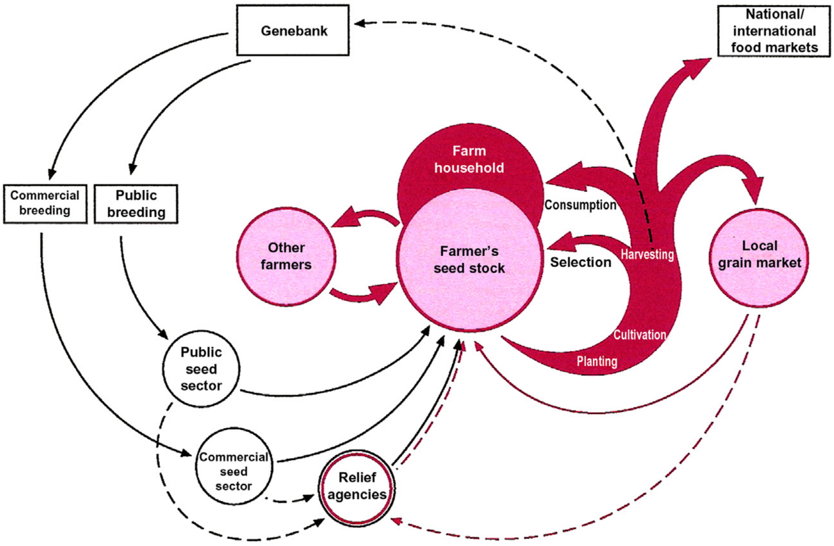

FIGURE 8.4 Formal and informal seed systems. Own seed production, purchase from other farmers, or local markets are informal channels, whereas public or private seed outlets and relief supplies constitute formal channels. *From Sperling, L., Christinck, A., 2005. Developing strategies for seed production and distribution. In: Christinck, A., Weltzien, E., Hoffmann, V. (Eds.), Setting Breeding Objectives and Developing Seed Systems With Farmers. Margraf Verlag, Weikersheim, Germany, and CTA, Wageningen, The Netherlands, pp. 153–176.*

TABLE 8.2 Strengths and Weaknesses of the Formal and the Informal Seed System

Formal Seed System	Informal Seed System
Makes varieties available that tend to be widely adapted and are often suited to favorable environments	Makes all kinds of varieties locally available that can be reproduced on-farm: locally adapted modern varieties, traditional landraces, and farmer varieties
Seed has to fulfill certain legal requirements regarding purity, germination rate, etc.	No "official" quality testing, but certain standards of reliability are being ensured through social relationships
Only varieties which fulfill the official requirements can be distributed	Varieties, mixtures, or unstable populations (for further selection) can be distributed along informal channels
Official recognition of ownership and intellectual property rights; however, it may be difficult to get farmer or community recognition inserted in formal release channels	Ownership and intellectual property rights are usually not considered in the informal seed system: traditionally, seed is multiplied, sold, or exchanged by all farmers, irrespective of their varietal identity

(*Continued*)

TABLE 8.2 (Continued)

Formal Seed System	Informal Seed System
Requires a certain "minimum market size" in order to make the investment in multiplication, certification and distribution economically feasible	Because seed production is embedded in the normal agricultural production, even small quantities of seed can be produced and distributed
The seed price is often much higher compared to locally produced grain; this can hinder the access of poor farmers to certified seed	The seed price is usually much lower, often similar to normal food grain price or slightly more
Seed has to be paid with cash or credits/ loans	Flexible modes of payment, depending on social relationships; seed may even be given for free in certain situations
In some regions, the formal seed market is generally weakly developed, particularly in remote areas	The informal system is locally organized, which ensures access to seed even in remote areas
Large quantities of seed can be handled and distributed even in geographically distant areas and to different social groups	The seed flow through the informal system is limited by quantity, and geographical as well as social distance
Formal seed distribution implies investment in communication strategies; however, the information may not always be relevant to farmers for taking informed decisions	Communication is personal, from farmer to farmer; it is thus slower, but the information is usually perceived as highly relevant by other farmers of the region

important if poor farmers are potential customers for the PPB variety. Also, narrowly adapted varieties can be multiplied and distributed easily on a limited scale, e.g., within one or several villages, and even very small quantities can be distributed or exchanged. However, varieties from PPB programs are not always narrowly adapted: they can be equally relevant for farmers in other regions, or even other countries (Joshi et al., 2001, 2007). In such cases, particularly if the formal system is well developed, official variety release and distribution could be considered for the diffusion of PPB varieties.

In any case, the distribution of seed from PPB programs needs to be planned carefully and strategically according to the situation of the seed system for the targeted crop in the project area and the overall project goals (see Box 8.6). For example, PPB programs that have components targeting farmer empowerment may aim at creating or supporting local institutions or organizations that can sustain these activities possibly without project support, e.g., farmer seed cooperatives or local seed enterprises. However, to achieve rapid adoption and widespread impact from the use of the newly identified varieties, it is also common to partner with existing NGOs, community-based

BOX 8.6 Building Blocks of Successful PPB Seed Distribution Strategies

- Identify and develop highly superior varieties that are attractive for farmers;
- Estimate the market volume;
- Develop a solid understanding of seed channels that farmers use and the key actors;
- Consider the specific legal, political, and socioeconomic framework and conditions;
- Find innovative solutions to overcome key weaknesses and gaps in the seed systems;
- Include information exchange aspects along with the seed diffusion targets;
- Collaborate with NGOs, farmer organizations, or the private sector for distributing seed on a larger scale.

organizations, extension services, or local traders to diffuse small bags of seed widely among the target group of farmers. In all cases where seed is mainly distributed along informal channels, care should be taken to ensure the sustainability of seed supply: there should be possibilities to get new seed of the variety in cases of involuntary seed loss, or for supply to newly interested farmers. Frameworks for planning seed outreach strategies in PPB projects have been summarized by Sperling and Christinck (2005); useful information and documents on seed systems, seed system development, and seed relief is also accessible at www.seedsystem.org, a website focusing on seed systems run jointly by the International Center for Tropical Agriculture (CIAT) and a number of other research and aid organizations.

However, restrictive variety protection and seed laws tend to be a major obstacle to variety diffusion from PPB programs, as stated, e.g., by Bocci et al. (2011). The Integrated Seed Sector Development (ISSD) approach has been suggested as a framework for accommodating diverging and complementary goals, and needs and interests of private sector and public breeding initiatives (Louwaars and de Boef, 2012). In short, this approach acknowledges that private and public breeding can each make different contributions to plant breeding and seed sector development, e.g., by focusing on different crops, variety types, and user groups. Accordingly, states should develop legal frameworks that facilitate, rather than restrict, the contributions of each sector. This discussion is ongoing, and particularly in view of the commitments of signatory states of the ITPGRFA and human rights (Pimbert, 2011; Christinck and Tvedt, 2015).

PRACTICAL ELEMENTS OF PARTICIPATORY PLANT BREEDING IN VIEW OF AGROECOLOGICAL ISSUES

This section shows how agroecological issues can be practically addressed through PPB in each of the different stages of a breeding program (as shown in Fig. 8.1).

Develop Breeding Objectives Based on Deeper Understanding of Agroecological Conditions and Typical Constraints

Classical objectives of breeding programs, such as yield improvement or disease resistance, may be too general to develop varieties that will have to fulfill various functions in complex farming systems. Therefore, PPB projects have been particularly successful if they invested in the development of breeding goals based on a deeper understanding of agroecological conditions, farmers' needs, and the typical constraints of the farming systems.

This type of assessment can start from several points. One possibility would be to identify problems and constraints by means of a general assessment of the farming and food system, including soil qualities, crops and varieties grown, resources and technologies used, gender-specific roles and responsibilities, as well as local food habits, and possibly a detailed analysis of specific factors contributing to malnutrition. Participatory communication tools can be used to make sure that the assessment is centered on the farmers' perceptions and their definitions of problems and needs. One important point is to carefully select the participating farmers; e.g., various wealth or ethnic groups should be considered. It is also essential to use a gender-sensitive study design. For this purpose it may be necessary to work with women and men in separate study groups. The methodologies could range from individual or group interviews, to more specific tools such as transect walks, mapping, or modeling exercises. These communication tools have been described in the PRA literature (see Box 8.2) or, more specifically in view of breeding programs, by Christinck et al. (2005a). However, not only are farmers' needs and constraints that relate directly to farming important for developing innovative breeding objectives, consumer and processing qualities are also an important point. New varieties are only acceptable for farmers if they can be processed with local technologies, and meet a certain threshold level of important quality traits. Food habits and preferences of rural people are part of their cultural identity; they may also be related to agroecological conditions, including, e.g., seasonal fluctuations in production, or problems of storability of certain products.

If farm households are mainly the consumers of their own produce, interviews with farmers on preferred quality traits and testing of culinary quality could be organized. As women tend to be mainly responsible for food storage, processing, and cooking in most cultures, their expertise should be searched through gender-sensitive participatory study designs. In those cases where crops are marketed and processed on an industrial level, it is advisable to consult key persons from relevant private or public enterprises with regard to required processing qualities.

Starting with a general assessment of problems and constraints is a good option if there has been little contact between farmers and researchers previously; PRA exercises and interviews can help initiate dialogue, identify potential research partners, and find a "common language."

Another possibility for developing breeding objectives would be to start by envisioning an end product with the required qualities. Based on a good understanding of the advantages and weaknesses of locally used varieties, and insights about new options based on farmer evaluations of a range of already existing varieties, jointly the characteristics of an "ideal variety" can be developed. This activity is often done in combination with interviews or group discussions regarding the reasons for selecting certain varieties or discarding others. This is a good option wherever rather complex traits or trait combinations are under discussion that cannot be dealt with theoretically; real objects (plants, seeds, harvest products, etc.) can help to better focus such discussions.

In practice, both approaches (problem analysis and assessment of a desired end product) are often combined. For example, the results of a problem analysis can be particularly useful for identifying appropriate material for PVS. PVS can help depart from discussions on problems and needs toward finding practical solutions, and actually working together. Developing and refining breeding objectives, as well as understanding dynamics of farming systems, should be considered as a continuing process of joint learning.

Example: Improving a Local Maize Variety in Nepal

Maize is an important crop for the upland areas of Nepal. While 59% of the total maize planting area in Nepal is sown with modern varieties, the situation is completely different in the western hills of Nepal. Only during part of the year are these parts of the country accessible by roads, and farmers have very limited access to improved seed and information on new varieties. The existing crop research system had not adequately addressed location-specific problems, resulting in very little impact of formal research and breeding institutions in the area. Thus, starting from 1998, a participatory maize breeding project was initiated jointly by LI-BIRD (Local Initiatives for Biodiversity Research and Development, Pokhara, Nepal; email: info@libird.org) and farming communities in the Gulmi district of Nepal, in collaboration with the National Maize Research Program.

Around 90% of the farmers in the study area depend on maize production for their livelihood. Five major cultivars are grown by the farmers, out of which the three most important ones are landraces. The most widely distributed landrace is called *Thulo Pinyalo*, which accounts for 75–80% of the planting area. After identifying two project sites, a village workshop was organized. During this workshop, farmers and researchers assessed the existing diversity of maize, analyzed problems and needs, identified preferred and undesirable traits, and set breeding goals. The methodology of this workshop was based on the PRA approach (see Box 8.2 for more information).

The local variety *Thulo Pinyalo* was appreciated by the farmers because of its high yield potential, good culinary and processing qualities, resistance to storage pests and diseases, fodder quantity and quality, and adaptation to local management practices. A major problem of the variety is its susceptibility to lodging. Furthermore, women and poor farmers particularly expressed a need for a maize variety that could be grown in mixture with legumes. Another important issue was that a new variety should be useful for roasting the immature cobs, as this is an important food supplement for poor farmers in the "hungry season" (before the main harvesting season).

The farmers selected a farmer research committee and a larger group of farmers, men and women, who would participate in the breeding activities. It was decided to introduce exotic germplasm for broadening the genetic base of the landrace by using a PVS approach.

Elite germplasm provided by CIMMYT and the National Maize Research Program, as well as further exotic lines identified by the researchers based on the analysis of farmers' preferences for traits, was tested in farmers' fields. Results were evaluated through farm walks and a traveling seminar at the maturity stage. Farmers also conducted focus group discussions and preference ranking on their own. These activities helped farmers: (1) evaluate the exotic material for performance under local conditions and identify new traits that could complement the traits of the landrace; and (2) finally select breeding parents for improving the local maize variety *Thulo Pinyalo*.

After crossing the landrace with several exotic cultivars followed by several cycles of selection, the resulting populations were again tested extensively by farmers. The three most promising ones were less tall, less affected by lodging, and had shorter duration, while still giving nearly the same grain and fodder yield as the original landrace.

However, developing maize varieties for a marginal production environment was not the only outcome of this approach; with the help of LI-BIRD, farmers organized themselves collectively and established new linkages to government units, the National Maize Research Program, private companies, and NGOs. The project activities were an effective entry point for training activities, and empowered farmers in their problem-solving capacities. Breeders from formal institutions appreciated the cooperation, and changed their attitudes regarding their perception of varietal characteristics and the benefits of cooperating with farmers and informal institutions (project description based on Sunwar et al., 2006).

Generate or Assemble Variability Based on Farmers' Knowledge and Local Germplasm

As outlined earlier, local crop varieties are often used as breeding parents in PPB projects, mainly because of their specific adaptation to agroecological conditions, as well as culinary and postharvest quality traits. Farmers' traditional knowledge is often the main source for relevant information on local crop germplasm.

However, not all villagers may have the same level of knowledge in this regard. It is likely that local experts can be identified, often experienced farmers. Collections and inventories of local varieties can serve to assemble seed and planting material for the breeding program, while at the same time documenting the associated knowledge on adaptation and specific traits. Particularly in cases where breeding programs aim at safeguarding or increasing local biodiversity, such activities can also be an excellent means of raising awareness and increasing the information flow within or among village communities with regard to traditional crop varieties and their specific qualities.

Various participatory forms of action have been described for the purpose of sharing and documenting knowledge on traditional crop varieties (Christinck et al., 2005b; Rana et al., 2000; Rijal et al., 2000). Some put more emphasis on informal communication and knowledge sharing, either among villagers or between farmers and researchers; examples are transect walks, diversity fairs, community biodiversity registers, or rural poetry or song festivals related to biodiversity. However, tools such as biodiversity mapping, four-square (or four-cell) analysis, or matrix ranking aim at systematic documentation of distribution, specific traits, and uses of a range of varieties. Various tools can be combined or brought into action in different phases of the research process.

In addition to selecting breeding parents, farmers can also be involved in generating new variability through crossing. In practice, this is often done in the case of cross-pollinating crops such as maize, where sophisticated technical operations are not required; this was the case, e.g., in the maize breeding project described earlier. However, in some projects, farmers have also been trained to make crosses in self-pollinating crops (McGuire et al., 2003).

Example: Selecting Breeding Parents for Participatory Rice Breeding in Nepal

In Nepal, a PPB program was launched in 1998 by the national Agricultural Research Council, together with LI-BIRD and other local institutions. This PPB program had a strong focus on testing and developing methodologies, and aimed particularly at conserving local biodiversity, while at the same time providing benefits to the farming communities.

The main actors were aware that on-farm conservation of agrobiodiversity could only be achieved with a high level of community participation, and that the capacities of local farmers to search, select, and exchange germplasm would be key to reaching the project goals. Furthermore, the setting of breeding goals and the selection of landrace parents for the PPB program were regarded as closely related activities for which community participation had to be organized.

As a first step, relevant agroecosystems and interested communities were identified. The study sites comprised mid- to high-altitude regions (Begnas village, 600−1400 m above sea level) with a high diversity of rice landraces, as well as sites with higher production potential in the Indo-Gangetic plains (Korchowa, 54−100 m above sea level).

In the initial phase of the program, "diversity fairs" were organized at each site, with the goal of raising community awareness of local crop genetic resources, promoting the value of landrace diversity, and locating and collecting material. The local varieties presented at the fairs were then grown in farmers' fields as "diversity blocks," which were used to assess the performance and analyze preferred and undesired traits of local varieties with the participation of various groups of farmers. Furthermore, the diversity blocks were used as a seed source for crossing programs. In a next step, the communities were encouraged to maintain "community biodiversity registers" (CBRs), which means a systematic documentation of varieties held by the farmers, including information on special characteristics and uses. The CBRs allow monitoring dynamic changes in local crop diversity over time. Another tool used to prepare the selection of breeding parents was "four-cell analysis," through which the diversity of local varieties is grouped according to two criteria: the number of households that grow a certain variety, and the area on which it is grown. This tool allows identifying those landraces that are in severe danger of being lost (grown by few households on small areas), just as those that are widely used (many households, large areas), or those that may be somehow specialized for certain conditions or uses (few households, large areas, or many households, small areas) (Rana et al., 2005).

The project then conducted focus group discussions in order to identify the breeding parents. The aim was to select at least one landrace from each of the four cells, and the project used a preference ranking exercise (Guerrero et al., 1993) for identifying preferred traits and those traits that needed improvement. At least one landrace (the best one) from each cell was identified. The other parent (exotic parent) was then found by looking at the traits that needed improvement, new desirable traits, and adaptability to local conditions and germplasm.

Using this procedure, the research team finalized cross combinations for each study site. The resulting materials were then tested in farmers' fields and assessed jointly by farmers and researchers during "farm walks." Several new populations, which combined yield potential of introduced varieties with adaptive and quality traits of local landraces, were selected from this material and spread through farmer-to-farmer networks (project description based on Sthapit et al., 2002).

Farmer Participation in the Selection Phase of a Participatory Plant Breeding Program

In the selection phase of a breeding program a farmer can: (1) identify the selection criteria; and (2) perform selection in the breeding populations.

In many parts of the world, farmers invest considerable time in the production, selection, and storage of their own seed. They may harvest the seed grain from particular fields or field patches, or have preference for certain plant types, shapes or colors of leaves, stems, harvestable organs, or grains. They identify single plants that show unique properties or a trait combinations that may be of particular use for certain purposes or conditions. Thus, farmers who select their own seed generally have knowledge, as well as practical skills that could be important for reaching the goals of a breeding program.

Understanding selection criteria of farmers can help identify important adaptive or quality traits. Criteria used by the farmers may be directly or indirectly associated with environmental adaptation and/or quality issues. This knowledge is often embedded in traditional practices and ways of doing something that may not be communicated easily: it is implicit or "tacit" knowledge. Communicating tacit knowledge generally requires methodology, which is based on action, demonstration, and observation rather than on questioning. Thus, understanding farmers' own selection criteria may be one reason why farmers are practically involved in the selection of diverse populations in many PPB projects.

Given the fact that selection in the target environment is generally an essential element of most PPB projects, farmer participation in selection is a logical consequence. In some cases, farmers and scientists made their selections independently from each other in the same material for later comparison of the results (Ceccarelli et al., 1996).

Example: Learning From Farmers' Selection Criteria in Rajasthan, India

In Rajasthan, a semiarid state in Northwest India, pearl millet is the staple food crop. Adoption of modern varieties has been very limited, particularly in the driest western parts of the state, where low and unpredictable rainfall is the main problem faced by the farmers. However, landraces are commonly grown, and many farmers also grow mixtures of traditional and exotic varieties. With pearl millet being a cross-pollinating crop, these mixtures result in highly diverse populations from which many farmers select seed for the coming season. However, also in traditional landrace material, many farmers select seed very keenly, most often from harvested panicles on the threshing floor, and sometimes in the standing crop.

When scientists from ICRISAT started applying the PPB approach for developing new, drought-resistant varieties for western Rajasthan in the year 1991, they assumed that farmers' own selection criteria were probably based on their traditional knowledge of environmental adaptation, and that understanding more of this knowledge could guide a way toward developing new, better-adapted varieties. Consequently, the seed selection practices of farmers in Rajasthan were assessed by applying a participatory research methodology that comprised observation of farmers' practices, simulation exercises, interviews, and workshops (in villages as well as on research stations).

One workshop was conducted in 1997, in the course of which farmers from various villages and researchers evaluated 15 demonstration plots grown at a research station near Jodhpur. Populations grown on the demonstration plots included traditional landraces from various parts of Rajasthan, farmer-selected varieties, and improved landrace-based materials selected by plant breeders, as well as some hybrid varieties bred from "exotic" germplasm. Farmers and researchers evaluated (separately) the 15 demonstration plots. Evaluation criteria used by farmers and scientists, respectively, were documented and compared.

The workshop revealed that the farmers used far more criteria (42) for their evaluation than the scientists (24). Grain and fodder yield were considered by both groups, as were time to maturity, panicle characteristics, number and productivity of tillers, stem diameter, disease incidence, and performance under drought. However, most quality-related criteria were not considered by the scientists, neither were labor requirements and market price. The main differences were found, however, regarding many traits related to specific aspects of environmental adaptation, which were only considered by the farmer participants.

Many more interviews and PRA exercises, particularly direct observation and classification exercises using pearl millet panicles showing different traits, revealed how farmers in Rajasthan relate panicle and plant characteristics to performance, environmental adaptation, and quality issues (Fig. 8.5, Christinck et al., 2000).

Formal multilocational field trials in which farmers' evaluation and selection criteria were applied systematically (by scientists) showed that the farmers' way of associating visual traits, such as stem and panicle diameter, tillering ability, or grain characteristics with drought resistance, is in fact supported by yield data gained in drought environments (Christinck et al., 2002). This outcome allows two conclusions:

1. Selection and evaluation criteria used by the farmers are based on a deep understanding of plants and the environment; and
2. Farmers' knowledge and skills could contribute considerably to the selection of varieties adapted to the drought-prone environments and complex farming systems of western and central Rajasthan.

Participatory Methods for Variety Testing and Evaluation

As outlined earlier, variety testing and evaluation in the target environment are core issues of PPB. First, testing in the target environment reveals the degree of environmental adaptation of the experimental variety; second, it allows farmers to evaluate the overall "usefulness" of the new cultivar in the context of their own farm and household over the whole production cycle,

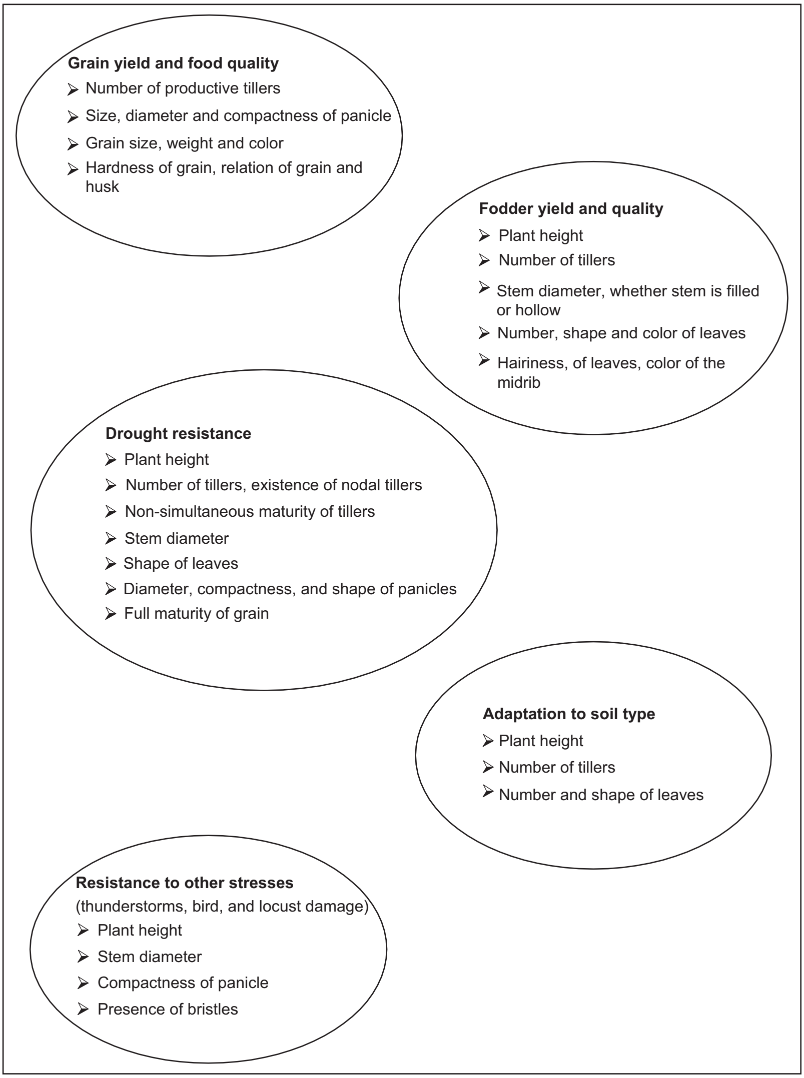

FIGURE 8.5 How farmers in Rajasthan, India, relate traits of pearl millet plants to relevant aspects of performance, stress resistance, and quality. *Adapted from Christinck, A., 2002. This Seed Is Like Ourselves: A Case Study From Rajasthan, India, on the Social Aspects of Biodiversity and Farmers' Management of Pearl Millet Seed. Margraf Verlag, Weikersheim, Germany.*

including growing phase, harvesting, storage, consumption, and yield stability (if evaluated over several seasons).

Farmers generally tend to evaluate varieties in all the different stages of their development, and spend considerable time in the fields while doing normal field work. Furthermore, it is also a general custom to discuss the value of new materials with family members, neighbors, and colleagues in an informal way. Therefore, participatory variety evaluation is an activity that is relatively close to the farmers' reality.

Methods and tools for organizing farmer-managed trials for variety evaluation differ very widely, and are usually determined by seed availability, commonly used field size, minimum plot size for reliable yield evaluations, and the number of farmers who are keen to conduct trials in a village. Furthermore, the tools used for assessing individual varieties differ with the level of literacy of the participating farmers, the types of observations required, and the number of varieties being evaluated (Weltzien et al., 2005).

Generally, it can be distinguished between rather informal evaluation methods (i.e., farmers grow one or several test varieties and share their experience in interviews or village workshops), or more formal methods (evaluation trials with replications, documentation of observations, yield measurements, etc.). The decision about such issues depends much on the institutional background of a PPB program, the resources available, and the overall goals of the program. A higher level of "precision" may be required by scientists for their work, but does not necessarily lead to better results compared to informal methods, which require much less resources (Joshi and Witcombe, 2002; Witcombe et al., 2005). A widespread trial design used for decentralized participatory variety testing is the "mother—baby trial" design, which allows farmers to test subsets ("baby trials") of a general trial ("mother trial") on their farms. The "mother trial" can be grown either on a research station, or in a village, and includes several within-site replications of treatments. The "baby trials" are grown in different farmers' fields, often with larger plot sizes, and under farmers' normal management. They are considered as additional replications (Snapp, 2002). Using this method, it is also possible to relate qualitative observations made by the farmers to yield and other quantitative data gained from the baby trial in which the farmer made his/her observations. Furthermore, ranking and scoring exercises are widely used for participatory variety evaluation, particularly during on-station workshops or for evaluating larger on-farm trials (Weltzien et al., 2005) (Fig. 8.6).

Example: Participatory Variety and Clone Evaluation With Potato Farmers in Peru

In 1997, the International Potato Center (CIP) and CARE-Peru started a collaborative project on the integrated management of late blight, an economically important potato disease. Part of this participatory technology development process was to facilitate farmers' access to new, resistant genotypes in order to reduce the use of fungicides.

As a first step, farmers evaluated 12 varieties with different degrees of resistance to late blight. Based on the information gained through this

FIGURE 8.6 Women farmers scoring sorghum varieties in Mali. *Photograph by S. Siart.*

activity, the breeding program of CIP provided 54 promising clones, which were divided into clusters and evaluated by 13 different farmer groups. In the following year, the farmers continued evaluating 25 selected clones from the previous season.

Taking into consideration that many farmers of the study area were illiterate, a simple evaluation method was used to classify the potato clones in three categories: good, moderate, and bad. The farmers received paper cards with smiling, serious, or "sad" faces drawn on them, and were asked to put a respective card into a paper bag located near the clones for evaluation. At the end, all participants should have given their judgment on each genotype.

After finishing this activity, the cards were counted and the results were written on a board. Each genotype had a certain number of positive, medium, and negative judgments, so it became clear which genotypes were preferred by the farmers. These results led to a discussion on the reasons and underlying criteria. The method is also useful for distinguishing the preferences of different groups of farmers (i.e., women and men) if done separately or with different colors of paper (project description based on Ortiz, 2002).

Seed Production and Diffusion Strategies in View of Agroecological Issues

Ideally, new crop varieties that are adapted to local agroecological conditions and farmers' needs are the final outcome of PPB programs. However, a positive impact can be realized only if the farmers have access to the seed of such varieties at the time needed, in sufficient quantity and at a reasonable price. Here, PPB projects often face serious problems because efficient seed distribution in the longer term, and at large-scale, on the one hand, and offering a range of diverse varieties for special agroecological conditions, particularly for poor farmers, on the other, are potentially conflicting goals.

As seen earlier, the informal seed system offers various potential advantages for seed diffusion, particularly in those cases where the amount of seed required is small, i.e., varieties grown only locally and on small areas. However, the maintenance and distribution of seed require a high degree of long-term commitment and motivation from the involved actors if the seed supply is to be sustainable. Traditional values and ways of sharing seed do not always continue to function. Therefore, awareness raising and building of organizational structures based on the local traditions may be required for ensuring seed supply from farmer-to-farmer in the longer term. Many PPB programs seek cooperation with NGOs or farmer organizations for this purpose.

It may be useful to effectively link “grass root” seed production to formal institutions (such as gene banks, national breeding programs, private, or public seed companies) to ensure sufficient seed supply of agroecologically relevant varieties even in times of crisis, drought, or other events that may disturb the functioning of local seed systems.

However, it should be considered that seed supply of varieties grown by few farmers and on small areas is generally vulnerable in the longer term. A solution could be to test the materials developed through PPB also in other, agroecologically similar, regions through participatory variety evaluation and selection schemes. Thereby, the demand for such varieties could increase.

A potential obstacle to linking informal and formal seed supplies could be seed legislation in some countries. Seed spread from farmer to farmer is often tolerated, as long as the varieties sold are not registered by any private company or breeder. However, as soon as the formal sector gets involved, official registration is inevitable in many situations. Some countries, such as India, have recently revised their legislation in order to allow for the registration of varieties also under the name of farmer groups. Signatory states to the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) have committed themselves to protect and promote “Farmers Rights,” including rights to save, use, exchange, and sell seeds, in their national legislations. However, the wording of the ITPGRFA is weak in this regard, and leaves a lot of discretion with regard to the ways how exactly this could be done in a way that is considered “appropriate” in each country (Christinck and Tvedt, 2015).

Example: Seed Fairs

Seed fairs provide an opportunity to facilitate farmer-to-farmer seed distribution, particularly of traditional or locally important varieties. Seed fairs can reach a large number of people, particularly if they are organized as a side event to other culturally important happenings, such as religious festivals, which attract people from larger areas. Furthermore, seed fairs can be a means to facilitate seed exchange between people who do not interact otherwise, because of geographical or social distances. Not only seed will be

FIGURE 8.7 A seed fair in Mali. *Photograph by S. Siart.*

exchanged, but there will also be much discussion and sharing of information, e.g., on cultivation practices, uses, and food preparation.

Seed fairs are a tradition in some countries, e.g., in the Andean region of South America (Tapia and De la Torre, 1998; Tapia and Rosas, 1993). However, they have been organized successfully in many other countries, often by NGOs or other locally based institutions (Almekinders, 2003).The focus can be more on the diffusion of traditional varieties, or also on new varieties, such as PPB varieties (Weltzien et al., 2006).

The farmers are usually invited to offer seed of their own production to other farmers. If required, some form of quality control may be installed prior to opening the fair. Competitions, prizes, awards, and cultural events can serve as further incentives to increase the attractiveness of the fair. Once established, seed fairs often catch the attention of more and more participants year after year. In addition to promoting the farmer-to-farmer exchange of varieties, they offer a range of possibilities for links to other biodiversity-related activities. For example, the diversity displayed can be monitored regularly, thus providing indications for the loss or revival of varieties. Furthermore, potential collaborators for planned in situ conservation or PPB activities could be identified among the participating farmers, and personal relationships can be established (Almekinders, 2003) (Fig. 8.7).

EXAMPLES OF SUCCESSFUL PARTICIPATORY PLANT BREEDING FOR MARGINAL ENVIRONMENTS

The examples mentioned earlier merely focused on illustrating methodological aspects of PPB. This section provides examples of how PPB successfully addressed specific agroecological problems or constraints, particularly in marginal environments. Such problems can be relatively straightforward to describe, such as adaptation to soil acidity or tolerance to a specific pathogen. However, we would like to emphasize that the breeding objectives of farmers are often multifaceted, and include use-related parameters as well.

Furthermore, the general wish to increase yield potential and/or yield stability of existing varieties can only be realized if the complex relationship between various plant traits and environmental adaptation is well understood.

Participatory Maize Breeding for Low-Fertility Soils in Brazil

In Brazil, as in other tropical countries, low soil fertility and either insufficient or excessive water supply are major problems in large areas of the country. Soil acidity associated with toxic levels of aluminum content, and phosphorus and nitrogen deficiencies, are the main soil parameters limiting agricultural production in the community of Sol da Manhã in the state of Rio de Janeiro. Maize, the economically most important crop in this area, is particularly affected by nitrogen deficiencies. However, chemical fertilizer is expensive for the farmers and is usually not applied. Therefore, the yield level of the maize crop used to be very low (roughly 1000 kg/ha).

Given the multiple difficulties faced by the farming community, some of their representatives sought technical support from the University of Rio de Janeiro and EMBRAPA (Brazilian Agricultural Research Corporation). A breeding program was set up, with the main objective to develop maize varieties with improved nitrogen use efficiency, using a participatory approach. As a first step, a participatory variety evaluation of 16 maize varieties with good tolerance to low soil nitrogen levels was organized. Farmers selected one variety that they considered best, which was called *Sol da Manhã*, after their community. *Sol da Manhã* is a variety with a wide genetic base consisting of 35 populations from the Caribbean and South America. The introduction of *Sol da Manhã* in the community increased the average production level by 100%. The farmers reproduced and selected their own seed from it over several years, leading to various versions of the variety.

Simultaneously, a breeding program for improving and adapting *Sol da Manhã* for the local conditions began in 1986. It was aimed at conserving the genetic variation and general crop characteristics of the variety, while improving its nitrogen use efficiency and productivity under the conditions of the farming community. After six cycles of selection done by plant breeders, the “EMBRAPA version” of *Sol da Manhã* was introduced to the community in 1992, and was subjected to six further cycles of mass selection performed by the farmers. The selection was done at five community locations, and at the EMBRAPA research station. All the locations showed different levels of nitrogen supply; the selected seeds were bulked at the end of each season to avoid loss of genetic variability due to severe stress conditions, and in order to maintain an effective population size. To select for high nitrogen use efficiency, plants with more accentuated dark green coloration were marked at the flowering stage. After harvest, the farmers selected again for other plant characteristics, such as grain yield, plant and ear characteristics, and resistance to lodging. Introduction of the EMBRAPA version of

Sol da Manhã, along with farmers' selection, again increased the yield level in the community by another 100%, from 2000 to 4000 kg/ha.

In 1994, after six cycles of EMBRAPA improvement and two cycles of community improvement, a further evaluation trial in the community proved the high yield potential of *Sol da Manhã* compared to other varieties, and under low as well as higher levels of soil nitrogen. It was found to be in the group with the highest nitrogen use efficiency of the trial (Machado and Fernandes, 2001).

Participatory Barley Breeding for Drought-Affected Regions (Syria)

The barley breeding program of ICARDA (Syria) adopted the PPB approach in the mid-1990s. Not only was the wish to better target the needs of farmers in marginal, drought-prone environments the background for this decision, but also theoretical considerations on plant breeding for drought environments.

Drought is one of the major factors limiting crop production worldwide, particularly in the rain-fed agricultural systems of the semiarid tropics and subtropics. One main characteristic of drought is its unpredictability in occurrence, timing, severity, and duration. In addition, the effects of drought on crop production are often further aggravated by high temperatures, reduced soil nutrient availability, or pest and disease incidence, as these abiotic and biotic stresses are closely interrelated with the occurrence of drought.

From a theoretical point of view, the variation between different target environments (i.e., test sites for trials) is much higher in dry areas compared to areas with high and reliable rainfall. Furthermore, the variation between years (for the same location) also tends to be very high in drought environments. Therefore, decentralized PPB can address the complexity of dry areas more efficiently and effectively than a centralized plant breeding program.

The model for decentralized, participatory barley breeding that has been brought into practice in Syria and various neighboring countries foresees that scientists make controlled crosses and select (on station) within the F1 and F2 generations. From the F3 generation onward, there is usually enough seed available for multisite testing, which is done during three more seasons in farmers' fields. Initially, a large number of entries (60—165) are grown in formal trials (unreplicated). Different sites may receive different germplasm from the beginning of the breeding cycle, so that the total number of entries tested over all sites is even higher. Advanced trials in the following 2 years are grown with two replications, a reduced number of entries, and with larger plot size, as well as under farmers' own management strategies. The selection is done each year by farmers and scientists. After 3 years of testing, farmers from a given village usually select one to three entries for large-scale testing and seed multiplication. These selected test varieties also enter the next breeding cycle (crossing on station).

Practical results of this breeding strategy were higher yielding and highly drought-resistant barley lines, with an average yield advantage between 7% and 47% compared to local varieties grown previously by farmers in areas where centralized breeding programs have not resulted in any alternatives to local landraces in the last 25 years (Ceccarelli et al., 2006).

New Rice Varieties for West and Central Africa

In West and Central Africa, the demand for rice has been growing at a rate of 6% per annum over the last three decades. This demand has been met partly by the import of rice, and partly by increasing domestic production, particularly in upland areas and under rain-fed conditions in lowland agriculture.

Rice cultivation has a history over 3500 years in Africa. The African rice *Oryza glaberrima* is well adapted to pests, diseases, low soil fertility, and other prevalent stress factors, but also has some undesirable traits, particularly lodging, grain shattering, and a low-yield potential. The Asian rice, *Oryza sativa*, which was brought to Africa about 500 years ago, has a higher yield potential and replaced the original species on a large scale. However, it is less adapted to typical stress factors prevalent in West and Central Africa.

There have been previous attempts to produce interspecific hybrids from both rice species, but they failed due to widespread sterility of the resulting material. However, in 1991, WARDA (West Africa Rice Development Association (WARDA), now called Africa Rice Center (AfricaRice), based in Ivory Coast) launched a new effort to combine the potentials of both species by combining conventional breeding and tissue culture, in order to overcome sterility. By the end of the 1990s, a range of interspecific lines, showing radically new plant types, had been developed and were being tested and evaluated in a range of environments. This new rice was called NERICA (New Rice for Africa). The main characteristics of NERICA are as follows:

- Early maturity;
- Strong stems that support heavy heads of grain without lodging;
- More tillers with grain-bearing panicles than either parent, and nonshattering grains;
- Drought tolerance;
- Tolerance to acidic soils;
- Resistance or tolerance to important pests and diseases.

At this stage, AfricaRice (formerly WARDA) adopted PVS for the further process of variety development. In a 3-year program, "rice gardens" with up to 60 different varieties (including *O. sativa*, *O. glaberrima*, NERICA, and local checks) were planted in the vicinity of study villages. Farmers were allowed to visit the gardens as often as possible; however, at three key stages (tillering, maturity, and postharvest), farmer groups were formally invited to participate in the evaluation. The farmers' evaluation criteria and selections were reported, and from the second year onward, each participant received up to six varieties of his/her choice for further evaluation on farm. The farmers' observations and the yields were recorded by NGO technicians, extension agents, or breeders. From the third year onward, farmers could buy the seed of desired varieties for sowing on a larger scale. Some of the most preferred varieties were then tested in official multilocation trials to generate data required for official release. The NERICA varieties have now been introduced using similar approaches in 17 countries of West and Central Africa. The farmers' selection of varieties varies among the countries, reflecting a combination of differing varietal adaptation to the wide range of farm (micro-) environments and diverging consumer preferences (Gridley et al., 2002).

Developing Sorghum Varieties for Changing Agroecological and Socioeconomic Conditions in Mali

Sorghum is the typical staple crop in the 700- to 1200-mm rainfall zones of southern Mali, where the soils are not too sandy. The duration of the rainy season is 4–5 months in this area (from May/June to September/October). It is important to note that agroecological conditions have changed markedly since the mid-1970s.The length of the rainy season has decreased, and the mean annual rainfall in the Sahel is now between 20% and 49% lower compared to the period between 1931 and 1960 (IPCC, 2001).

The status of soil fertility is also changing: it is decreasing in certain areas because of decreasing fallow periods, and increasing in cotton-growing areas because of fertilizer use in cotton production. Therefore, there are demands for sorghum varieties that could profit from residual fertilizer effects, and for others that are adapted to low-input conditions, especially low phosphorus availability.

Lack of labor is an important limiting factor to agricultural production. There is a general trend that people seek other sources of income (in addition to farming), e.g., through part-time jobs or temporal migration, and children and young people go to schools.

The adoption of new varieties from formal breeding programs has been very low, partly because of the weak development of the formal seed sector, but also because the varieties developed by breeding programs did not fit into the local farming systems: in Mali, the *guinea* race dominates sorghum production. Improved local varieties of *guinea* race show slightly earlier maturity, but no major yield advantages over local landraces. The *caudatum* and *kafir* races, which make up the bulk of the breeding materials that have been advanced in other regions of the world, are not adapted to the farming system in Mali because of their photoperiodic insensitivity, which results in early flowering and subsequent grain mold. Furthermore, they are susceptible to bird attacks, the grains do not meet farmers' quality requirements for processing, and they do not store well.

Participatory variety evaluation was used as an entry point for future breeding activities. Along with these activities, diagnostic studies were conducted for the identification of priority selection criteria, evaluating a wide range of available lines and varieties with many farmers. The material they evaluated included inter-racial crosses between *guinea* and *caudatum* race parents, improved landraces from previous collections and farmer varieties, as well as several *guinea* race dwarf lines.

The diagnostic studies revealed that grain yield increase was in fact the main objective expressed by farmers, while culinary and processing quality of local varieties, as well as adaptation to local conditions (soil, climate, pest resistance), should be maintained. Farmers tend to grow sorghum without mineral fertilizer, under generally phosphorus deficient conditions, with pressure from weeds being high—specifically the parasitic weed *Striga* sp.

To achieve yield improvements in farmers' fields, the project developed procedures for efficient participatory yield evaluations of new varieties. The approach focused on facilitating yield testing of the varieties and farmer evaluations in at least 10 locations per year to ensure that more productive, well-adapted and farmer-preferred varieties could be identified. Testing of 32 entries was done for two consecutive years in at least 10 villages, because farmers did not want to take selection decisions based only on 1 year observations and experiences, which was confirmed by later data analysis: genotype by year interactions are the most important contribution to G × E in this particular agroecological environment.

In the next step, the participating farmers selected up to four varieties from these test entries for large-scale participatory on-farm evaluation using their normal farming practices. The set of varieties tested varied among locations. Results of these trials showed that newly selected open-pollinating varieties could achieve 15–20% grain yield advantages, and hybrids 30–40%, over a wide range of growing conditions (Weltzien et al., 2008; Rattunde et al., 2013). On-farm testing resulted in increased demand for seed for several varieties, and especially for the hybrids.

Establishing semiformal structures for seed production and diffusion is a further activity of the program, meant as an answer to the weaknesses of both formal and informal seed supply systems. Seed fairs and local seed producing associations were organized in cooperation with local farmer organizations and an NGO, in order to meet the existing demand for seed of the new varieties and hybrids (Weltzien et al., 2006; Christinck et al., 2014).

TYPES OF IMPACT ACHIEVABLE THROUGH PARTICIPATORY PLANT BREEDING FOR SUSTAINABLE DEVELOPMENT OF FARMING SYSTEMS AND FARMERS' LIVELIHOODS

We stated earlier that adapting plants to human needs could be referred to as the basic goal of plant breeding. Plant genetic resources are, more than anything else, the "bridge" between the site-specific set of natural resources and people's livelihoods; only where a sort of balance can be achieved, between the natural conditions and availability of resources on the one hand, and human needs on the other, is sustainable agriculture possible.

This section summarizes the types of impacts that can be achieved through PPB for the sustainability of farming systems, by referring to some of the cases and examples given in the previous sections. Last but not least, the progress of rural peoples' livelihoods that may result from these impacts is mentioned.

Increase Farmers′ Options to Adapt to Variable Conditions and Changing Needs or Demand

Changing conditions can be a reason why farmers need to adapt traditional farming practices, including the portfolio of crops and varieties grown. This was discussed earlier in the example of Mali, where (like in other parts of the Sahel) rainfall patterns have gradually changed over several decades. A further common type of change is the reduced availability of family labor, as a consequence of migration for jobs or education. However, interesting new options may also result from changing food habits and emerging food industries wherever urban markets for such products are developed; examples are high-value dairy products, convenience foods such as snacks, noodles, biscuits, and chips, or beverages such as soft drinks and beer.

Relatively new is an emerging market for "biodiversity food," such as fruits and vegetables with extraordinary shape, color, or taste, or beverages and specialty foods made from less common species or varieties. Moreover, marketing possibilities may arise to meet a demand for specific health products or diets, e.g., gluten-free products. New varieties that are tailored specifically to such new use options, while still being adapted to local environmental conditions, can be developed from local and/or exotic genetic resources.

Make Best Use of Limited Resources

Marginal environments are characterized by limitations with regard to the availability of natural resources that are essential for crop production; reduced availability of soil water and soil nutrients are very common limiting factors. Plant genetic resources show strong variation regarding their efficiency for using such limited resources; traditional varieties, as well as wild or semiwild crop relatives, often show specific adaptation to marginal conditions, which can be combined with other important traits through breeding. Examples such as maize breeding for nitrogen use efficiency in Brazil, sorghum breeding for low phosphorus availability in Mali, as well as barley breeding for drought tolerance in Syria, were presented in the previous section. A further advantage of improved resource use efficiency would be that negative impacts on the environment, such as groundwater pollution through excessive fertilizer use, or decreasing groundwater levels through inadequate irrigation systems, could be reduced.

Maintain Useful and Eco-Friendly Traditional Practices Related to Certain Crops or Varieties

Mixed cropping, typically a mixture of legumes and cereals or tuber crops, is a common practice in marginal agroecological environments, which fulfills a variety of functions, including complementary use of growth factors, such as soil nutrients, light, and water; reduced pest and disease incidence, reduced soil erosion, more total biomass production, more yield stability, and more household food security. Furthermore, the mixtures can be flexibly adjusted to conditions such as late or early onset of the rainy season or status of soil fertility in different fields.

Because formal breeding programs seldom consider such farming practices, the resulting varieties have usually never been tested for their ability to function under such conditions. In PPB programs, however, it is common for farmers to test experimental varieties on their own farms, thereby identifying genotypes for specific "niches" of their farming systems, including mixed cropping.

Reduce Susceptibility to Pests and Diseases

The incidence of pests and diseases not only reduces crop yields; attempts to control them, particularly the use of pesticides, can result in negative effects on the environment and on people. Examples are soil and groundwater pollution, reduced biodiversity (of insects or soil organisms that may be affected by the pesticide use), accidents while handling pesticides, and long-term effects on human health.

Plant breeding in general can help identify resistance genes and incorporate them in new varieties, thus reducing pest and disease incidence. One example given earlier was the breeding of NERICA rice from African and Asian rice types. PPB and farmer breeding tend to work with broad-based resistance based on genetic diversity, both among and within varieties. Thus, biodiversity-oriented PPB programs *per se* reduce the possibility that pests and diseases occur on a devastating scale, which has not always been the case with formal breeding programs using varieties with a very narrow genetic base.

Improve Livelihoods Through Increased Food and Nutrition Security and Empowerment of Farmers

Food and nutrition security can be improved through PPB in various ways. For example, the yield or yield stability may be increased, the "hungry season" may be reduced (through earlier maturing varieties), or the quality of the diet may be improved through selection for important quality traits (vitamin or protein content, etc.). Furthermore, additional income can be generated in such cases where the plant breeding activities go hand-in-hand with improving or developing marketing options.

Empowerment of farmers, whether addressed directly or indirectly as a goal in a PPB program, can take many forms, starting from improved communication between farmers and researchers, to farmers gaining influence on scientific institutions and their research agendas, including raising and distribution of research funds. However, the most important impact of PPB with regard to empowerment is probably the improved access to seed of improved varieties that are suited to farmers' needs and can be reproduced on the farm.

Farming system stability, resilience, and agricultural livelihood options depend intricately on the available crop varieties and their specific traits. In this context, it is of key importance to recognize that individual crops and specific varieties can serve very specific, but very different, functions within farming systems, and that plant breeding offers targeted methods and tools for balancing agroecological issues and human needs. The particular strength of PPB is that farmers' knowledge on the agroecological environment, as well as their practical observation and selection skills, can be united with scientific knowledge focusing on how to achieve breeding progress for specific traits or trait combinations in a targeted way.

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Chapter 9

Research on Livestock, Livelihoods, and Innovation

Peter Thorne and Czech Conroy

INTRODUCTION

It has been estimated that livestock production contributes directly to maintaining the livelihoods of almost 1 billion people, and enhances the well-being of many more consumers of meat, milk, eggs, and other animal products (Robinson et al., 2014). In combination, there are enough larger livestock (cattle, sheep, goats, pigs) for all the human beings on the planet to own one; and chickens outnumber us by 3:1. Of course, not everybody keeps livestock. What we actually see is livestock spread unevenly, in terms of both where they are produced (their geographical distribution) and how (by system of production).

Geographical Distribution of the World's Livestock

Fig. 9.1 clearly illustrates how global distributions of the four major classes of livestock (cattle, small ruminants, pigs, and poultry) are not at all even. Firstly, there are many areas of the world where livestock populations are very low. In some areas—particularly those that are very dry and very cold—this is because domesticated livestock are not well adapted to the prevailing environmental conditions, or because carrying capacities are very low. The other striking feature of the basic distribution map is the "hotspots" that occur for the different types of livestock. In south Asia, e.g., populations of cattle and small ruminants are very high, but there are very few pigs found. These high populations are, to some extent, present because south Asian countries are also the home to many human beings. However, the types of livestock found are very much influenced by the strong cultural traditions of keeping cattle, sheep, and goats, and not keeping pigs. In China, there is a clear population hotspot for poultry—principally chicken and ducks—reflecting cultural preferences in this region.

Fig. 9.2 (which shows the livestock population density in relation to local human populations) corrects, to some extent, for the fact that, by definition,

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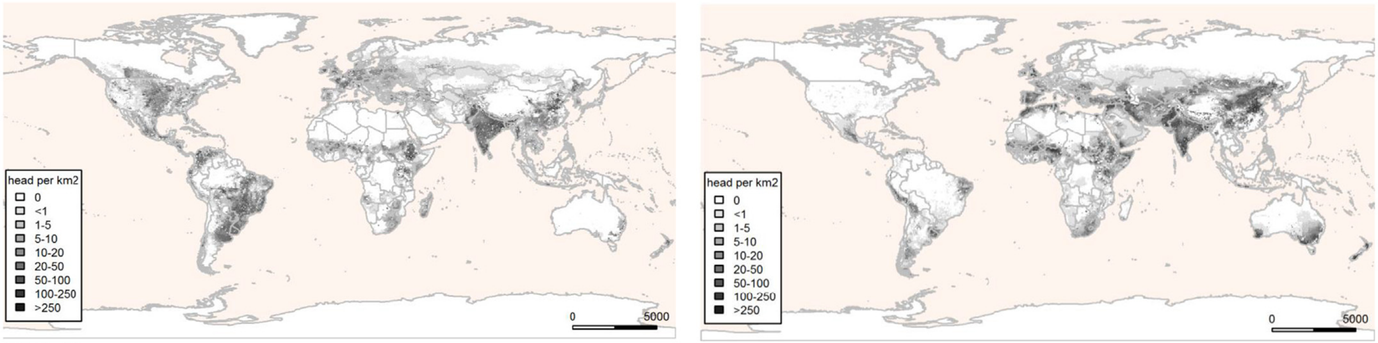
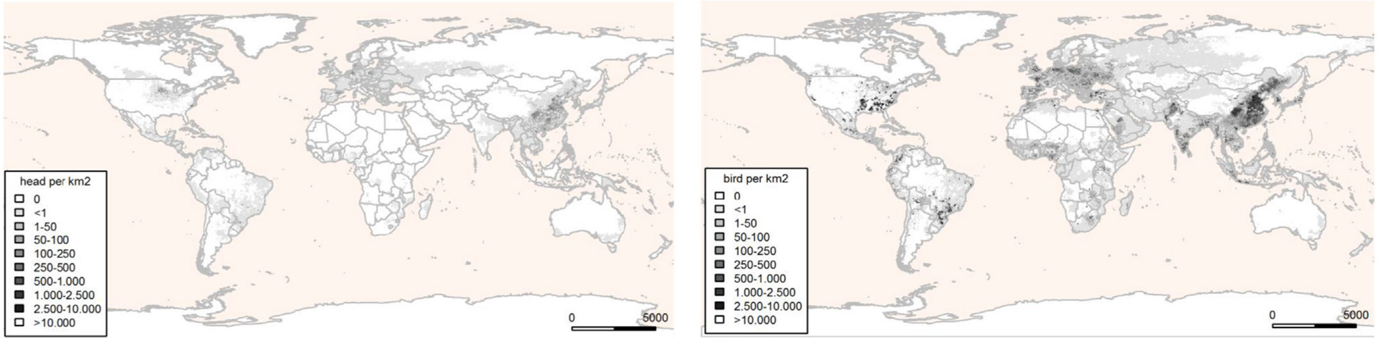


(A) Cattle

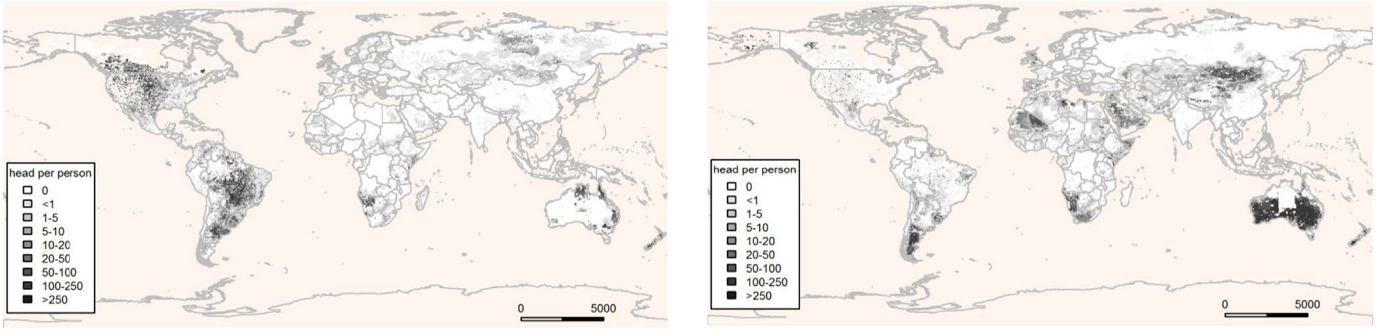
(B) Small ruminants



(C) Pigs

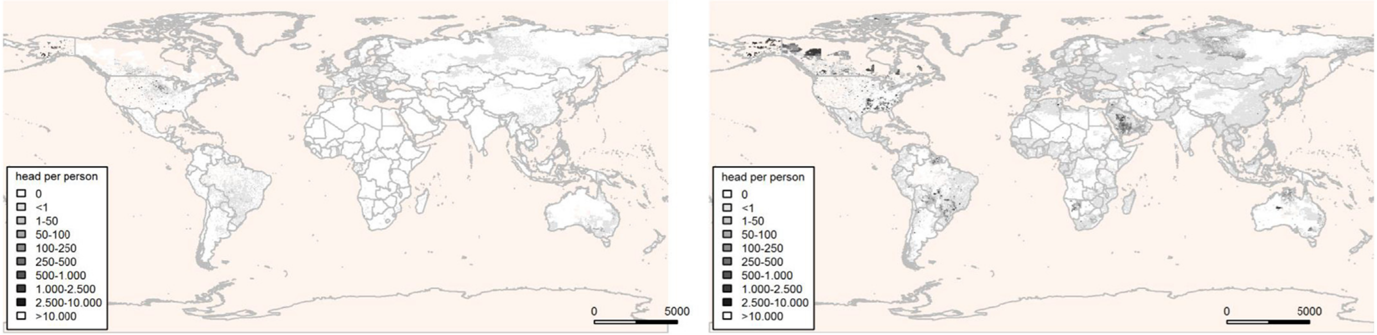
(D) Poultry

FIGURE 9.1 Global distribution of major classes of livestock.



(A) Cattle

(B) Small ruminants



(C) Pigs

(D) Poultry

FIGURE 9.2 Global distribution of population densities of major classes of livestock on a per capita human population basis.

large populations of domesticated animals tend to be associated with large human populations. As such, it allows us to make some more subtle inferences. Livestock population densities per capita of human population are also very unevenly distributed globally, but the hotspots occur in rather different places. Many of these (e.g., Australia and New Zealand for small ruminants, and South America for cattle) correspond to producer countries that are net exporters, mainly of meat. Another interesting feature of these maps is that that the importance of livestock becomes more apparent in some of countries that appear to have very low total populations in Fig. 9.1. This is particularly striking in some of the countries that straddle the Sahara desert, where the small human populations clearly keep relatively large flocks of small ruminants that are well adapted to the extreme weather conditions found there.

LIVESTOCK PRODUCTION SYSTEMS

There have been many attempts to define discrete types of livestock, and indeed, other, production system (e.g., Dixon et al., 2001; Jahnke, 1983; Robinson et al., 2014; Sere and Steinfeld, 1996). These classifications can provide a valuable basis for identifying common problems, and solutions for addressing these through research and development activities. However, there are limitations to this approach:

- Different perspectives generate different categories within different systems classifications. Sometimes it seems as if there are almost as many classification systems as there are actual production systems! In practical terms, this does not help to establish standards of good practice, or common approaches and goals across different research and development initiatives.
- Many studies emphasize the heterogeneity in farmer's management practices, even within the same community. The coarse granularity of generic systems classifications can mask the significance of this heterogeneity if they are applied too dogmatically. Participatory approaches are particularly suited for dealing with heterogeneity in ways that are more likely to generate adaptable and adoptable solutions.
- Ignoring this within-system heterogeneity, and following the assumption that all practitioners within a particular system will benefit from similar interventions, can lead to a top-down, interventionist approach. This often leads to preconceptions that skew the research and produces solutions which are developed in inappropriate directions.

Nonetheless, there are systems in which gross differences can be identified, and focusing on these can help in developing and implementing robust lines of research for development (R4D). In this chapter, we will refer to the

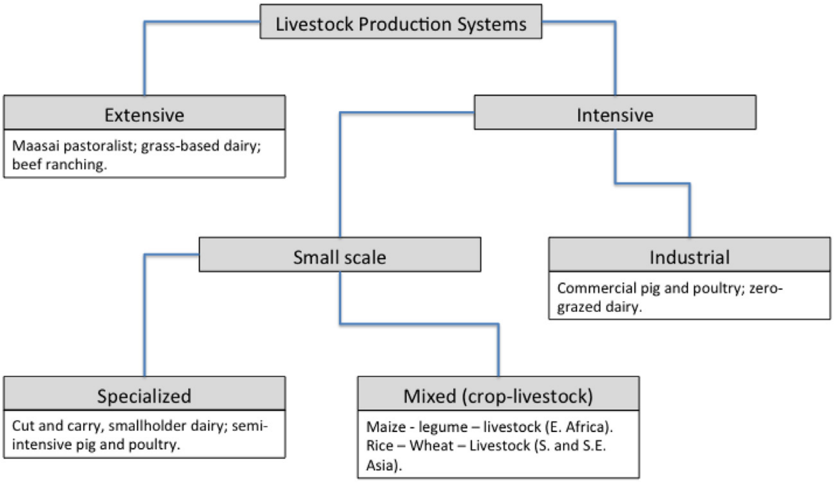


FIGURE 9.3 A pragmatic livestock systems classification scheme.

scheme outlined in Fig. 9.3, which is a simple composite of some of the systems classifications referenced above.

Extensive Livestock Production

In extensive livestock systems, intensity of input use is low; there is little or no investment in infrastructure (confinement, shelter, handling equipment) or veterinary support and products, and a large proportion of animal feed has traditionally come from grazing on common lands, in forests, and on fields of stubble after crops have been harvested. In the latter case, there is a symbiotic relationship between livestock and crop production, with crop residues an input to the former, and manure to the latter. Two common trends have been for human populations and livestock numbers to increase over time, leading to the shrinkage of common land areas (as land is privatized and access is restricted), and degradation of the forage resource base as the pressures on remaining pastures intensify. These trends may eventually encourage people to ban or control grazing on common pastures, invest in the improvement of the pastures (by fencing them off, and planting and managing improved forage species), and switch to cut-and-carry fodder systems, as has happened in numerous villages in Rajasthan, India (Conroy and Lobo, 2002). However, this is only likely to happen where there is good social cohesion and a history of collective action, and where the social group is confident in its rights to the land, and its capacity to benefit exclusively from the investment in rehabilitating it. There usually needs to be a high degree of land or fodder scarcity before planted fodder, and cut-and-carry methods of feeding, become more attractive than open grazing (Tiffen et al., 1994).

Intensive Livestock Production Systems

The process of intensification may be defined simply, but generically and robustly, as increasing the ratio of productive outputs to inputs. In this sense it is equivalent to improving the overall resource use efficiency of the system practiced. In practice, the situation is more complex, as systems are dependent on multiple inputs that often generate a portfolio of outputs via a web of interacting input–output relationships operating with differing efficiencies; something like a plate of spaghetti! This means that targeting one potential intensification process may have unintended consequences for another. Where these consequences are positive for the system as a whole, they are regarded as synergistic. Synergies do occur, but more commonly trade-offs are negative, sometimes with the dis-benefits accrued outweighing the initial benefit sought (see below).

It is useful when considering intensive livestock production systems to distinguish between smallholder, intensive systems, and "industrial" systems. In essence, the key difference is that industrial systems seek to maximize productive outputs, as well as optimize the efficiency with which they are produced. Smallholder systems may settle at points of optimum efficiency that are considerably below maximum genetic production potential, but still make highly efficient use of the inputs that are available to them.

Smallholder Intensive Livestock Production Systems

Smallholder intensive livestock production can be regarded as efficiency-driven rather than output-driven. Generally, these systems are highly integrated, with efficiency gains coming from the interactions between different enterprises on the farm (e.g., efficient use of crop residues for feed, multiple productive outputs from system components such as dairy – draught). Capital investment and the use of external inputs are relatively uncommon in these systems, but sometimes these are used in a targeted fashion; particularly when there is a degree of market-orientation that generates income to be invested or allocated to the purchase of inputs (when a cost benefit is perceived). Examples of this would include investment in livestock housing, use of veterinary services and medicines, and purchase of concentrated or supplementary feed in small-scale dairy or poultry production systems.

Industrial Livestock Production Systems

Industrial livestock production systems are largely beyond the scope of this chapter, but they are becoming increasingly important in some least developed countries (LDCs). These rely on purchased feed rather than local feed resources, and hence the local agroecological linkages are often severed in these systems. It should be noted that industrial does not necessarily connote large units. Locally, industrial production may be practiced at a relatively small scale; e.g., broiler and egg production systems with just a few hundred birds in Southeast Asia, high input/high output family pig units in China, or commercially oriented dairy production in India. Such systems are managed much more as an investment proposition by entrepreneurs who may "buy-in" their technical expertise. Operating at the highest levels of efficiency, when effectively managed, these systems can outcompete smallholder producers in the market place, resulting in adverse social consequences for the community as a whole.

LIVESTOCK TRENDS AND PREDICTIONS

In recent years, livestock consumption and production has been growing faster than any other agricultural subsectors, and it has been predicted that by 2020 livestock will account for more than half of total global agricultural output in value. This process has been termed the "livestock revolution" (Delgado et al., 1999). Total meat consumption in developing countries overtook that of developed countries in the mid-1990s, and is now substantially higher, driven by increasing overall populations and the burgeoning middle classes in many LDCs who, as household wealth increases, have tended to switch to diets based more on livestock products. This process is at the core of the livestock revolution, and has been seen by many to represent significant opportunities for livestock producers to, literally, cash in on the opportunity by becoming more efficient, and more market-oriented. Current evidence (summarized by Thornton, 2010) suggests that this situation will continue to change (Fig. 9.4). In developed countries, demand for livestock products appears to have peaked alongside more stable populations, and increasing health concerns around the excessive consumption of livestock products. Projected growth appears to be concentrated in Southeast Asia and the Pacific region for pigs and poultry, with small ruminant numbers largely static and large ruminant populations growing largely, again, in Asia.

Livestock Ownership

Smallholder mixed farming systems have been strongly influenced by some important trends in many LDCs. These include replacement of animal traction with tractors, reduction in farm sizes, and reduction in off-farm grazing and water resources. The latter two factors have made it increasingly difficult to make a living from agriculture and, together with "pull" factors (better wages), have encouraged members of a rapidly growing number of households to migrate for labor, either seasonally or long-term. However, there have also been some positive trends for livestock production, namely the development of stronger market linkages, and a rapid growth in the demand for livestock products in many LDCs, particularly those in Asia. These trends

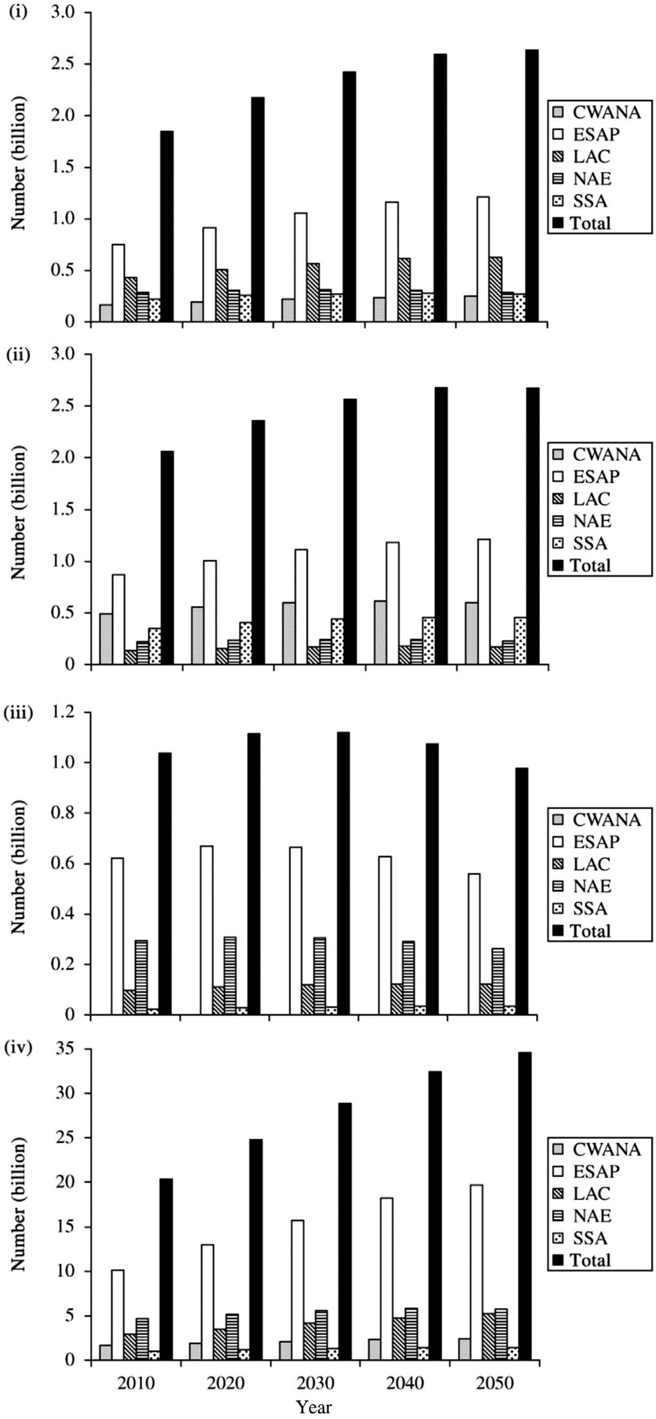


FIGURE 9.4 Projected trends in livestock numbers by region from Thornton (2010). (i) bovines; (ii) sheep and goats; (iii) pigs; (iv) poultry. CWANA, Central and West Asia and North Africa; ESAP, East and South Asia and the Pacific; LAC, Latin America and the Caribbean; NAE, North America and Europe; SSA, sub-Saharan Africa.

have brought about significant changes to livestock in mixed farming systems, including a reduction in the number of large ruminants per farm, a shift from cattle to small ruminants on farms, a shift from cattle for traction to cattle for milk (particularly in India), and intensification of livestock production, especially in peri-urban areas.

Consumption of Livestock Products

The livestock revolution has been characterized by the following production trends:

- From resource driven (shaped by local feed availability) to demand driven;
- From local demand to regional, national, and international, and from rural to urban;
- From extensive (land-based) to intensive;
- Production expansion has mainly involved monogastrics (pigs, poultry) rather than ruminants;
- Geographical clustering of production units, either in a peri-urban belts around consumption centers, or close to commercially produced feed resources.

There are two schools of thought on the implications of the livestock revolution for poor producers: some observers see it mainly as an opportunity, whereas others believe it poses a serious threat. The optimists argue that it represents an opportunity for bringing about sustained and increased revenues for the poor, and making a major contribution to the achievement of the millennium development goals, whereas the pessimists are concerned that livestock production by the poor could be undermined by increased competition from larger production units, with their economies of scale, and by more stringent sanitary requirements, with their high compliance costs.

It is likely that both viewpoints are right, in the sense that either of these outcomes could materialize, depending on the enabling environment (prevailing policies, laws, livestock services, and marketing systems), which may vary from country to country. This point can be illustrated by the example of India. Despite the large numbers of various types of livestock in India, the productivity of all species is low, with the exception of commercial poultry. This suggests that the enabling environment there, primarily livestock services (research, extension, veterinary services) and policies, leaves much to be desired.

CONTRIBUTIONS OF LIVESTOCK TO DEVELOPMENT

Livestock contribute to the livelihoods of most rural households, both farming and landless, in LDCs. They generally play a number of roles, including being a source of cash (planned sale), or serving as liquid assets (emergency sale); providing inputs to crop production; spreading a farmer's risks by acting as a buffer to poor crop yields; being a source of food; providing a means by which the poor can derive benefits from land owned by others; and having a cultural value. In mixed farming systems, livestock may provide manure, fuel, and draught power as inputs, while consuming crop residues from the crop production side of the farm. The relative importance of these different roles is liable to vary by production system and over time, as internal (to the farm and household) and external factors change.

There is often a perception that, in most rural households practicing mixed farming systems, the contribution of livestock to livelihoods is seen as being less than that of crop production. This is, however, something of an oversimplification. In some situations, depending on the production system and the agroecology, livestock predominate. This is particularly the case in dryland regions where crop production is either not possible, or is less remunerative and relatively risky. Even in more balanced, mixed systems, attributing greater importance to one component of the system can be misleading. Farmers, over time at least, tend to take management decisions around the system as a whole for a range of livelihood functions. Asking this kind of farmer the question "what is more important, your crops or your livestock?" would generally only raise a baffled expression in response. Notwithstanding, there are two particularly important issues that can strongly influence the livestock management decisions that are taken within households.

Trade-Offs

All farmers, even those managing industrial systems in North America or Europe, do so with limitations on their resources (inputs). This is particularly acute for farmers managing smallholder systems in LDCs where resources, particularly land and working capital, are scarce. Where there are scarce resources and a range of possible production enterprises, decisions must be taken about the most effective way of allocating those resources. As we have already seen, farmers derive multiple benefits from their livestock, and indeed from their crops, which result in considerable complexity when trying to identify intensification trajectories. As a result, different combinations of resource allocation decisions will result in different combinations of benefits derived. A trade-off is effectively the evaluation that a farmer must make as to whether the change in benefits associated with moving from one combination of resource allocations to another will, on balance, have a positive or a negative impact on household livelihoods.

An awareness of possible negative trade-offs is imperative when seeking to promote innovation in livestock and other farming systems. In mixed farming systems, particularly, negative consequences may be found in other parts of the system than that in which the intervention is principally targeted. For example, the practice of conservation agriculture (CA) has been widely promoted to improve long-term soil fertility in many agroecosystems and farming systems (FAO, 2007). In mixed farming systems, it has often proved unadoptable because of rigid adherence to the retention of crop residues on the land when farmers place greater values on these as feed for their livestock.

Positive synergies are probably less common than negative trade-offs that can compromise adoption. However, they do exist. For example, in the early stages of the green revolution, plant breeders tended to select for short-strawed cereal varieties. Many of these varieties proved highly effective in industrial monocultures, as they reduced the tendency of plants to lodge and improved productivity by shifting resource partitioning within the plant, thereby contributing to higher grain yields. However, these varieties were often rejected by smallholders with both crop and livestock priorities, as the availability of crop residues for feeding purposes was severely compromised by the reduction in straw biomass.

Participatory approaches have an important role to play in helping researchers to understand and deal with trade-off situations and identifying synergies. The factors that render technologies such as CA unadoptable by many farmers often relate to their own complex priorities, rather that the technical efficacy of the intervention. Similarly, researchers can only become fully aware of the desirable characteristics of multipurpose crops if farmers tell them what they are looking for in those crops. It is only by including farmers, as end-users, in a participatory process that the right questions can be asked to plan and implement research that will generate innovation that is both technically viable and adoptable.

Many research projects have attempted to make systematic evaluations of such trade-offs using simulation modeling or optimization (single and multiple criteria) studies. The findings of these studies often generate illuminating insights into the ways in which system components interact, and can help to identify some of the key considerations that should underlie decision-making. However, they rarely, if ever, generate combinations of decisions that are similar to those employed by farmers. Resource allocation decisions are amongst the most complex decisions that farmers make, and they must do so with imperfect knowledge of the outcomes and under conditions (e.g., climatic, social, market) that are constantly changing.

LIVESTOCK AND LIVELIHOOD OUTCOMES

We have already seen that people do not keep livestock to make their fields look pretty for passers-by. Their role as an integral part of farming systems is complex, both allowing these to function more effectively and efficiently—by, e.g., providing draught power and manure—and directly providing income that can support a number of needs in the households. Even these do not represent the ultimate needs of people. They cannot eat cash, and livestock manure applied to a crop does not generate an outcome if the crop fails, for whatever reason. People undertake any farming activity, including livestock keeping, because this allows them to meet some of their more fundamental livelihood needs. In order to understand the importance of this, we can break it down into a set of livelihood outcomes. There is much debate about which outcomes can make the greatest contribution to improved livelihoods, both in the short and longer-term. The following cover some of the key dimensions that need to be addressed, either individually or in combination, for peoples' lives to improve. Clearly livestock are not unique in being able to address these outcomes, but some of the characteristics of livestock production are distinctive, and help them to contribute in specific ways to securing sustainable livelihoods.

Income Generation

Income generated by members of a household can be channeled into savings that contribute to resilience, capital investments to underpin activities that contribute to livelihoods, and the purchase of inputs that allow these activities to be undertaken. Livestock are unique amongst household assets, in that they are not only productive resources, but they also form part of the household's relatively liquid assets. They might be described as a "bank on legs." Individual animals may be sold to cover periodic expenses, such as school fees and, particularly in more extensive systems, may be sold *en bloc* to generate at least some hard cash when acute events, such as crop failure or bereavement, occur. In some livestock enterprises, such as fattening, the individual animal is more like a cropping enterprise, in that it represents a one-off source of income, albeit with generally more flexibility in the timing of the sale. Other enterprises, such as dairy and egg production, are somewhat different in that they generate product on a daily basis, providing regular income or a source of high quality food. Very few crops do this, and even then (e.g., fruit trees or roots and tubers that can be retained below ground) for only a part of the year. This feature is generally considered beneficial to household cash flow, and means that income is more likely to be allocated to activities that benefit the household as a whole, without the need to resort to local savings and credit schemes to even out the availability of money.

Improved Human Nutrition and Health

Many people in developed economies have come to perceive the consumption of livestock products as a contributing factor in the growing obesity epidemics that many of these countries are experiencing. To the extent that livestock products are concentrated sources of nutrients and energy, this is undoubtedly true *when they are consumed in excess*. However, when consumed as part of a balanced diet or, particularly, when contributing to the intake of individuals in poorer households, the high levels of protein with amino acid profiles that are well-balanced to human requirements and are characteristic of livestock products can dramatically improve the nutritional quality of the overall diet. Human nutritionists often divide nutritional issues into problems associated with: (1) availability of more nutritious foods; and (2) access to more nutritious foods. The intensification of livestock production can improve availability by ensuring there are more edible livestock products (meat, milk, eggs) available to the farm household, and increased market participation by livestock producers can generate cash that can, in part, be allocated to diet diversification through the purchase of a wider range of foods. The access issue is not just about the physical proximity of food products, but also includes access to the knowledge required to design and prepare healthy meals from appropriate combinations of livestock and nonlivestock products.

When improperly managed, livestock and livestock products can lead to health problems for the humans that they are associated with. Zoonotic diseases, such as *salmonella*, *cysticercosis*, and *brucellosis*, are directly transmissible from livestock, while feed-borne toxins, such as aflatoxin, can be concentrated in livestock products to levels that are dangerous to the humans that consume them.

More Equitable Access to Inputs and Control of Outputs

Many livestock production systems do not require much land. In societies where men control decision-making about land allocation, livestock can offer food production and income generation opportunities for women and young people. This improved access to productive assets, and the income derived from them, can improve the situation of women in the household. Differences in spending patterns between women and men are widely reported. Strengthening women's income streams through engaging in livestock production can be of great benefit to the family as a whole, as they may spend as much as twice as much as men in ways that benefit more members of the family, such as education, food, clothing, and health care.

Environment and Sustainability

The negative impacts of livestock on environmental parameters through land degradation and deforestation have been widely publicized. More recently, their contribution to greenhouse gas emissions (GHG) has been quantified at an estimated 18% of global anthropogenic CO_2 equivalent emissions (FAO, 2006). While there have undoubtedly been negative impacts of livestock enterprises under certain production systems, e.g., through forest clearance for extensive, grass-based cattle production, or through poor waste management practices in intensive pig, poultry, and feedlot systems, in other systems livestock can be pivotal in ensuring low environmental loads for the system as a whole. In the mixed farming systems of the developing world, livestock manure is not considered a waste product, but a valuable resource, providing nutrients and enhancing physical soil characteristics (soil carbon and water holding capacity) for crop production. The consumption of crop residues by livestock also has an environmental dimension, in that it increases the efficiency of resource use across the system as a whole, thereby reducing waste.

Systems sustainability is a complex concept both to grasp and to measure. How long does a system have to be sustainable for? How do we know the systems we are considering are sustainable when, by definition, the measurement must be taken at a point in the future? Sustainability has a number of dimensions (production-related, environmental, economic, human, and social; Smith et al., In press)—is it possible to address these together, or are trade-offs inevitable? If there are trade-offs, how can they be managed acceptably? Taking this multidimensional view of sustainability throws some interesting light on systems sustainability. Livestock must be managed in ways that do not undermine environmental sustainability but, at the same time, they serve as tools for promoting sustainable rangeland management, preserving wildlife habitats, and supporting biodiversity. The importance of the economic dimension of sustainable systems is often overlooked. Systems that are not economically viable in the longer-term will not persist and, therefore, cannot be considered to be sustainable. Livestock that are integrated in systems have the potential to strengthen economic sustainability by smoothing out income variability and generating cash that can be used to secure inputs for other productive enterprises.

LIVESTOCK RESEARCH

Despite the important contribution commonly made by livestock to poor people's livelihoods in LDCs, the productivity of these animals tends to be well below their potential, due to a variety of problems that livestock keepers and their animals face. If these constraints could be overcome, the benefits to huge numbers of resource-poor people would increase significantly. There is a major need, therefore, for innovations that will enable poor livestock keepers to improve the productivity of their livestock, enhance the subsistence and income benefits that they derive from them, and benefit from the livestock revolution. Traditional livestock research has achieved much in terms of elaborating the technical constraints (genetics, health, management, and feeding and nutrition) to efficient livestock production in LDCs and identifying technically viable solutions. However, the benefits of these solutions have often not been realized by poor livestock keepers, because the wider contexts that determine adoptability have not been adequately accounted for. In this section we will look at some of the issues around traditional livestock research, and explore some examples in which the inclusion of a more participatory approach has led to better targeted and/or more adoptable solutions.

"Traditional" Livestock Research

Animal science research in the south has been strongly influenced by that in the north. The latter has a history of being orientated toward meeting the needs of estates, and more recently "factory farms," and being geared to increasing the production of livestock and their products (Waters-Bayer and Bayer, 2002). Specialization and commercialization have been common themes. Another feature of this research has been manipulating the environment so that it contributes to maximum production or productivity: e.g., feeding systems are based on the nutritional "demand" of the animals, rather than on the availability of various feed resources at different times of the year (Bayer and Waters-Bayer, 1998).

The traditional "northern" or "western" paradigm of animal science research for developed countries has been dominant and pervasive. It was transferred directly to LDCs by researchers from the north who turned their attention to these countries, and indirectly by its influence on the education of animal scientists from LDCs. If scientists had been more sensitive to the needs and priorities of livestock keepers in LDCs, they might have reoriented their research so that it was more appropriate and relevant to them. However, they were not particularly sensitive or responsive, they often failed to understand the circumstances of small farmers (Roeleveld and van den Broek, 1996), and the old paradigm persisted. They were aware that traditional systems in LDCs were often substantially different from those in the textbooks, but they saw these traditional systems as backward, and in need of change. Hence, they did not make much effort to understand why these systems were different, and it did not occur to them that resource-poor livestock keepers might have different objectives to resource-rich, commercially oriented ones. They failed to take proper account of the fact that most livestock in LDCs belong to farmers, and are an integral part of a mixed farming, crop–livestock system, providing inputs into crop production (in the form of draught power and manure), and receiving inputs (e.g., crop residues) from crop production.

Another reason why old attitudes, methods, and beliefs persisted was that researchers' contact with resource-poor livestock keepers was quite limited. They did most of their research on the research station because it was more convenient, and also because it enabled them to exert more control over treatments and nonexperimental variables. This in turn meant that they could produce sound, scientifically valid results that were publishable in journals, which has been more important for scientists' promotion than has the usefulness of the results for farmers (Bayer and Waters-Bayer, 1998). Reward systems in research organizations tend to be strongly dependent on the extent to which staff are able to publish articles in respected scientific journals. Such journals tend to be prejudiced against material based on on-farm trials, particularly participatory ones, because it may not satisfy conventional criteria for experimental design and statistical rigor (Chambers, 1997; Morton, 2001). It is hardly surprising, therefore, that there has been a "lack of participation and interest among animal scientists" in on-farm animal research (Amir and Knipscheer, 1989).

Furthermore, scientists' accountability to resource-poor livestock keepers has been almost nonexistent, and there has been little pressure on them to work with these groups. Where research has been geared to livestock keepers' needs, it has been primarily addressing the needs of relatively resource-rich, commercially oriented groups because they have more influence, and also because traditional research is more likely to be relevant to their needs anyway, as their production systems tend to be more similar to those in the west.

NEW PARADIGMS FOR RESEARCH TO ADDRESS DEVELOPMENT NEEDS

Over the last 30 years, a number of new research and development paradigms have emerged with at least the partial aim of addressing the divide between technical solutions and the wider contexts in which they must be adopted (Table 9.1). These paradigms have, to some extent, evolved sequentially such that later approaches have absorbed many of the "best" elements and practices of earlier ones. As such, they tend to share a number of common features:

- They should be implemented in a demand-driven manner, requiring careful assessment of the status quo, and where there are constraints and opportunities during some sort of diagnostic phase;
- They are participatory, generally at many levels, but essentially with end-users playing a role in evaluation and adaption of innovation;
- They are not restricted to deriving, testing, and adapting technical innovations, but can cover a much wider range of disciplines, such as social interactions, market function, and provision of knowledge and skills;
- Drivers of change are accounted for, as are the multiple dimensions of outcomes. This will include unintended consequences and trade-offs, and will not be restricted to increasing productive outputs;
- To some extent, enabling environments have always been addressed in these approaches, but the methodologies for doing so have been strengthened more recently, and institutional innovation may also be explicitly addressed by researchers.

TABLE 9.1 The Evolution of Participatory, Multistakeholder Research Paradigms

Paradigm	Transfer of Technology	Farming Systems Research	Farmer First/ Farmer Participatory Research	Interactive Learning for Change/ Innovation Systems
Era	Widespread since the 1960s, but building on a very long history	Starting in the 1970s and 1980s	Starting in the 1990s	Work in progress
Farmers seen by scientists as	Progressive adopters, laggards	Objects of study and sources of info	Colleagues	Key actors among many others
Farmers' roles	Learn, adopt, conform	Provide information for scientists	Diagnose, experiment, test, adapt	Cogenerate knowledge, processes, and innovation
Driver	Supply push from research	Scientists need to learn about farmers conditions and needs	Demand pull from farmers	Responsiveness to changing contexts
Key changes sought	Farmer behavior	Scientists' knowledge	Scientist—farmer relationships	Institutional, professional, and personal, affecting interactions and relationships between all actors
Innovators	Scientists	Scientists adapt packages	Farmers and scientists together	Potentially all actors

Source: Adapted from Hall, A., 2009. Challenges to strengthening agricultural systems: where do we go from here? In: Scoones, I., Thompson, J. (Eds.), Farmer First Revisited: Innovation for Agricultural Research and Development. London: Practical Action (Hall, 2009).

It has been shown that people, households, and communities involved in livestock production may be spontaneously involved in innovation, driven by various factors such as changes in their personal circumstances, population pressures, increasing land scarcity, or improved access to markets. These innovations can take various forms, including changes in livestock species kept, new production technologies, new arrangements for obtaining input services, or innovations in the way they process or market livestock and livestock products. Nevertheless, improvements in the productivity of, and returns from, resource-poor people's livestock in LDCs have been disappointing, and have not benefited from the livestock revolution as much as resource-rich and corporate livestock producers. In this 21st century era of globalization, if small-scale livestock producers are to survive, they must increase the efficiency of their operations and the productivity of their animals.

Technological innovations developed and promoted by the private sector, such as vaccines and other veterinary products, tend to be inaccessible or unaffordable to poor livestock keepers. Government and donor efforts to underpin such activities have often floundered, because of unfamiliarity with the commercial environments in which these innovations must be scaled. Moreover, technologies developed by public sector researchers are often inappropriate and unaffordable (often in terms of the opportunity costs of labor or land involved, as well as the cash expenditure required). The formal research system may even completely fail to address key constraints, such as high mortality rates as a consequence of predation in the scavenging poultry system (Conroy et al., 2005). However, the case studies presented, and others (see Conroy, 2005a), show that livestock research by government researchers and nongovernmental organizations (NGOs) can be relevant and beneficial to the resource-poor, provided various conditions are satisfied.

Social and institutional innovations can be as important as technical ones (as illustrated in Case Study 9.6), and may take two forms: (1) innovation among producers; and (2) development of innovatory linkages/networks between producers and service providers. Social innovation among producers may be formal or informal, and includes the development of cooperatives, farmer groups, and self-help groups. The formation of groups of farmers or livestock keepers can have a number of benefits, including:

- Making government research and extension services more client driven and efficient;
- Strengthening farmers' bargaining power with traders;
- Reducing transaction costs for input suppliers and output buyers;
- Economies of scale (e.g., from bulking up in output marketing or storage);
- Facilitating savings and access to credit;
- Reducing public sector extension costs.

The following case studies are presented to illustrate how some of these participatory, multistakeholder paradigms have been implemented to address specific constraints to livestock production and the role that livestock play in securing livelihoods in LDCs. When reading these, it will be helpful to consider the following points:

- To what extent are the activities focused on technology, on social contexts, or on institutional environments (e.g., market, policies)?
- Was a participatory approach necessary to the outcomes achieved? If so, how did it enhance the research, and what could not have been achieved without it?
- How might the research have been improved?
- What are the next steps suggested by the research? This could be more research, or a shift toward development investments for scaling.
- Where do the activities sit in the evolution of participatory research activities (see Table 9.1 above)?

CASE STUDY 9.1 Fodder Innovations in Southeast Asia

This case study was based on experiences from a project over 8 years, from 1995 to 2003, eventually operating in six countries. The Forages for Smallholders Project (FSP) was coordinated by the International Center for Tropical Agriculture (CIAT), whose goal was to work with resource-poor upland farmers. In this project, "forages" mean grass and legume crops that are specifically cultivated to provide feed for animals. There are usually planted within a complex pattern of other food and cash crops, utilizing farm space and labor in a multiple and optimal way, such as in lines along contours on farm land; as cover or green manure crops in fruit trees, coffee, and tea; as live fences for demarcation of external and internal boundaries; and as pastures and fodder banks in backyards, or under young palm oil or coconut plantations. Forages are often of secondary importance to poor farmers as food security is their main concern, so developing technologies of interest to them can be a major challenge. The project initially evaluated some 500 species and accessions of forages, and found 25–40 of them to be well adapted to climate, soils, and diseases: these were the ones recommended for evaluation by new farmers. The process of farmer participatory research (FSP), in which farmers were involved in planning and carrying out the evaluation of new species and in adapting the management of them to their farming system, has been a major contributor to farmer adoption of forage technologies. A farmer was considered to have adopted a technology when she or he experimented with a species or a forage technology, and subsequently expanded the cultivated area with his or her own resources. About 25% of farmers dropped out of the evaluation process after 1–3 years. Farmers have developed some unique systems that they discovered to be more profitable, such as feeding cut fodder to carp instead of cattle. More than 4000 farmers benefited from this project over a 3-year period (2000–02). One reason for the project's success has been its recognition that no two smallholder farms are the same, and that farmers need to experiment with and develop their own forage systems. Thus, the project aims to provide "building blocks," and not "finished products." In other words, the project shows the farmers the species and forage systems that have worked in other places, while

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CASE STUDY 9.1 (Continued)

at the same time allowing new farmers to evaluate a range of optional species and develop their forage systems within their overall farming system. Where feasible, new farmers were taken on cross-visits to other farmers who had been working with the project for several years, as these were seen to be best placed to demonstrate how forage can make a positive contribution to livelihoods, livestock, and the environment. Perhaps because it covers such an unusually large geographical area, the project identified important ways of enrolling in-country partners, both organizational and individual, into supporting and promoting the project. At the organizational level, it was found that building partnerships at local, provincial, and national levels is crucial to obtain broad support for the initiative. Therefore, the project makes a serious effort to invite key agricultural or political officials at district or provincial levels for various training workshops and courses. At the individual level, the project seeks to identify enthusiastic farmers and extensionists. In every new community exposed to cross visits from participating farmers, new champion farmers emerge, whose enthusiasm and experience is harnessed by the project. They in turn will become key farmers able to receive other farmers from new areas, to show them their experience in forage evaluation and utilization. Promising field staff are often identified during training courses: apart from skills, attitudes are also an important selection criterion for staff. In very remote areas, where extension workers can be scarce, another option that has worked well is the use of experienced farmers as extension workers.

Source: *Roothaert, R., Kerridge, P., 2005. Case study G: Adoption and scaling out—Experiences of the Forages for Smallholders Project in South-east Asia. In: Conroy C. (Ed.), Participatory Livestock Research—A Guide, pp. 225–236. Bourton-on-Dunsmore, UK: ITDG Publishing (Roothaert and Kerridge, 2005).*

CASE STUDY 9.2 Development of the Kebkabiya Donkey Plow in Darfur

The Kebkabiya smallholder project (KSP) was initiated by Oxfam after the 1984–85 drought. The KSP aimed to empower the communities, strengthen the position of the poor, and increase food security. This project focused on the development of an animal traction technology, something that was largely absent from the area at the outset, but which project staff saw as an important means of increasing food security. The only plowing was that provided to rich farmers by people hiring out camel plowing services, but this practice had been declining for various reasons, including increased theft of camels. The only widely owned animal capable of plowing was the donkey. A careful needs assessment was undertaken, which proved to be a prerequisite for success. It was decided to develop a donkey-drawn plow suitable for the local conditions that could address farmers' main constraints on crop production, which were weeding and excessive runoff. A participatory process was adopted, involving blacksmiths as producers and farmers as users. The project developed and tested a number of plow designs over a period of several years.

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CASE STUDY 9.2 (Continued)

Initially, the traditional moldboard camel plow was adapted for use by donkeys, and a moldboard donkey plow brought from the United Kingdom in 1987was found to be unsuitable when tested. A donkey-drawn seeder/weeder developed in another area for a different soil type was tested; it was found to facilitate quick sowing, but was less effective at weeding, which was the main constraint in Kebkabiya. Local blacksmiths were then brought into the project by Oxfam to play a role in further modification of donkey plow designs. Because they had no previous experience of manufacturing plows, they were given some training first. In addition, a blacksmith from a nearby area, who did have experience of plow manufacture, was involved. Plows produced by blacksmiths, based on a modified design, were tested in community demonstration farms. A few farmers showed interest and borrowed the plow. It was too heavy and did not speed up agricultural operations significantly, but plow development continued and in 1988 the Intermediate Technology Development Group was contracted to provide technical support. The ITDG decided to develop two different types of plow—a moldboard one and a chisel plow, such as the traditional ard—so that farmers would have choices. A prototype ard was brought from the United Kingdom, copied, and tested by local blacksmiths. Various problems were identified by the blacksmiths, who produced modified ards to address these problems. At the same time, modifications to the moldboard design were being made by another blacksmith group. Both new designs were tested on the same demonstration farms; various problems were identified with the ard design, and there was greater farmer acceptance of the moldboard design, although this had its own problems. Blacksmiths then produced seven moldboard plows, which were tested in 1990 on demonstration farms, and by some farmers in their fields. The results were encouraging, so development of the design was continued. This was done in a participatory, iterative annual process involving blacksmiths as producers, and farmers as users, plus a little technical advice from the project engineer. By 1994 the technical weaknesses had been addressed, and a final and accepted donkey plow was developed. This reduced labor requirements and increased crop yields, planted area, and food security. However, the poorest farmers faced two barriers to using the plow: lack of cash to buy plows, and lack of donkeys; about one-third of the poorer households had none. These were addressed by developing a pay-by-installment system, and by facilitating the sharing of a donkey and plow between two households, one owning the donkey and the other the plow. Now more than 3000 plows have been distributed. Capacity building of blacksmiths and farmers, through training and group formation, has been an essential part of the project, as has the provision of credit. These activities were made possible because the technological development process was part of a larger development project. The development of the plow took about 10 years, longer than most research projects last.

Source: *Suliman, M.S., 2005. Case study I: Development of the Kebkabiya donkey plough in Western Sudan. In: Conroy, C. (Ed.), Participatory Livestock Research—A Guide, pp. 247–256. Bourton-on-Dunsmore, UK: ITDG Publishing (Suliman, 2005).*

CASE STUDY 9.3 Development of a Low-Cost Egg-Cooling Technology

A 5-year scavenging poultry research project in Rajasthan looked at issues of egg management. The project was managed by the Scottish Agricultural College's Avian Science Research Centre, and implemented, in collaboration with the BAIF Development Research Foundation, an Indian NGO, with inputs from a socioeconomist. Poultry keepers in Udaipur, Rajasthan, informed the research team that during the summer months (March—June), when temperatures can reach more than 40°C, the percentage of spoiled eggs increased. It is well known in poultry science that high temperatures (>27°C) can increase the incidence of abnormal embryos, and the percentage of embryos that die during incubation. Thus, the project team hypothesized that this was the cause of poor hatchability, and suggested to poultry keepers in the project villages running an experiment to test a technology to address the issue based on the principle of evaporative cooling. After discussions with the poultry keepers, a simple technology was identified based on locally available materials that had the potential to reduce and stabilize the temperature of the eggs. The technology involved the use of a half-moon-shaped bowl in which the eggs would be kept cool by evaporative cooling. The bowl was filled with an earth/sand mixture that was kept moistened with water. Then a piece of jute bag was placed on the sand to prevent the eggs coming into direct contact with water (which could facilitate contamination). The eggs were placed on the bag, and a cotton cloth or woven basket was placed over them. The bowl was placed either on a shelf or ledge, or on the floor inside a family building. When the hen stopped laying, all the eggs were placed under her, as per existing traditional practice. The project conducted a pilot trial in February—May 2003, with two groups of poultry keepers to test this technology in which all eggs were candled first to confirm fertility. The temperature in the vicinity of the eggs and in the egg storeroom (ambient) was recorded each morning (between 8:00 and 10:00). The numbers of eggs that hatched viable chicks, that contained dead-in-shell embryos, or that had spoiled (were infertile or had bacterial rot) were recorded. The first trial, held in 2003, showed promising results, and hence was repeated on a larger scale, with more birds and eggs, in March—June 2004. Of the fertile eggs available for hatching in the first trial (2003), the percentages of chicks that hatched were 97.0% and 69.0% for the modified storage and control groups, respectively. In the second trial (2004), the equivalent figures were 84.3% and 69.5%, respectively. The minimum room temperature during storage tended to exceed physiological zero, and often the maximum temperature achieved was in excess of 32°C: the highest temperature recorded was 42°C. Results provided clear evidence that the modified storage of eggs did improve the overall hatchability of the eggs, and data were consistent with the hypothesis. Development of the cooling technology went through an iterative process. Initially, clay pots were used, but because these had a tendency to crack, locally available iron pots were used (e.g., in the 2004 trial). Although the latter proved to be effective, reed baskets lined with cloth have been used more recently. One advantage of these is that evaporation may also occur through the side of the container, leading to greater cooling than the iron pot technology; they may also be less expensive. The technology was adopted by a large proportion of the poultry keepers in the project villages, and

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CASE STUDY 9.3 (Continued)

by many others in nearby villages who heard about it from people in the project villages. It has also been adopted in a few villages in the state of Tamil Nadu, where it was publicized through farmer poultry schools.

Source: *Sparks, N., Acamovic, T., Conroy, C., Shindey, D.N., Joshi, A.L., 2004. Management of the Hatching Egg. In: Paper presented at XXII World Poultry Congress, June 8–13. Turkey: Istanbul (Sparks et al., 2004).*

CASE STUDY 9.4 Indigenous Knowledge of Tree Fodder Quality and Its Implications for Improving the Use of Tree Fodder in Developing Countries

Many interventions generated by research with the aim of improving the nutritional status of livestock in developing countries have failed to realize their apparent potential when implemented on farms. It is now widely accepted that this is because farmers try to meet a wide range of objectives in feeding their animals. Their decision-making can be supported by a sophisticated, indigenous knowledge. When researcher-developed technologies fail to account for this, they may be deemed unacceptable by the farmer. One example of an indigenous knowledge system that relates to the quality of tree fodder is used by farmers in Nepal. A participatory research study found that the knowledge of tree fodder quality possessed by the farmers is quite consistent with the level of information that may be generated from the laboratory analyses that are commonly used by nutritional researchers for the same purpose. Of the two distinct indigenous knowledge systems from Nepal used, one (*obanopan*) appeared to relate to the digestibility of tree fodder (as predicted by an in vitro test), and the other (*posilopan*), that was perceived to be an indicator of general nutritional quality, may relate to the ability of a tree fodder to promote the supply of protein at the duodenum. However, the relationship between *obanopan* and in vitro digestibility indicated that Nepalese farmers, in preferring to use *obano* fodder, also preferred less digestible fodder, due to its ability to fill animals in times of feed shortage. This observation—and the fact that recommendations derived from a panel of nutritionists viewing a set of laboratory indicators describing the tree fodder studied did not appear to account, in any way, for the *posilopan* criterion, judged important by farmers—highlight the paramount importance of interpreting nutritional information against farmers objectives for a given set of circumstances. The participatory approach adopted allowed the research to accomplish this. An initial analysis of complementarity between the information provided by farmers' perceptions of fodder quality and those generated in a laboratory would appear encouraging for a more integrated approach to assessing fodder quality for the smallholder farmer. This work demonstrated, more generally, that combining participatory and "traditional" research approaches is feasible, and can enrich the findings of both.

Source: *Thorne, P.J., Subba, D.B., Walker, D.H., Thapa, B., Wood, C.D., Sinclair, F.L., 1996. The basis of indigenous knowledge of tree fodder quality and its implications for improving the use of tree fodder in developing countries. Anim. Feed Sci. Technol. 81, 119–131 (Thorne et al., 1996).*

CASE STUDY 9.5 Promoting Goat Markets and Technology Development in Semiarid Zimbabwe for Food Security and Income Growth

An increasing demand for livestock products, including goat meat, offers small-scale farmers in semiarid Zimbabwe opportunities for increased market participation. However, existing goat markets are largely informal, with poorly developed inputs and services. Transaction costs are high, resulting in low prices. In addition, access to market information is limited, and negates informed decision-making. Also, farmers are unable to realize the full potential of their herds, because of insufficient investment in management practices. Farmers use the cash from goat sales for food, education, and human health. Yet, they lose up to 26% of their goat herds to mortality, attributed to dry season feed shortages, animal health, and inappropriate housing. While farmers do react to market development, it is not in a consistent enough manner to realize the returns from their investments. More needs to be done to improve production, reduce transaction costs, and increase market access to ensure growth within the sector. We hypothesize that improved market access will provide farmers with the incentive to invest in management technologies to enhance offtake, and increase the quality of their goats. Innovation platforms (forums that facilitate communication between farmers, market players, and input and service suppliers around local production and marketing systems), were established in two locations in Zimbabwe. The stakeholders meet to identify challenges and opportunities with regards to both production and marketing, and collectively identify and evaluate improvements in management technologies and markets. This new approach places technology and market development in a local context, based on common interests and strong partnerships between the private and public sectors. It builds local capacity, aligns production with market demands, and improves the overall efficiency of the system, thereby increasing food security and income growth, and supporting the development of sustainable impact pathways.

Source: *Van Rooyen, A., Homann Kee Tui, S.H.K., 2009. Promoting goat markets and technology development in semi-arid Zimbabwe for food security and income growth. Trop. Subtrop. Agroecosyst. 11(1), 1–5. ISSN 1870-0462 (Van Rooyen and Homann Kee Tui, 2009).*

CASE STUDY 9.6 Why Ethiopian Farmers Reject Improved Faba Bean Management in Favor of Their Traditional Practices

Low productivity of staple crops is often attributed to poor management by smallholder farmers. "Improved" crop management practices have been widely promoted for many staple crops in Ethiopia. Adopting these practices can result in significant yield increases under on-farm conditions but, in spite of these benefits, they are often not adopted in the longer-term by smallholders. This study, conducted by ILRIs Africa-RISING project in Ethiopia, explored some possible reasons for nonadoption or dis-adoption of improved variety × management practice packages for faba bean. It was based on the hypothesis that smallholders do not use improved management practices, because these do not adequately improve upon the overall benefits that farmers derive from faba bean plots under

(*Continued*)

CASE STUDY 9.6 (Continued)

traditional management. Earlier diagnostic studies indicated that men and women farmers in SNNPR and Amhara regions deliberately weed their faba bean fields much later than is recommended for improved management systems. This creates the opportunity for volunteer "weeds" like oats and *Trifolium* spp.—species that are in fact relatively nutritious fodders—to create an *ad hoc* forage intercrop in areas with limited grazing land. The study assessed the impacts of this farmer-preferred practice on bean and crop residue yields, and on the likely overall benefits derived from bean plots when the value of the weed forage produced is also taken into account. It revealed that there were no statistically significant differences between improved and traditional practices in terms of faba bean grain and straw yields. Moreover, results at one site indicated no economic benefits of the improved management practices, and at the other site, where the incremental benefits were greater, they still failed to reach the value – cost ratio (VCR) of two that is widely regarded as necessary to incentivize the adoption of new management practices. Effectively, the opportunity costs associated with the loss in weed biomass when the improved practices were adopted were not adequately offset by the economic gains from increased grain yield and crop residue biomass. It should be noted that these observations are based on VCR calculations alone, and do not account for qualitative factors that, potentially, are even greater barriers to adoption. Some farmers have no other options for providing feed for their livestock during the periods when these weeds are available. Foregoing this indispensible forage resource would force these farmers to sell their animals. Using the terms "improved" and "weed" indiscriminately, and without properly understanding the multiple benefits that farmers wish to derive from the plots they cultivate, can be highly misleading. Accepting these terms uncritically can lead to misperceptions of farmer irrationality because they do not adopt "improved" practices. Studies such as this one take a broader, "systems" view of the factors constraining adoption. They are demonstrably more informative, and help us to identify more adoptable intensification strategies. These strategies might prove to be stepwise, leading ultimately to greater specialization; e.g., allocating land systematically to both grain and forage production. The next step for future studies will be to examine the benefits of managed forage – bean intercrops to increase total plot productivity, and the quality of the forage component of the system.

Source: *Adie, A., Mekonnen, K., Bezabih, M., Thorne, P., Kemal, S., Tesfahun, G., et al., 2015. Awaiting Posting (Adie et al., 2015).*

WAYS FORWARD

Funding for all areas of agricultural research that seek to ultimately support the livelihoods of households in LDCs has been variable in recent years, and that for livestock is no exception to this. The early successes of the green revolution guaranteed strong funding streams through the 1970s and 1980s from donor governments, multilateral agencies, and philanthropic foundations such as Ford and Rockefeller. More recently, donor priorities have changed, and donor organizations have become more demanding in terms of the justifications that they require for issuing specific grants. While greater scrutiny of the use of public funds is to be encouraged, short donor timeframes often mean that the long-term benefits that are characteristic of research, i.e., by its very nature, speculative and unlikely to generate a precisely predictable outcome, may be foregone. This kind of funding environment is likely to be with us for the foreseeable future, so livestock researchers need to be articulate in making the case for their share of the limited resources available. There are a number of opportunities here. Donors now look at broader research outcomes than mere productivity. The potential for livestock products to contribute to improved household nutrition aligns with this, as does the differential benefit that women and young people can derive from some forms of livestock keeping. There are also signs of a shift from donors prioritizing single discipline research at the expense of all else, to a genuine attempt to consider intensification from a more holistic, livelihood perspective that includes livestock as one of the livelihood opportunities available to households amongst many others and in an integrated way.

Success in conducting research that makes a tangible contribution to livelihoods in the long-term is not just about the research part. Participation is key to ensuring that the whole raft of measures required to create an enabling environment that will boost the small-scale livestock producer sector in developing countries, including an *institutional revolution* on the scale of the livestock revolution itself, are implemented. Livestock service organizations must be made more accountable and responsive to poor livestock keepers by facilitating the articulation of the latter's priorities and demands, and research organizations should give greater emphasis to species that are important to the poor (Conroy, 2005b).

Changing the public sector working environment so that it supports demand-led, pro-poor, participatory multistakeholder research, rather than hindering it, is a major challenge, particularly as government agencies' rules and norms may be determined outside the agency itself. Common constraints include lack of *incentives* (or even perceived disincentives) for this kind of work, and lack of *resources*, including funds to cover the travel and subsistence costs of fieldwork. In Kenya, the National Agricultural Research System has taken the following initiatives to address these constraints Okuthe et al. (2002):

- *Incentives*: Changes in appraisal procedures so that staff are rewarded for undertaking participatory work instead of being penalized;
- *Resources*: The establishment of competitive research funds specifically for demand-led participatory research.

With a supportive enabling environment, the livestock revolution can become an opportunity for resource-poor livestock keepers in LDCs rather than a threat. Their ability to take advantage of the burgeoning demand for livestock and livestock products can make a significant contribution to poverty eradication, and broader social and economic developments.

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Chapter 10

Gender and Agrarian Inequities

Rachel Bezner Kerr

INTRODUCTION

This chapter focuses on agrarian inequalities at multiple scales: the global, community, and household level. Several global scale issues—land struggles, climate change, and trade agreements—are examined to consider the implication for agrarian inequalities. A focus on the gender dimensions of inequality and associated struggles is highlighted, to bring attention to gender equity into rural development planning and agricultural innovations. Several case studies highlight the need to consider gender and other social inequalities in agroecological approaches.

INEQUALITY AND AGRICULTURAL SYSTEMS IN PERSPECTIVE

Inequality at a Global Scale

Farmers around the world are operating within radically unequal political economic contexts. For example, let us start with a successful maize farmer in the US corn belt, who farms thousands of acres of a single crop with expensive machinery, purchasing vast amounts of hybrid seeds, pesticides, and fertilizers, drawing on computer-processed satellite data, and receiving a sizable share of his income from government subsidies. Near the other end of the farming spectrum, we could find a small farmer in Malawi, working a one-acre field by hoe, cultivating maize and other edible crops while the best land in her region is devoted to tobacco, lacking much capital or access to credit, and struggling with the increased cost of fertilizer and seeds (the latter which might be purchased from the same transnational corporation as our American maize farmer), receiving virtually no extension support, and facing additional responsibilities within her household as a caregiver to children of relatives who have been orphaned by AIDS. From this basic example, which has innumerable global permutations, a number of questions might jump out. For instance, what do these disparities mean for agricultural scientists?

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How did farming systems get shaped this way? What does "development" mean for the Malawian farmer? What are the prospects for the Malawian farmer in an increasingly competitive market with other producers, such as the American farmer? What policy changes might help support her farming? Where does agricultural science fit in all of this?

This chapter attempts to provide some context for these questions relevant to small farmers in the Global South, reviewing some of the major dimensions and scales of inequality affecting rural development. It makes the case that effective development interventions, including those of agricultural science, require attention to the historical, political, economic, and social context. At a basic level, inequality entails differences in economic, political, and social power that are discernible between and within nations, regions, communities, and households. We begin with the international scale, and move downwards in scale toward the household.

GLOBAL INEQUALITY: THE BIG PICTURE

On an international level, development and inequality are most commonly framed in terms of per capita income. The United Nations Development Programme (UNDP) has sought to broaden the criteria for understanding development with the "human development index" (HDI), which includes health and education as well as income, published annually in its *Human Development Report*. In 2014, the poorest two-thirds of the world's population received less than 13% of the world's income, compared to the richest 1% who received about 15% (UNDP, 2014, p. 39). Inequality within countries rose in 50% of all nations making up 70% of the global population between 1990 and 2012 (UNDP, 2014, p. 38). High inequality makes it more difficult to reduce poverty, threatens social stability, and undermines democratic values.

Agriculture provides a telltale sign of development rankings. On a global scale, the higher the percentage that farming represents within a nation's employment structure, the lower that nation tends to be in terms of both per capita gross domestic product (GDP) and the HDI and, ironically, the more food insecure it tends to be, a point that will be returned to in the third section of this chapter. An estimated 1.2 billion people around the world are estimated to live on less than US$1.25 per day: and three-quarters of them live in rural areas of the Global South (UNDP, 2014, p. 19). The term 'Global South' is used as an alternative to 'developing countries', which has problematic assumptions (i.e. development is a linear process and 'developed' countries are more 'advanced' along a universal trajectory), or 'Third World' which was more appropriate during the Cold War era. An additional 1.5 billion people subsist on US$2.50 per day or less. Over 870 million people globally suffer from chronic undernourishment (UNDP, 2014, p. 28). Again, a large majority of this chronically undernourished population lives in rural areas. However, poverty and desperation in rural areas are also linked to the urbanization of poverty; the United Nations Human Settlement Programme estimates that roughly 860 million people currently live in slum conditions in the Global South, and if current trends continue this population is expected to *double* by 2030 (UNHABITAT, 2014).

Contemporary inequality trends have been shaped in part by historical factors, particularly European imperialism. Europe and its settler colonies are at the top of all indices of development, along with Japan, Korea, and Hong Kong, while the nations of Africa, Latin America, the Caribbean, and Asia that were formerly controlled by Europe are positioned at varying levels below. Global economic inequality has profound political manifestations in such things as the ability to establish the rules for economic governance through multilateral institutions such as the International Monetary Fund (IMF), World Bank, and World Trade Organization (WTO). It also has environmental dimensions that are most stark in the uneven responsibility for global climate change, and in the uneven vulnerability to its fallout (see Box 10.1). The challenges posed by climate change are taken up again in Chapter 13, Climate Change and Agricultural Systems, of this book.

Another crucial dimension of macroscale inequality that influences prospects for rural development is the increased global market concentration (or the share of global industry sales by the largest firms) of agricultural input and food processing industries. By 2009, the top eight firms in crop seeds, agricultural chemicals, animal health, and farm machinery accounted for a share of between 61% and 75% of all global market sales (Fuglie et al., 2011). This concentrated corporate economic power significantly affects both the input and output sides of agriculture. Fewer firms supplying inputs to farmers means increased corporate control over the types of inputs available, tensions over intellectual property rights, and often means higher input prices. Agricultural input prices have risen faster than farm commodity prices globally. At the same time, the fertilizer industry has invested limited

BOX 10.1 The Inequality of Climate Change

In addition to assessing and summarizing mounting scientific evidence on anthropogenic climate change, the Intergovernmental Panel on Climate Change (IPCC) has consistently drawn attention to the fact that the world's wealthiest, most industrialized nations have a disproportionately large role in emitting destabilizing greenhouse gases. Many of the world's poorest nations (and particularly the poorest people within them) will be most adversely affected by changing precipitation patterns, more severe weather, and rising sea levels. Some of these changes have already been observed, and have had impacts on crop production, according to the recent IPCC reports (IPCC, 2014).

Source: *See http://www.ipcc.ch/.*

research and development (accounting for an estimate less than 0.25% of sales, according to a recent review of 42 of the largest firms), such that profits have not led to increased innovation by the private sector, the common justification for high profit margins (Fuglie et al., 2011, p. 69). Table 10.1 provides some indication of the magnitude of corporate power within the agricultural input industries.

Corporate control over agricultural processing, distribution, and retailing is also intensifying, with vertical and horizontal integration occurring at a swift pace over the past few decades. This is a significant factor in the long-term declines in farm-gate earnings, as increasing value within agrocommodity chains is concentrated at these levels.

The long-term decline in the prices of basic foodstuffs in global markets is also linked to the complex issue of agricultural subsidies. Although only about 10% of all agricultural production in the world is traded across borders, as trade is progressively liberalized (i.e., the tariffs levied upon imports by states decline), world market prices established through international trade have a large and increasing influence on prices in domestic markets. International agrotrade is dominated by the production from a small number of powerful exporting nations, including the United States and the nations of

TABLE 10.1 Corporate Control in Selected Agricultural Sectors

Agricultural Industry	Year	Eight-Firm Concentration Ratio (Share of Global Market)
Crop seeds and biotechnology	1994	29.0
	2000	43.1
	2009	63.4
Agricultural chemicals	1994	50.1
	2000	62.6
	2009	74.8
Farm machinery	1994	40.9
	2000	44.7
	2009	61.4
Animal health	1994	57.4
	2000	67.4
	2009	72.0

Source: Fuglie, K.O., Heisey, P.W., King, J.L., Pray, C.E., Day-Rubenstein, K., Schimmelpfennig, D., Ling, S., et al., 2011. Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide. ERR-130. U.S. Dept. of Agriculture, Econ. Res. Serv.

the European Union (EU), where the large majority of global agricultural subsidies are concentrated (Harvey et al., 2014). Agricultural subsidies, which are concentrated very disproportionately on the largest farmers within these nations, have an especially distorting impact on global price levels for the integrated supply of cereals, oilseeds, and animal products (the grain—livestock complex).

Because the United States and EU produce far more than can be absorbed in their domestic markets, especially with respect to the grain − livestock complex, exports are essential in order that domestic price levels do not collapse on farmers. This "export imperative" grew throughout the second half of the 20th century via aid, trade, and various forms of "dumping" (i.e., selling exports at prices *below* those in home markets), with subsidies playing a considerable role in keeping a system based on large-scale and heavily mechanized production, vast surpluses, and low prices (and margins), operational. The market distortions associated with the relatively cheap grain and livestock exports from the world's wealthiest countries grow further when the extensive environmental costs from highly mechanized agriculture are aggregated, including those associated with fossil fuel consumption by machinery, agricultural inputs, water pollution, waste production, and the long-distance transport of food. Because these environmental costs are almost entirely unmeasured in conventional accounting systems—or are "externalized" in the language of economics—they do not affect competitiveness in world trade (Weis, 2007).

Meanwhile, most of the world's poorest nations are net food importers, with increasing dependence upon cheap grain and livestock products from industrialized agricultural systems, at the same time as large segments of the best agricultural land are devoted to mostly low-value tropical commodities, as discussed below. The export sector in poor nations also tends to dominate the marketing infrastructure and capital invested in agriculture, while small farmers, with limited capital or access to credit and declining state supports for things such as extension and inputs, are overwhelmingly oriented toward domestic markets. Thus, trade liberalization is occurring on a highly uneven playing field, which is important to keep in mind when considering the implications of global market integration.

In short, macroscale inequality bears on the prospects for rural development and sustainable agricultural systems in the Global South in many ways, with the pivotal role of multilateral institutions in shaping development and trade policies discussed later in this section.

THE STUDY OF GENDER RELATIONS

Inequality is multidimensional and multiscaled, and one of its most important dimensions relates to gender, which can be understood within and across different scales. While the suggestion that there are inequalities between men and women is not likely to surprise many people, understanding gender and the study of gender relations are more complicated than they might appear at first.

To understand gender it is first necessary to distinguish it as a social category distinct from sex. A person's *sex* is their *biological attributes* as a man or a woman. A person's *gender* constitutes a multifaceted set of relations and characteristics that are related to their biological sex, but also involve their social meanings, position, and relationships to others as a man or a woman. These are, in turn, constructed and interpreted through social interactions and vary across time, space, and culture, which is why gender is referred to as something that is *socially constructed.*

The study of gender relations explores the different, and often highly uneven, roles, responsibilities, access to resources, authority, decision-making patterns, and perceptions about gender held between men and women within societies. This often starts from fundamental questions about inequality, such as: What is the division of labor? Who determines access to resources? Who benefits from the use of these resources? It also involves asking them across different scales, from within households, communities, and institutions, and up in scale to national and global levels. Understanding the implications of these differences is, in turn, generally done within a normative framework that assumes we should seek to find ways to reduce inequalities between men and women.

Gender is not the only socially constructed category that influences a person's position or activity; other social differences like class, age, ethnicity, and occupation also influence social outcomes and interact with gender in complex ways. Two examples illustrate how age and class intersect with gender roles to influence agricultural systems. First, in India, while rural farming women carry out much of the agricultural labor in poorer households, they often have only a limited role in agricultural decision-making. At the same time, Indian rural women have a much heavier workload than men in terms of household work, including food preparation, child care, and the collection of fuelwood and water. However, these roles vary with class, as some women in wealthier households are able to "buy out" of agricultural labor by hiring casual laborers. A second example comes from northern Malawi, where older women usually have more decision-making authority than younger women, and also have more ability to mobilize labor through social obligations. If older women have married sons living nearby, they are able to ask those sons to assist with different agricultural tasks. A younger married woman, who has usually moved to her husband's home, is less able to draw on social and kin ties for mobilizing help in agricultural activities. Older women, however, are also facing escalating household burdens. Increases in HIV/AIDS rates and adult mortality are pushing greater responsibility upon older women for early child care, which is compounding the workload associated with their farming responsibilities.

The study of gender relations is informed by a variety of theoretical approaches, and reviewing some of the major developments provides useful background and tools for addressing gender issues in agriculture. One of the most important pioneers in the study of gender relations was Ester Boserup, whose seminal book “Women’s Role in Economic Development” (Boserup, 1970) heralded a new attempt to conceptualize and analyze the role of women in agricultural systems. Boserup examined women’s roles in different farming systems, and how such cultural practices as dowries and bride price are related to women’s economic status.

Around the same time, feminists were also working to raise the profile of women’s issues within various international and national bodies. For instance, the Commission on the Status of Women began to raise the profile of what were framed as distinctively women’s issues within the UN system, and the establishment of the Office of Women in Development (WID) within the US Agency for International Development (USAID) helped to raise the profile of development issues specific to women within the sphere of official development assistance (ODA). The 1975 United Nations Mexico City Conference on Women, coinciding with the first International Women’s Year, highlighted the need for enhanced legal rights for women, and for their economic empowerment. In terms of development policy and planning, the most recognizable outcome of the conference was the adoption of the WID approach.

The WID approach focused on increasing women’s access to training and resources, emphasizing women’s individual legal rights to social, economic, and political advancements, and it became a fairly standard operating guideline for development agencies in the 1970s and 1980s. The WID approach did draw attention to the issue of gender equality (see Box 10.2), as well as drawing finance to women’s programming at a time when ODA made up a much greater proportion of total money flowing into the Global South than it

BOX 10.2 Gender Equality

Gender equality essentially means that women and men should have equal conditions to realize their full human rights, and equal potential to contribute to national development in all of its facets. Work toward gender equality must start from a recognition that current social, economic, cultural, and political systems are gendered; that women’s unequal status is systemic; that this pattern is further affected by race, class, ethnicity, and disability; and that it is necessary to incorporate women’s specificity, priorities, and values into all major social institutions. Gender equality is essential for progress in human development and peace.

Source: *Adapted from the Canadian International Development Agency’s gender definitions, see www.acdi-cida.gc.ca/equality.*

does today. However, by the end of the 1980s there were widespread concerns that the WID approach tended to marginalize women's concerns by confining them to a specifically "women's" office or program, at the same time as they continued to be ignored within the most significant development policies. Another criticism was that the emphasis on individual rights was too Western in approach, and ignored structural economic inequalities.

In the 1990s a new approach emerged based on the basic argument that considering women's issues in a "silo" was in many respects counterproductive, and that fundamental change in gender relations required the integration of men's concerns and perspectives with those of women. An associated image is the tearing down of the silo where women's issues were separated and largely isolated. In contrast, the gender and development (GAD) approach encouraged what became known as gender *mainstreaming*—the attempted integration of gender concerns into all development programs. The GAD approach also emphasizes the diversity of cultural perspectives on gender issues globally, and the need to take a participatory, empowerment approach to addressing the needs of poor women from the Global South.

GENDER AND UNEQUAL ACCESS TO PRODUCTIVE RESOURCES IN AGRICULTURAL SYSTEMS

Gender relations profoundly influence agricultural outcomes in a number of different ways. While women are critically important cultivators throughout much of the world, they tend to have very unequal access to land, as well as to other productive resources in agriculture: labor, capital, inputs/technology, and the institutions which support agriculture (Quisumbing et al., 2014; Ravazi, 2006; Whiteside and Kabeer, 2001). For example, in Burkina Faso, and across much of West Africa, women are accorded access to poor quality land, after it is depleted through production of the staple cereal crop for several years. Rehabilitation can be accomplished by practices such as sowing a legume crop (a crop class that is primarily grown by women—Fig. 10.1A), but highly degraded soil requires heavy labor investment to construct rehabilitation structures, such as zai pits, with added organic materials (Fig. 10.1B).

The marked gendered character of land inequality must first be understood in the context of the gendered division of agricultural labor. On a global scale, according to the FAO, women make up 43% of the total agricultural labor force in the Global South (Quisumbing et al., 2014) (see Table 10.2 for an example from Kenya). For instance, throughout most of sub-Saharan Africa, agriculture also tends to be extremely labor intensive, and women carry out an estimated 45–75% of all agricultural labor, with a wide variation in practice (Doss, 2014). Recent studies have noted that much of women's labor in agriculture goes uncounted, excluded, or underestimated, so the actual contribution of women to agricultural labor is likely

FIGURE 10.1 (A) Woman are often responsible for legume crops, such as peanut (groundnut). (B) A women's group constructing zai pits for soil reclamation in Burkina Faso.

TABLE 10.2 The Role of Women and Access to Assets in Agriculture: A Kenyan Example

Agricultural Roles and Credit	Sex (%)		
Agricultural Roles By Sex	**Male**	**Female**	
Food production	20	80	
Agricultural workers	30	70	
Crop production labor	50	50	
Smallholder farm manager	60	40	
Agricultural Assets By Sex	**Male**	**Female**	**Joint**
Agricultural credit	98	2	0
Hold registered land titles	93	2	5
Credit allocated to smallholders	92	8	0

Source: Modified from World Bank, 2009. Gender in Agriculture Sourcebook. Washington, DC: International Bank for Reconstruction and Development/World Bank.

considerably higher (Doss, 2014). Particular agricultural practices and technologies, therefore, may require high amounts of women's labor, taking them away from other important activities such as income generation or child care, while a lack of attention to their role renders these costs invisible. Yet, in marked contrast to their contribution to agricultural labor across much of the Global South, women are often treated as unequal partners within their households, and as a general rule hold much less and lower quality land than do men (Lastarria-Cornhiel et al., 2014). There are complex and culturally diverse reasons for this, but it generally cannot be understood without reference to the colonial period. Boserup (1970) was one of the seminal authors outlining how the colonial promotion of male land ownership in Africa and Southeast Asia, and the associated privileging of male access to technology and cash incomes during colonialism, meant that it was not only small farmers who were disadvantaged in a general sense, but women specifically within this broad category, with the net result being worsened food production in these regions.

Women have fewer representatives in political power, and their interests are often marginalized in politics. Women's representation in decision-making positions within ministries of agriculture and other government bodies dealing with rural development is similarly low. At the same time, national ministerial units focused on the advancement of women have been formed in the majority of countries around the world, and have had some success in addressing gender concerns in policies and programs, including agriculture. The level of support for these units varies tremendously,

TABLE 10.3 Individual Holders of Agricultural Land by Sex in Selected Latin American Countries

Country	Men (%)	Women (%)	Year of Data
Chile	70	30	2007
Panama	71	29	2001
Ecuador	75	25	2000
Peru	80	20	1994
Uruguay	82	18	2000
Nicaragua	82	18	2001
Dominican Republic	90	10	1998
Belize	92	8	2003
Guatemala	92	8	2003

Source: FAO Gender and Land Rights Database, cited in Lastarria-Cornhiel, S., Behrman, J.A., Meinzen-Dick, R., Quisumbing, A.R., 2014. Gender equity and land: toward secure and effective access for rural women. In: A.R. Quisumbing, R. Meinzen-Dick, T.L. Raney, A. Croppenstedt, J.A. Behrman, A. Peterman (Eds.), Gender in Agriculture (pp. 117–144). Dordrecht: Springer Netherlands. Retrieved from http://link.springer.com/10.1007/978-94-017-8616-4_6; p. 126.

depending upon the level of expertise, political support, and resources supplied (World Bank, 2009). Some of these policies include gender equity laws and legal reforms, which have been promoted and shaped by a range of civil society and farmer organizations, and social movements operating at different scales and intensities.

At the local governmental level, in many countries few women hold decision-making positions and they are very rarely involved in traditional authority structures. As these bodies are often responsible for the allocation of resources, women's lack of representation at this level has many negative implications in terms of how resources are distributed (FAO, 1995). In addition, most financial institutions have policies and practices (e.g., collateral requirements) that systematically discriminate against the poor, and women in particular. The unequal access of women to land, capital inputs, and other productive resources within different agricultural systems can mean that different land management strategies are used.

As Table 10.3 illustrates, access to and control over land is a fundamental inequity facing women farmers. There are stark inequalities in land distribution between men and women in many parts of the world (FAO, 2011). Women have lower access to and control over land in both statutory and customary land systems (Lastarria-Cornhiel et al., 2014). In some places, women simply have no or limited land property rights, or gain access to land through men. While women do have legal rights of access in many freehold land sectors, they generally lack the economic resources to acquire such land. In many parts of Africa, women are often unpaid laborers on their husbands' land, while simultaneously cultivating separate plots of their own, which they may not have legal ownership of, and thus risk losing upon the death of their spouse (World Bank, 2009). African women who become "de facto" heads of households when males migrate for work also sometimes face threats to their access, as they are rarely endowed with stable property or user rights (FAO, 2011). Female-headed households (FHH), a heterogeneous group which include those women who are divorced, widowed, or single, as well as those whose partners have migrated to other places, when they do own land, have significantly smaller plots of land in the majority of countries worldwide (FAO, 2011; Croppenstedt et al., 2013).

In the 1960s and 1970s there was considerable energy for land reform, but most of the land reform that took place was "gender blind"; i.e., it failed to recognize how gendered relations were embedded in different cultures and legal practices. This failure produced outcomes where women were either not empowered by land reforms, or were made more vulnerable if the household dissolved (e.g., separation, divorce, or widowhood), in some instances producing outcomes where women had less "bargaining power" within the household in terms of workload and resource management.

The dominant approach to land reform has been through market forces from the 1990s onwards. While some have professed hopes that this could improve gender equality in land access if accompanied by efforts to improve women's legal rights to land tenure, a recent study by the United Nations Research Institute for Social Development (UNRISD) suggests otherwise, having found that women's access to and control over land has not significantly improved on a global level. Although there are some contextually specific reasons for the failure of post-1990s land reforms to improve women's access to land (see Box 10.3), the report concludes that legal improvements alone are not likely to be a transformative force; rather, they are part of an array of changes needed to improve women's access to land, with the state, political parties, and social movements also named as having crucial rules in addressing rural women's needs in agriculture (Ravazi, 2006).

Different cultural, historical, and social factors shape the legal rights that women have to land. In patrilineal and patriarchal societies, i.e., where sons inherit land, and women are considered less equal to or valuable as men, women often have very limited rights of inheritance (Lastarria-Cornhiel et al., 2014). Countries in Latin America, which are dominated by patrilineal systems of inheritance and have severe land inequalities, have shown little improvement or worsening land ownership for women in the last two decades (Table 10.3). Despite active efforts at land reform in several Latin American countries in the last few decades, such as Chile, Ecuador, and Peru, the vast majority of beneficiaries have been men (Deere and Leon, 2003). One very notable regression occurred in Mexico, where communal

BOX 10.3 Why Have Land Reforms Failed to Improve Women's Access to Land in South Africa, Brazil, and Tanzania?

South Africa: The fall of apartheid and the transition to democracy in 1994 promised improvements for women, but there have been:

- Institutional weaknesses and lack of political accountability for gender policy at high levels;
- Weak rural women's movements since 1994;
- A market-based land reform model which tends to build on inequitable community structures and disadvantages women.

Brazil: Constitutional guarantees (1988) and vibrant rural social movements promised hope for rural women to gain access to land, but:

- By the mid-1990s Brazilian women were beneficiaries of only 12.6% of land reforms;
- Women's land rights have not been a priority within social movements; in some cases they are seen as being "incompatible" with class issues for landless peasants,

Tanzania: Market-based land reform processes (1991–99) combined with gender advocates did not result in substantial change because of:

- Divisions about how to change customary inheritance laws;
- Disagreement amongst gender advocates over whether land markets are the best solution for land reform.

Source: *Ravazi, S., 2006. UNRISD Research and Policy Brief 4: Land Tenure Reform and Gender Equity. UNRISD, Geneva.*

lands were opened for privatization in order to accede to the North American Free Trade Agreement, and the outcome was to reduce women's traditional access to land by granting formal title to only the household head, who was usually male (Deere and Leon, 2003).

Varying land tenure patterns in Asia pose different problems for women. In India, patrilineal inheritance laws have limited women's access to and use of land. In Vietnam, Laos, and China, where the state is the dominant landowner, land allocated through contract is often the highest quality and tends to go largely to men. Women have the right to own property in China, but married men often control the land in practice; further, if the husband dies, the land sometimes gets taken by the husband's kin (Agarwal, 1994). In parts of Indonesia which are predominantly Muslim, bilateral kinship and inheritance practices are followed, i.e., sons and daughters share equal rights to inherit land, while those regions with matrilineal cultures in Indonesia give women greater rights over paddy land (Quisumbing and Otsuka 2001, cited in Lastarria-Cornhiel et al., 2014).

There is strong evidence indicating that women have unequal access to and control of land throughout sub-Saharan Africa (Lastarria-Cornhiel et al., 2014). State support for customary land tenure systems has often reinforced discriminatory practices toward women, while increased privatization of land tenure has generally worsened women's access to land (Khadiagala, 2001; Lastarria-Cornhiel, 1997; Whitehead and Tsikata, 2003). In southern Africa, the increased levels of HIV/AIDS infection have also made women's access to land more precarious, with the forced removal of widows and property seizures a serious concern in many countries. Analysis of nationally representative surveys in 15 sub-Saharan African countries found that fewer than half of widows reported inheriting any assets, with higher education and wealth positively correlating with the likelihood of inheritance (Peterman, 2011).

Agricultural inputs such as fertilizer, seeds, and equipment are important resources for improving agricultural systems. One review of 20 recent studies on gender differences in the use of inputs (inorganic fertilizer, insecticide, hybrid seed varieties, and mechanical power) found that in 16 out of 20 studies, men use more inputs on average than women (Peterman et al., 2010). Structural adjustment policies (SAPs) and neoliberal development policies have reduced state subsidies for inputs, and increased corporate control over the agroinput sector, which has also led to rising costs. In general, women typically face greater barriers than men in accessing agroinputs for a variety of reasons, including:

- Having less access to credit and capital, as women typically have a harder time getting loans, particularly if credit is tied to evidence of surplus production of cash crops (Doss, 2001);
- Having fewer assets to sell, and having fewer and lower paid off-farm employment options than men (Whiteside and Kabeer, 2001);
- Having less access to land to use as collateral to gain loans; Within married households, in many cultural contexts, control of money to purchase inputs is considered the male's responsibility (Jewitt, 2002; Whiteside and Kabeer, 2001).
- Social constraints prevent participation in credit or farmer clubs (Croppenstedt et al., 2013).

There is considerable empirical evidence that SAPs have had a disproportionate and largely negative impact on rural women and children. Under SAPs, large-scale farming and commercial crop production were promoted, and some productive resources got reallocated from subsistence production to the production of export crops. Women farmers, largely concentrated in the subsistence sector, had limited ability to move into export crops due to various constraints. The increased emphasis on export crops, associated with neoliberal development policies, can force women to reduce the time spent on food production and move them into the export sector. With less access to capital, land, and inputs, women can be pushed out of food production and into marginal employment opportunities with low wages. Even if women are successful in participating in the production of export crops, they often do not control the marketing and sale of these products. Thus, the push to increase export crops can exacerbate existing unequal gender and community relations (Garcia et al., 2006). The gendered dimensions of this can be broadly understood in terms of:

1. *Time*: Given the double burden of productive and reproductive tasks facing women;
2. *Systemic discrimination*: As women tend to have lower access to credit, technological packages, and marketing information;
3. *Sociocultural traditions*: In which women act as the primary care-givers, responsible for feeding and taking care of the household.

Debt and adjustment also involved the reduction of government expenditures on social services such as education, health, and rural infrastructure (e.g., water and energy supplies), which levied further demands on women's time and energy to make up for shortfalls in these areas (FAO, 1995). The fact that these public expenditure cuts had an uneven gendered impact stems, in large part, from under-appreciation of the all-encompassing nature of women's household work, which gets magnified yet is largely unmeasured. In general, women work longer hours than men, contributing significant agricultural labor, in addition to a myriad of other types of work within the household that are gender specific (Doss, 2001) (see Box 10.4). Women are almost exclusively responsible for household food production and preparation, child care, cleaning, and the collection of water and fuelwood. The range of responsibilities women face can add up to a very significant amount of time, though much of this is not measured as "work." This is partly because many of the forenamed gender-specific tasks take place outside the market, and are therefore seen to have less value in a monetized system, while market-based activities (whether from selling agricultural produce or from waged earnings) are conceptually privileged by the fact that they bring

BOX 10.4 Facts About Women's Labor in Agriculture

- A study of the household division of labor in Bangladeshi villages found that women worked almost 12 hours a day—compared with the 8–10 hours a day worked by men in the same villages.
- In many poor regions, women spend up to 5 hours a day collecting fuelwood and water, and up to 4 hours preparing food.
- In Africa and Asia, women work about 13 hours more than men each week.
- In Southeast Asia, women provide up to 90% of the labor for rice cultivation.
- In Africa, 90% of the work of gathering water and wood, for the household and for food preparation, is done by women.
- In Pakistan, 50% of rural women cultivate and harvest wheat.

Source: *http://www.fao.org/Gender/en/labb2-e.htm.*

money into the household. This conceptual privilege, part of the disciplinary bias of economics, can range from things like elevated household status for the money-earners, to the fact that development policy historically tended to focus on "economically active" (earning an income) men and women. This focus on the economically active, in turn, led to development interventions that sometimes ignored those who had no measurable income, as well as those who were at once "economically active" while retaining heavy household responsibilities (what was described as the "dual burden"), with women heavily over-represented in both groups.

Scholars such as Dixon-Mueller (1985) have done a tremendous amount to help draw attention to this dual burden and reconceptualize the distribution of work within the household, with detailed time-budgets (which measure a broader conception of work by hours, rather than by income) one useful methodological tool for highlighting the disproportionate share of work that tends to fall on women. Empirical time-budgets have routinely shown that irrespective of how household monetary earnings were generated, women tended to be working more hours per day than men.

One of the implications of this unequal workload in agriculture is that it can be difficult for women to take on new agricultural tasks or technologies. So while the application of fertilizer might seem like an unmistakably positive thing, e.g., it may also increase women's weeding tasks, and further, if the increased production is not controlled by women and gets used for other purposes, the overall outcome may be negative. Decision-making processes and control over agricultural outputs are, therefore, an important aspect in considering the implications of gender relations on agricultural systems, and conversely the implications of agricultural interventions on gender relations.

Another dimension of inequality in agricultural support is the fact that research and extension efforts have typically focused on male farmers. One facet of this is the shortage of women in agricultural research: there are few women agricultural scientists; an absence of women farmers in demonstration plots and engaged in on-farm experimentation; and limited numbers of women extension workers (Doss, 1999). Further, women farmers' knowledge about seed varieties, crops, or land management is often ignored, unknown, or underreported by agricultural scientists and extension workers (Ferguson, 1994), while crops that women tend to have the greatest time invested in managing, such as legumes, hardier grains, and vegetables, have long been under-researched. The absence of women in agricultural research, and the lack of attention to gendered divisions of labor on the farm and in households, sometimes means that efforts to increase agricultural production inadvertently expand women's workloads, e.g., through weeding, which can result in reduced time for other important household activities, such as child care or food processing (Van den Bold et al. 2013). Several studies have documented how women farmers are excluded from extension services (see, e.g., Due et al., 1997; Saito and Weidemann, 1990). Often it is poor farmers in general who are excluded; for instance, one study in Zambia found that extension services only reached 25% of the nation's farmers, with this support concentrated amongst the wealthier farmers (Alwang and Siegel, 1994). Surveys in three African countries in 2010 showed that in some cases the gender gap has been improved: in Ethiopia, 20% of women had been visited by an extension agent, compared to 27% of men, while in Ghana, 12% of male-headed households had received a visit, but only 2% of FHH had received a visit, despite Ghana having the highest proportion of female extension officers (World Bank and IFPRI 2010, cited in Croppenstedt et al., 2013). The same study showed that in Karnataka, India, 29% of male-headed households received an extension visit compared to 18% of FHH, while the livestock extension had a much higher and more equal proportion of visits (79% of FHH compared to 72% of male-headed households, World Bank and IFPRI 2010, cited in Croppenstedt et al., 2013).

The net result of the gendered nature of agricultural science is that women farmers often lack substantial technical information that might assist them in farming, and their needs, preferences, and concerns are systematically excluded from agricultural research priorities. By primarily focusing agricultural research on male farmers' production issues, researchers have neglected areas, such as food processing, which could significantly reduce women's work burdens, and improve the quality of life for women and children.

The neglect of women farmers in agricultural research and extension is linked to the ways in which households have been modeled by the sciences and economics. Systematic exclusion from agricultural research has had major implications for women's labor, and consequently household food security and child nutrition. To better understand these linkages, we turn to an examination of household-level studies in agriculture.

UNDERSTANDING GENDER DYNAMICS AT THE HOUSEHOLD SCALE IN AGRICULTURAL SYSTEMS

A fundamental starting point for approaching household gender relations in agricultural systems is to ask what is a *household*, and what *household model* best approximates reality. This task can be partially framed with the questions: to what extent do households act as a unit, and to what extent are their interactions competitive or cooperative? These questions are important when considering the implications of policies, environmental changes, and other dynamics affecting poor rural households in the Global South—from trade liberalization to climatic stresses, to the challenges of coping with the HIV/AIDS pandemic.

At times development policy makers, practitioners, and agricultural scientists have assumed that households everywhere follow the Western norm of nuclear families, with a married couple and children. However, households can be defined in many ways, often by what they share (e.g., a home, a “common pot,” economic resources, etc.), and many different types of households exist between different cultures. For instance, a basic household unit might include grandparents and grandchildren, or several generations of married families, or same-sex couples, or polygamous couples with separate households for each wife. An extension of this is that a married couple might not meet the definition of a household in some cultures, and assuming some level of coordinated household effort in agricultural practices can be very misleading, as husbands and wives may maintain separate fields, harvests, and act largely independently of one another.

Despite the variety of forms that households take, and the array of dynamics within them, many economic and agricultural studies still assume that households have a set of common preferences and act as a unit when making decisions and allocating resources. However, a number of empirical studies have challenged this assumption (see, e.g., David, 1998; Dwyer and Bruce, 1988), demonstrating that households are not always sites of sharing and equity and that, by contrast:

- Men and women can have different preferences for household resource use that can lead to overt or subtle conflicts;
- Resources are not always “pooled” within households, with incomes sometimes kept separately and spent for individual gain;
- Men and women sometimes farm different plots of land and manage crops separately;
- Different forms of conflict and cooperation play out over household resource and labor use;
- Domestic violence and other abuses of power have an important negative role in household relations in myriad ways.

Some theorists argue that a *bargaining model* in which women and men negotiate for different resources is the most appropriate theoretical tool for examining households (Agarwal, 1997). This model explicitly integrates issues of *power* within the household into the framework, and encourages the consideration of a number of factors. For instance: what different elements of cooperation and conflict are evident? How much “bargaining power” do different members possess (and what sort of outside options do they have if cooperation fails)? How do different members frame the benefits and disadvantages of cooperation? What are the general decision-making patterns, and how do these relate to the division of household labor? How does this intrahousehold bargaining connect to the gender relations beyond the household, such as those evident in the market, community, or state? Women’s access to land and other resources outside the household, in particular, has been found to have strong effects on their bargaining position within households. Women may also have relatively greater decision-making power within a marriage if they have been married longer, or if they earn more money through small businesses (Doss, 2001).

Household conflict should not be assumed either, as other theorists have emphasized that joint interests and cooperation can be the overarching dynamic, even when women and younger males are systematically disadvantaged (Whiteside and Kabeer, 2001). A central point here is that the different priorities, preferences, tasks, and control over resources that occur within households often have major implications for agricultural systems in terms of crop types, crop use, land management (e.g., soil and water conservation strategies, intercropping, the use of tree crops), and other farming decisions, and conversely that agricultural development interventions can have critical implications for household relations. The bargaining power and amount of cooperation within households will influence agricultural systems, and therefore needs to be understood if agricultural scientists want to appreciate how their technological recommendations will be utilized by farmers.

An example from the Gambia illustrates how the introduction of a new agricultural technology can change household decision-making patterns and power dynamics. The introduction of a centralized pump irrigation system was expected to benefit women farmers, along with the granting of legal land title to women for rice plots. Increased rice production subsequently shifted from being controlled by individual women to being under the authority of a male compound head. Women's labor in agricultural production went up, because pump-irrigated labor required 61% more labor than swamp rice. While overall calorie production went up, consumption of nutritious upland crops (e.g., groundnuts) went down. Women had less control over many aspects of rice production, and had increased labor requirements, which they often used hired labor for, thereby increasing costs (Von Braun et al., 1989; Von Braun and Webb, 1989). The issue of decision-making and introduction of new technologies will be explored here further through a case study from Malawi.

The influence that gender can have on crop types can been seen clearly in an example from Malawi, where research has found that gender differences relate to whether there is a preference for growing a flint versus a dent maize variety. Flint maize varieties are easier to pound into flour and can be recycled, while hybrid dent varieties need to be purchased annually but have higher yields if grown with fertilizer. Women were found to be more likely to grow local flint maize varieties, in large measure because they tended to have less access to credit to buy seed and fertilizer, but they could access flint seed through social networks, and because their responsibility for food processing made its ease of pounding and storability very desirable features (Smale and Heisey, 1995).

The management of harvested crops and the use of income generated from crop sales has also been found to differ considerably between men and women in many places, with evidence in many parts of the world indicating that women tend to invest more in household food, children's nutrition, and health, than men (Kennedy and Peters, 1993; Quisumbing and Maluccio, 2000; Duflo and Udry, 2004; Doss, 2006; Malapit et al., 2015; Sraboni et al., 2014). In a number of contexts, however, men have demonstrated a willingness to invest in children and households, highlighting the fact that these patterns and gender roles in decision-making are not static, but rather are dynamic and complex (Whitehead and Kabeer, 2001).

Agricultural labor is another arena in which gender relations need to be considered. In many parts of the world, agriculture continues to be a very labor-intensive activity (Fig. 10.2), with tillage, planting, weeding, and harvesting carried out mostly by hand, using simple tools such as hoes and machetes. The labor intensity of these agricultural systems makes the ability to mobilize labor within households and communities an important difference that affects production, management decisions, and agroecological methods. When women are also combining these tasks with income generation, child care, and other household responsibilities, the "triple-burden" of

FIGURE 10.2 Jennie Mumba, a woman farmer participating in an SFHC project in Zombwe, outside Ekwendeni, Malawi, incorporating crop residue.

workload becomes immense, and explains why women on average have far less leisure in agrarian communities.

PHOTO CREDIT: CARL HIEBERT (2004)

In many parts of the world, the gendered divisions of agricultural labor get segregated by task, crop, and even by crop variety. Although it is often stated that women are more responsible for subsistence crops and men for cash crops, the reality is often much more complex. For instance, it may be that women do not have access to the inputs or information to grow cash crops, they may be carrying out much of the labor but not controlling the income from the sales of cash crops, or a crop may be both a cash crop and a food crop (Doss, 2001). As new opportunities with a crop or technology arise, the gender and other divisions of labor may change for that crop, and the control and management of the crop may also change (Doss, 2001; Due, 1988) (see Box 10.5 and Table 10.4).

In married households, men may be able to mobilize women's labor to a much greater extent than vice versa, as well as having a greater ability to hire labor outside the household, as a result of differences in status, income, access to credit, and other gender inequalities (Whitehead and Kabeer, 2001). In some places where there are shared or cooperative labor practices,

BOX 10.5 Women and Irrigation: Who Benefits?

Irrigation is vital to certain crops and crop types, and may prove increasingly important with a changing climate with increasing variability of rains, especially in savannah regions. It is also a technology that is typically dominated by men. For instance, one study in highland Peru noted that although women contribute labor in agricultural systems with irrigation, they had little decision-making power over irrigation systems at the household or state level. The result was the exclusion of women from access to irrigation as farmers by a male-dominated irrigation bureaucracy, with women provided only marginal access based upon domestic needs (Lynch, 1997). Another study in southern India noted that irrigation rights were allocated based on land title, thereby excluding most women and reinforcing gender inequalities, since land tenure is granted primarily to men in this region (Ramamurthy, 1997; Ravazi, 2006). In areas where irrigation had been introduced, women's workloads in poorer agricultural households had significantly increased (see Table 10.4), and the increased input costs associated with irrigated agriculture (e.g., hybrid seeds, fertilizer) meant that poorer women also had to work as agricultural laborers to pay for these inputs. Wages for agricultural labor were lower for women, because the work was considered "lighter" (Ramamurthy, 1997). The overall effect of irrigation for poor households was negative, increasing costs and workloads, but not incomes.

TABLE 10.4 Comparison of Women's Labor Demands (Irrigated vs Rain-Fed) in Southeast Andhra Pradesh

Crop	Labor Demand (in Woman-Days/Acre)
Rain-fed sorghum	25
Rain-fed tobacco	55
Rain-fed cotton	44
Irrigated cotton	112
Rain-fed groundnut	23
Irrigated groundnut	45
Irrigated paddy rice	53
Irrigated onion	125

Source: Ramamurthy, P., 1997. Rural women and irrigation: patriarchy, class, and the modernizing state in South India. In: Sachs, C.E. (Ed.), Women Working in the Environment, pp. 103–126. Washington, DC: Taylor & Francis, p. 105.

men may still be better positioned to mobilize such arrangements than women. The seasonal nature of agricultural tasks adds another dimension to the importance of being able to mobilize labor, with labor bottlenecks a major issue that often emerge during critical periods in planting and harvesting. Women and men may have specific tasks in agriculture and in other arenas which conflict at these critical periods, and these specific tasks may vary by class, ethnicity, marital position, and other social distinctions.

The challenge of mobilizing labor is often greater for FHH, which tend to have lower incomes, less land, and fewer adult people within them to carry out agricultural labor, and they may not be able to mobilize labor as easily outside the household due to inequalities in social status and access to cash (Doss, 2001). Understanding how an FHH is formed is necessary to know whether the headship is relevant. For example, if an FHH is one in which the husband has migrated to another region for work (called an FHH *de facto*), and if remittances are sent back, labor can be hired. In this case, the household may be female-headed because there were few opportunities for agricultural production, causing men to migrate to another region, and the poverty of a household cannot be seen as having been *caused* by being female-headed (Doss, 2001). Focusing too much attention on the headship of a household can simplify problems, and mask other factors that affect poverty and low agricultural production.

The critical role that women play in child care, food production, and processing, and the different ways in which women and men use household resources also means that changing agricultural activities or women's control over agricultural resources can have significant effects on child nutrition and household food security (Berti et al., 2004). These linkages become very evident when considering the effect of HIV/AIDS infection rates in sub-Saharan Africa. In Malawi, e.g., women carry out much of the agricultural work, and also are the primary caregivers for family members who become ill. Increasing rates of adult morbidity from HIV/AIDS places a disproportionate burden on women as predominant caregivers for sick family members. The illness of an adult can mean the loss of two adults working in the fields, and can mean that key activities (e.g., weeding) do not get done, leading to lower agricultural yields.

CASE STUDY: GENDER, INEQUALITY, AND AGROECOLOGICAL APPROACHES IN NORTHERN MALAWI

This case study examines how agricultural scientists need to understand the broader historical context, as well as the social inequalities of a place, and how they can develop progressive partnerships to work toward agroecological solutions. We begin by considering how multiple types of inequalities both created agricultural problems and affected efforts to improve smallholder farmers' food security and soil fertility. This is followed by an overview of how the Soils, Food, and Healthy Communities (SFHC) organization in northern Malawi has integrated an equity focus into its science, extension, and education outreach, with evidence given about how this has improved not only agricultural systems and nutrition, but also equality at a household and community scale.

Some brief context is first necessary. On a per capita level, Malawi is one of the poorest nations in sub-Saharan Africa, and recent estimates place 70% of the population below the poverty line (World Bank, 2016). It is predominantly agrarian, and an estimated one-third of Malawian households experience chronic food insecurity and calorie deficiencies (Ecker and Qaim, 2011; FAO, 2014). Land degradation and low soil fertility are a persistent challenge. Malawian farmers devote over 70% of all arable land to maize production, and almost half of the Malawian diet consists of maize, which contributes to high rates of undernutrition (Ecker and Qaim, 2011; FAO 2014). In the last decade, the government of Malawi has prioritized investment in agriculture, through a national program which subsidized fertilizer and hybrid maize seeds to about 1.5 million households, first implemented in 2005 (Chirwa and Dorward, 2013). While maize production, and to a lesser extent income, has increased, food insecurity and child undernutrition remain high, while crop diversification has declined, leading to debates about appropriate policies (Bezner Kerr, 2012; Ecker and Qaim, 2011; Chirwa and Dorward, 2013; FAO, 2014; Kankwamba et al., 2012).

In addition to problems of food insecurity and child malnutrition, women in Malawi face difficulties of high workloads, unequal decision-making, and domestic violence. Malawi's experience with structural adjustment has compounded the problems facing most small farmers. Adjustment policies such as currency devaluation, the privatization of the National Seed Company of Malawi, and reduced funding for the Ministry of Agriculture resulted in dramatic increases in fertilizer prices, reduced agricultural credit, declining availability of legume seeds, and the reduction of extension services (Devereux, 2002; Peters, 1996).

In light of the challenges facing smallholder farmers in Malawi, a project was initiated in 2000 by community nurses at a hospital in the northern region, in collaboration with other researchers from both Malawi and Canada. The SFHC began as a project aimed at improving the health, food security, and soil fertility of smallholder farming families through participatory research using legume intercrops, and this was pursued by employing a holistic approach to understand the linkages between agriculture and health. The SFHC is now a farmer-led nonprofit trust organization, and has expanded its work in partnership with Chancellor College, the University of Malawi, and several North American universities to carry out the Malawi Farmer-to-Farmer Agroecology project. The SFHC is located near the town of Ekwendeni in the mid-altitude region (1200 m) of northern Malawi (Fig. 10.3). The average landholding of farmers in the region is roughly 1.1 ha. The long-term average annual rainfall is 1300 mm, but it is highly seasonal, with most (~85%) occurring from November to April. Smallholder farmers have limited access to irrigation, and grow primarily maize (*Zea mays*), which is planted on an estimated 60% of smallholder land, alongside a wide range of other crops grown at low density (Snapp et al., 2002). Prior to the onset of the SFHC, the legumes grown in the region, in order of decreasing frequency, were: groundnut (*Arachis hypogaea*), bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata* L. Walp), soybean (*Glycine max*), Bambara groundnuts (*Vigna subterranean* L.), and pigeon pea (*Cajanus cajan* L. Millsp).

The SFHC began after hospital staff and researchers interviewed farmers who were highly food insecure, with malnourished children, and found that many had few options for improving soil fertility and food availability. Further, unequal gender relations, including high levels of domestic violence and misuse of household resources, played a role in worsening these conditions (Bezner Kerr, 2005).

Earlier scientific research carried out in central and southern Malawi with smallholder farmers had identified several viable options for improving soil fertility and providing other household benefits: (1) groundnut and pigeon pea intercropped; (2) soybean and pigeon pea intercropped; (3) maize and pigeon pea intercropped; (4) *Mucuna* spp. rotated with maize; and (5) *Tephrosia vogelii* relay intercropped with maize (Snapp et al., 1998). These legume options were chosen by the SFHC for on-farm testing. Part of the rationale was that several of the legumes are well known edible crops,

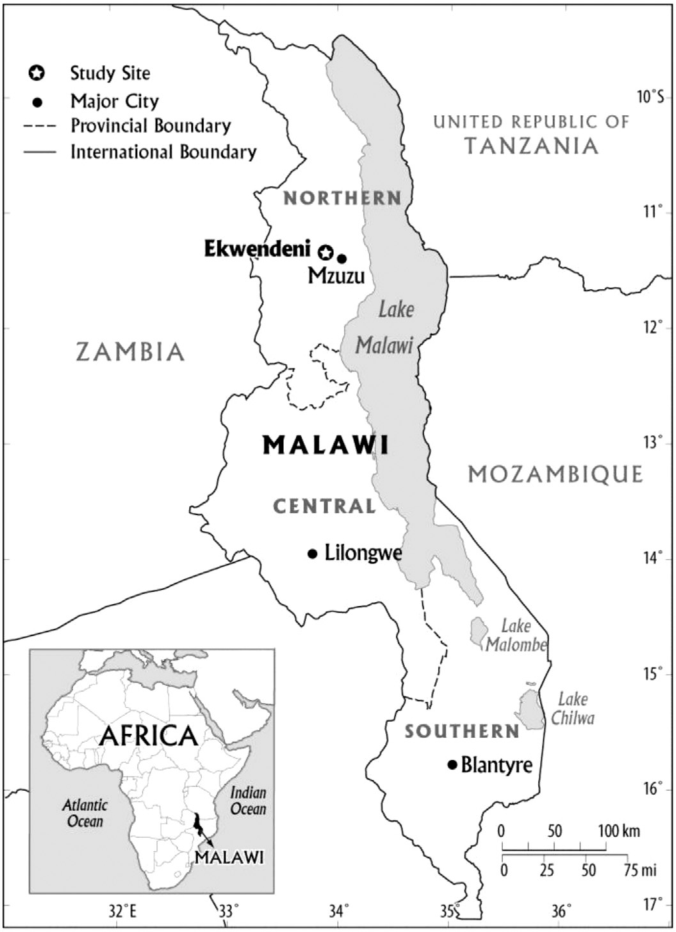

FIGURE 10.3 Site location of the SFHC organization, Ekwendeni, Malawi.

and it was expected that increasing cultivation would help to improve nutrition in diets. Another key motivation was to improve soil fertility, and one key way the project pursued this was by encouraging farmers to incorporate the legume residue into the soil as a means of improving nitrogen levels and organic material.

From the outset, the project took an explicitly participatory approach, centered on the Farmer Research Team (FRT), which is a volunteer, farmer-led organization formed at the start of the project to conduct research and share knowledge, both on behalf of and within the community. The FRT members are critical to the project's success, as they are involved in farmer training, seed distribution, data collection, and research. The FRT is comprised of a variety of different social groups (e.g., widows, divorced women, the highly food insecure, and well-off farmers), and approximately 50% of FRT members are women. In 2000, the project began with 30 farmer research members in seven pilot villages, but due to high farmer interest FRT membership had grown to include 120 members by 2007, while the project itself had grown to involve over 5000 participating farmers in more than 100 villages. As of the writing of this chapter, over 14,000 farmers had received training and seeds from the SFHC through a range of different projects, including 3200 farmers participating in the Malawi Farmer-to-Farmer Agroecology project.

After 7 years, the project had facilitated a significant expansion of legume options, and found evidence of increasing legume residue incorporation by the majority of participating farmers (Bezner Kerr et al., 2007). The outcome of this is that farmers are citing local indicators such as improved maize growth, soil color, and legume harvest, as evidence that their soil fertility has improved (see Fig. 10.4), as well as pointing to

FIGURE 10.4 Participating farmer, standing in a field of maize where legume residue was incorporated the year before, and no fertilizer was added, February 2008. *Photo credit: R. Bezner Kerr.*

enhanced food security within their households. Studies carried out with the SFHC and collaborating researchers show enhanced ecosystem services from this legume diversification, including greater soil cover, improved soil quality, and greater dietary diversity (Snapp et al., 2010).

Another important facet of the SFHC has been its explicit attention to problems relating to gender and other inequalities. One of the key mechanisms for this has been for project members to conduct periodic research and participatory workshops with farmers to assess these issues, to develop, in effect, an evolving baseline inventory on inequality, including how it is related to project interventions. Project staff have also contributed to this evolving inventory since the start of the project. Several key issues have been identified from this process, largely centered on decision-making, division of labor, and project and village leadership.

Initially women played a minimal role in decision-making about crop sales, although they made important contributions to the labor involved in legume production. Women noted that men sometimes sold legume crops and used the money for nonhousehold use, such as purchase of alcohol. At the same time, women noted an increase in labor requirements for crop residue incorporation, and a change in the gender division of labor with harvesting. In the past, crop residue was incorporated just before planting, usually by men, but the need for incorporating residue just after harvest meant that women often did this work, since women usually harvest the majority of legumes. Women also had difficulty feeding young children frequently in the rainy season, due to high agricultural labor requirements.

The legume options and project approach had appealing qualities for women farmers. High numbers of women joined the project following a severe national food shortage in 2002, primarily due to the project focus on child nutrition and food security. Women tended to select the doubled-up edible legumes, and men were more likely to select the nonedible *mucuna* legume crop. The average area of expanded legume production, however, was lower for women than for men (Bezner Kerr et al., 2007). Highly food insecure and/or HIV/AIDS affected households had difficulty utilizing the legumes due to conflicts with other labor requirements (e.g., care for sick family members, or labor on other peoples' farms to get seed or food).

Another complicating factor was that women had difficulty participating in the leadership of the FRT, despite making up a large proportion of SFHC participants, due to accusations of adultery if they visited other farms, or had to stay overnight in other villages. Village leaders also played an important role in the successful use of legumes to improve food security for poor households. For example, some landless migrants who gained access to communal land and improved the land with legume intercrops and residue incorporation had their land seized by village leaders. Other village headmen let their cattle roam into pigeon pea fields of participating farmers, to eat the pigeon pea and residue.

To help keep gender issues (e.g., household crop decision-making) at the forefront of project planning, a flexible, participatory process of problem identification is used, which in turn gets integrated into various project activities with farmers, such as seed distribution events, training programs for new participants, and annual "field days." (Field days involve farmers, hospital staff, government, media, and other farmer organizations visiting selected fields of SFHC participants and learning what crops and cropping methods they are using, followed by a range of social activities.) Additionally, the FRT is involved in giving presentations, dramas, and talks which emphasize the links between improved gender relations, agricultural improvements, and improved child nutrition. For example, farmers perform dramas highlighting common household and community conflicts, such as men selling legumes and using the money to purchase alcohol, or village leaders seizing land that has been improved with legumes by landless migrants.

Another important response to identify gender issues occurred when the FRT decided to make "family cooperation" a core project theme, emphasizing the need to work together within families and communities to improve food security. This decision led to the establishment of a Nutrition Research Team, which was tasked with carrying out informal education during mobile clinics, recipe days, home visits, and in public spaces more generally, on themes such as dietary diversity, family cooperation, and early child feeding practices. This work evolved into holding "recipe days," in which men and women make and share different recipes as a means of teaching new ways to cook legumes, and encouraging men to be involved in child care and feeding. These recipe days have been important sites of transformational change for men and women, in part because of the public aspect of these events, which have encouraged slow but critical changes in gender roles in the home (Patel et al., 2015; Bezner Kerr et al., 2016).

The FRT members and project staff also raised the issue of legume residue incorporation, which then became a topic of intensive discussion within households and communities (see discussion of this experience in chapter: Designing for the Long-Term: Sustainable Agriculture). After learning that women were largely responsible for legume harvest and subsequent residue incorporation, and that they were finding this task onerous during a busy time of the year, the FRT subsequently decided to organize legume residue promotion days in which the FRT visited villages and had very public demonstrations of legume residue incorporation in village plots, in an effort to encourage men to participate in residue incorporation and address women's workload concerns. Public discussions followed thereafter, with the FRT again emphasizing the importance of family cooperation and male involvement in residue incorporation and other farming activities. The residue incorporation days have continued, and are now held annually, and they have contributed to the dramatic increases in legume residue incorporation that has been documented, from 15% in 2000 to over 70% of farmers

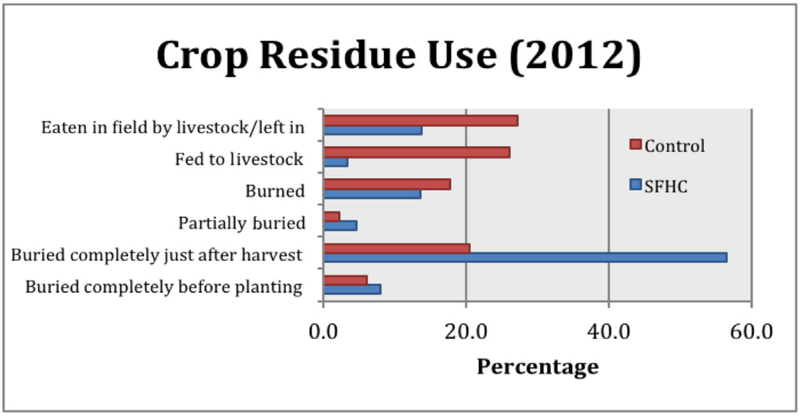

FIGURE 10.5 Frequencies of SFHC and control farmers' crop residue burial in 2012 ($n = 302$). *Source: SFHC survey data.*

in 2012 (Bezner Kerr et al., 2007; Madsen and Bezner Kerr unpublished data) (Fig. 10.5).

In recent years, the SFHC has undertaken training on soil improvement and conservation agriculture activities, with some farmers choosing to test mulching or compost as an alternative strategy for soil improvement. In all of these activities, the active involvement of men is encouraged. This is to help ensure that women are not facing additional excessive workloads. The implications of these new tasks, some of which are quite labor-intensive, however, are still being studied by the team.

Another institutional innovation—the Agriculture and Nutritional Discussion Groups (ANDG)—was initiated in 2005. The ANDGs seek to integrate agriculture, health, gender, and social relations in discussions, with the primary purpose of enhancing problem-solving and conflict resolution at a household level in a way that will support the adaptation of equitable legume systems that enhance food and nutrition security. The village area groups comprised about 80 members each, and had subgroups based on age and sex (i.e., older men, older women, younger men, and younger women). Each group met monthly and carried out participatory, problem-solving activities on different agricultural and nutritional themes, first in the subgroups, and then in the larger forum. For example, 1 month the groups might discuss ways that men and women can work to incorporate crop residue, and another month they might discuss how households can feed their children frequently during the "hungry season" (i.e., when food stores are at their lowest ebb), while ensuring that agricultural activities are carried out. The approach tried to build on previous work done on small group discussions and participatory educational methods, by recognizing the inherent power dimensions at work within community households, and by addressing these dynamics explicitly but with cultural sensitivity (Cornwall, 2003; Humphries et al., 2000). A qualitative study of this approach indicated that it was a safe and effective way for culturally sensitive issues to be shared and addressed (Satzinger et al., 2009).

The work done by the SFHC shows evidence of improved gender relations. One clear sign of this emerged from qualitative research done in 2005 and 2006, which indicated that women who participate in the SFHC project played an increased role in decision-making with regards to legume crops. In 20 focus groups with men and women of different ages in the project's "catchment," more than half the participants said that women are increasingly involved in decision-making with regards to legume crops. In 36 interviews in 2006 with SFHC participants, all but two talked about the ways that their relationship with their spouse had improved following participation in the ANDGs. Respondents, particularly younger fathers, remarked that spousal interactions had improved markedly, and spoke about the increased collaboration and cooperation with their partners that they felt resulted from these discussions. They also provided many examples of husbands making increasing efforts to help their wives with such things as cooking, carrying materials home from the field, looking after their baby, and making a fire for cooking in the evening. There is also considerable evidence that crop residue is being incorporated with the active participation of men in many cases (Bezner Kerr et al., 2007).

Project emphasis on "family cooperation" and the role of husbands in promoting good child nutrition through careful use of household resources seems to be having some effect on knowledge, and practice, although documenting changes in gender relations is difficult to confirm. Qualitative studies carried out in subsequent years continued to document some changes in the division of labor, decision-making within households, and leadership roles within communities (Bezner Kerr et al., 2016). While gender has been one prevailing concern, the SFHC project has also sought to identify other dimensions of social inequalities through various mechanisms such as:

- Project meetings with village leaders to address land seizures from landless migrants who had improved land with legumes;
- Community meetings to discuss livestock management and to reduce cattle roaming on pigeon pea fields;
- Legume seed distribution targeting more food insecure households and HIV/AIDS-affected households;
- Agricultural and social research to identify appropriate agricultural options for HIV/AIDS-affected households;
- Development of a community legume seed bank to try to improve legume seed access in the long-term;
- The formation of a farmer organization to link with other smallholder farmers and advocate for better access to productive resources at national and international levels.

Qualitative research carried out in 2005–06 also indicated that there were reduced problems with livestock eating pigeon peas in many villages, and that land seizure from new migrants was rare. Farmers also indicated that they felt there was increased cooperation at the village level to work together to solve problems, and that there was an increased pride and dignity, and a feeling that they have their own resources to solve problems.

In sum, the SFHC organization has used participatory methods, bridging social and agricultural sciences, to address a range of inequalities, including rising fertilizer costs, declining access to legume seeds, unequal women's workloads, and household conflict over use of legumes. Many of the inequalities identified are long-term problems that will require considerable social mobilization, but already clear strides have been made along a number of fronts. While agricultural development problems are always to some extent contextually specific, this case study nevertheless suggests a variety of ways in which agricultural research can partner with progressive rural groups and take flexible, participatory approaches as a means of addressing social inequalities in rural areas in the Global South.

Addressing Gender Inequality in Agricultural Research and Development

While there are many unanswered questions and there is a need for further research and focus on this issue, with many gaps in knowledge, some key findings and principles can be drawn from successful examples in agricultural research and development (Box 10.6). Rather than merely ensuring that a few token women participants are included in a research or community development project, there needs to be a much more explicit focus on specific processes and relations which shape gender inequality in a given place and time. Some studies have noted the importance of creating new spaces for rural women and men to learn agricultural skills, and to experiment, and share learning (Humphries et al., 2012; Davis et al. 2012; Bezner Kerr et al. 2016). Participatory research methods which invite flexible, adaptive learning rather than prescriptive technologies have also been shown to be effective at raising issues of gender inequality and to address concerns for socially disadvantaged groups (Classen et al., 2008, Humphries et al., 2012; Bezner Kerr et al., 2016). Mixed farmer research groups in Honduras, which focused collective action around food security using experimental plots, e.g., provided new opportunities for women to take on roles in agriculture, through experimentation. Women took on new leadership roles, and developed a greater capacity in participatory plant breeding, and there was evidence that these new roles had produced significant changes in household decision-making, community leadership, and involvement in other social organizations (Humphries et al., 2012). Long-term work by these farmer

BOX 10.6 Initial Steps to Address Gender Inequality in Agricultural Research

- Carry out baseline research using mixed methods (quantitative, qualitative, participatory) to understand women's roles in agriculture, livelihoods, and social relations more broadly, differentiating by other social axes of difference, such as age, ethnicity, class, and livelihood strategy.
- Establish or strengthen networks with local civil society organizations and social movements focused on gender and other dimensions of social inequality to understand the broader context, and build alliances for broader social change;
- When selecting farming households to conduct research or implement interventions, be attentive to the involvement of women and men, not just as "female-headed households," but in terms of both husbands and wives, of different social classes and groups;
- Have on-going reflection opportunities with men and women, in safe spaces that encourage dialogue to assess change, again ensuring that other axes of social difference are addressed in these dialogue-based participatory approaches;
- Use iterative and transdisciplinary research methods that allow for a flexible design, taking into account gender and other social issues as they arise, and adapting the design to address those unexpected concerns.

research groups eventually led to the release of several farmer-developed varieties of crops, and active social mobilization by the umbrella farmer organization on broader political – economic issues, such as international trade treaties and the role of the World Trade Organization in agriculture. Many social movements concerned about these broader issues of foreign land acquisition, international trade treaties, and the increased corporate concentration of agriculture in genetic resources have also made the explicit link between gender inequality and food sovereignty.

CONCLUSION: ADDRESSING GENDER INEQUALITIES IN AGRICULTURAL SYSTEMS

This chapter has attempted to define gender, and examine the household as a site of inequalities. The chapter has considered the ways in which gender inequalities and other inequalities (e.g., age, ethnicity) are embedded in agricultural systems, including access to productive resources, and access to and involvement in agricultural science. In order to address inequalities at this scale, agricultural scientists need to understand some of these basic concepts, and the ways in which these inequalities are formed and reproduced.

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INTERNET RESOURCES

Websites	Description and Comments
http://hdr.undp.org/	The annual Human Development Reports provide many useful statistics and insight into global inequalities for different measures of development.
http://www.jubileesouth.org/	These sites provide good background material on debt and ways to advocate for debt reduction.
http://www.jubileedebtcampaign.org.uk/	
http://www.dropthedebt.org/	
http://www.50years.org/	
http://www.etcgroup.org	The Action Group on Erosion, Technology, and Concentration (ETC Group) provides an excellent resource on the magnitude of corporate power and consolidation in agriculture in its *Oligopoly, Inc.* series of reports.
http://www.unctad.org/en/docs/gdsafrica20031_en.pdf	The United Nations Conference on Trade and Development (UNCTAD) has long been a world leader in providing information and analysis about the problems associated with commodity-dominated export economies. UNCTADs report *Economic Development in Africa: Trade Performance and Commodity Dependence* (2003b) is another very valuable resource on these issues.
http://www.fao.org/gender/multimed/videos.htm	Online videos about gender and agriculture by the FAO, the first video is especially recommended.
http://www.unicef.org/photoessays/37446.html	Online UNICEF photo essay about the “double dividend” of gender equity.
http://www.unicef.org/sowc07/lifecycle/index.html	Description of different gender issues at different stages in a girl’s life-cycle.

Websites	Description and Comments
http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTGENDER/0,,contentMDK:20206498~pagePK:210058~piPK:210062~theSitePK:336868,00.html	Case studies of gender and agriculture issues by the World Bank.
http://www.fao.org/docrep/009/a0493e/a0493e00.htm#Contents	Report by the FAO about agriculture, gender, and trade issues.
http://www.unrisd.org/80256B3C005BCCF9/httpNetITFramePDF?ReadForm&parentunid=64FF792CAE6DF527C1257108003F59AA&parentdoctype=brief&netitpath=80256B3C005BCCF9/(httpAuxPages)/64FF792CAE6DF527C1257108003F59AA/$file/RPB4e.pdf	Report by UNRISD about land tenure and gender issues.
http://www.fao.org/gender/en/stats-e.htm	This site provides some good, if somewhat dated, statistics on gender inequalities in agriculture.
http://www.unep.org/geo2000/ov-e/0002.htm	This report by the United Nations Environment Program gives a good overview of the major global environmental issues of this century.
http://viacampesina.org/	The website of Via Campesina, a major rural social movement made up of small farmers from around the world.
http://www.mstbrazil.org	The world's largest rural social movement.
http://www.landcoalition.org/	A series of excellent sites on land reform.
http://www.icarrd.org	
http://www.landaction.org/	
http://www.fmra.org	
www.focusweb.org	These sites provide information and analysis about the global trading system and multilateral institutions regulating it.
www.wtowatch.orgwww.ifg.org	
www.twnside.org.sg	
www.foodfirst.org	
www.iatp.org	

Chapter 11

The Innovation Systems Approach to Agricultural Research and Development

Barry Pound and Czech Conroy

INTRODUCTION

The results of any in-depth rural analysis, such as livelihoods analysis (see Chapter 3: Farming-related Livelihoods), reveal the breadth and interconnectivity of the social, economic, technical, infrastructural, and policy issues facing rural people. Conventional agricultural research and extension systems are not designed to deal with this complexity.

Agriculture is just one livelihood component of rural people's lives. Even if many are dependent on agriculture, rural communities often put education, employment, health, communications, and security as higher priorities than farming. Thus, agricultural research and development (ARD) needs to be cognizant of, and responsive to, the context in which rural families are working. This may require the skills of social and communications scientists to complement those of technical research and development staff, and the cultivation of linkages with other sectors outside agriculture.

Agricultural research has traditionally been structured around commodities, and focused on technical production issues, with a linear delivery process in which technologies are developed by researchers, and then passed on to farmers through extension agencies. However, it is now recognized that farmers and others need to be actively involved in the research process, and that the postharvest aspects of the value chain such as storage, transport, processing, and marketing are vital to the rural economy, and should be part of the same research and development (R&D) process.

Innovation is a buzz word in development circles, but what does it mean, what drives it, how is it stimulated, where has it been successfully harnessed, and how can it be supported?

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DEFINING INNOVATION

The term “innovation” has two different meanings. It can refer to a *process* or a *thing*.

Meaning 1 (as a process): a simple definition of innovation as a process is the application of technical, organizational, or other forms of knowledge to achieve positive changes in a particular situation.

Meaning 2 (as a thing): according to Wongtschowski et al. (2012), an innovation is anything new that has been successfully introduced into an economic or social process.

In both meanings, innovation is not just about trying something new, but it is also about successfully putting innovation into practice in a specific environment (Spielman et al., 2009).

The existence of two different meanings has caused a lot of confusion, and is one of the reasons why the thinking and recommendations of the agricultural innovation system (AIS) school have generally not been fully applied in development initiatives.

DEFINING AN INNOVATION SYSTEM

An innovation *system* is a network of organizations, enterprises, and individuals focused on bringing new products, new processes, and new forms of organization into economic use, together with the institutions and policies that affect their behavior and performance (The World Bank, 2007).

It is important to distinguish between “innovation” and the concept of “invention,” as they are quite different. Invention culminates in the supply (creation) of knowledge, but innovation encompasses the factors affecting the demand for and use of knowledge in novel and useful ways. The notion of novelty is fundamental to invention, but the notion of the process of creating local change, new to the user, is fundamental to innovation—specifically, the process by which organizations or individuals master the design and production of goods and services that are new to them, irrespective of whether they are new to their competitors, their country, or the world (Mytelka, 2000).

According to The World Bank (2006):

- Innovations are new creations of social and economic significance. They may be brand new, but they are more often new combinations of existing elements;
- Innovation can comprise radical improvements, but usually consists of many small improvements and a continuous process of upgrading;
- These improvements may be of a technical, managerial, institutional, or policy nature, or a combination of these (but have tended to be mainly technical in development initiatives to date).

Innovations can also be classified according to the degree of change they represent from existing practices—e.g., *evolutionary/minor* versus *revolutionary/major*. Differences between *evolutionary/minor* and *revolutionary/major* are really gradual over a spectrum. They can be defined as follows:

- *Minor innovations* are ones that require the same or similar amounts of each factor of production to what is already practiced, e.g., new crop varieties or crop types whose input needs are broadly similar to those of conventional varieties;
- *Medium innovations* require substantial increases in one or more inputs (e.g., a switch from traditional to cross-bred dairy cattle may require a lot more fodder, including green fodder year round, and more veterinary inputs);
- *Major innovations* involve not just the replacement of existing technologies with new ones, but *social* (e.g., the formation of an irrigation management group or society) and/or *institutional* innovations (e.g., contract farming, new market linkages) as well. They may even involve a complete change in the production system (e.g., from a scavenging poultry system to confined poultry systems, or a switch from rain-fed to irrigated agriculture).

Minor innovations, such as the adoption by farmers of a new rice variety (Maurya et al., 1988) may be implemented spontaneously by farmers on a significant scale without external support or encouragement, whereas major innovations may require extensive external support to producers of a technical, financial, social, and/or institutional nature.

Some major innovations may only be feasible for *resource-rich* producers or processors, who have access to the human, social, or financial assets required for the innovation to take place. The innovation may bypass the *resource-poor*, and could even leave them worse off (less competitive *vis-à-vis* resource-rich producers), unless pro-poor development agencies intervene to improve their access to the required assets.

Traditionally, the focus in agricultural development has been on technological innovations (such as new varieties or breeds, types of equipment, or methods of pest control). These can improve agricultural enterprises in various ways, such as by increasing growth, yield, and income, reducing cost, enhancing quality, or reducing risk. However, it is now increasingly recognized that social and institutional innovations can be as important as technical ones. These include: (1) new types of collaboration between producers; and (2) development of new networks between producers, traders, and service providers. Social innovation among producers may be formal or informal, and includes the development of cooperatives, farmer groups, and self-help groups (see Box 11.1).

BOX 11.1 Farmer Groups: A Common Type of Social Innovation

The benefits of social innovations can be as great as, if not greater than, those of technological innovations. For example, the formation of groups of farmers can benefit them by:

1. Improving their access to government research and extension services;
2. Strengthening farmers' bargaining power with traders;
3. Reducing transaction costs for input suppliers and output buyers;
4. Harnessing economies of scale (e.g., collective marketing or storage);
5. Facilitating savings and access to credit.

WHAT DRIVES INNOVATION IN AGRICULTURE?

Does innovation occur randomly over time and space, or are there certain factors or conditions that stimulate innovation? A number of theories have been developed that aim to explain how innovation is driven.

Population Pressure Model

Work by Boserup (1965) and by Binswanger and McIntire (1987) identified increasing population density as the main driver in the evolution of agricultural systems. Population growth provides the impetus for *endogenous* technological change, resulting in increased output per hectare. This model only addresses part of the processes driving agricultural innovation, and is not relevant to situations in which labor is the limiting factor to agricultural production—situations that are relevant in some circumstances due to disease, war, and migration to urban centers.

Science Push: The Transfer of Technology Model

The dominant view during much of the 20th century was that scientific research was the main driver of innovation, creating new knowledge and technology that could be transferred to different situations. The policy implications of the science push model were simple: if you want more economic development, you fund more science. In this model, technological change originates *outside* the agricultural systems that are expected to benefit from it. Although much of the Green Revolution was driven by the science-led advances from international centers like CIMMYT and IRRI, the adoption by farmers of innovations developed through this model has generally been disappointing, particularly in the case of resource-poor farmers, and those in complex, risk-prone situations.

Market Pull Model

With increased market integration and globalization, it has become clear that markets and output prices can exert a major influence on agricultural innovation. Good product prices provide an incentive to farmers to improve their production practices, or their marketing arrangements, and the cash to do so. A "market pull" situation is illustrated in Chapter 9, Research on Livestock, Livelihoods, and Innovation, which shows how ownership of cross-bred cows increased in parts of India during the last few decades, due to the growth in demand for milk, attractive producer prices, and the development of a milk marketing infrastructure.

There has been a trend in recent decades towards economic *globalization*, which has provided opportunities for farmers to export their products to international markets: "changing patterns of competition .... in global markets, changing trade rules and the need for continuous upgrading to comply with them..." have become major drivers of innovation (The World Bank, 2006). For example, global demand for dairy and meat products has been stimulated by "new hygiene and public health management requirements, as well as greatly increased product differentiation" (The World Bank, 2006). It is important to recognize, however, that globalization has been far more marked in Asia than in most of sub-Saharan Africa (Box 11.2).

BOX 11.2 Innovate or Perish

Globalization can be a double-edged sword, as it may expose producers to increased competition from countries who market their goods aggressively, or who may have a comparative advantage (e.g., due to economies of scale, more efficient marketing systems, or more suitable agroecological conditions) unless they can innovate rapidly.

Producers of groundnut oil in India in the 1990s faced increasing competition from imports of cheaper palm oil from Malaysia and Indonesia that led to a major fall in the demand for, and price of, groundnuts. In Andhra Pradesh, groundnut producers who failed to identify viable alternative crops suffered increasing hardship, and as a result many of them ended up committing suicide.

Induced Innovation Model

The induced innovation model closely links the emergence of innovations to prevailing economic conditions (as opposed to innovations occurring randomly). Earlier versions focused on production-related innovations. As a factor of production (e.g., labor) became expensive, solutions would be found. Thus, labor shortages in 19th century north America resulted in the steel plow being invented by John Deere, a farmer. This was one of several mechanical labor-saving innovations that "were of crucial importance to the westward expansion of US agriculture" (Sunding and Zilberman, 2001).

The Hayami and Ruttan version of the model (1985) identifies both scarcity of factors of production *and* market opportunities as stimuli of innovation. In addition, the emergence of innovations requires technical feasibility and the new scientific knowledge that will provide the base for the new technology. The development of these innovations is induced by changes in relative factor and product prices; the scarcity of a factor of production (e.g., labor) may attract the attention of scientists, administrators, or inventors. In this respect, technological change is *endogenous* to the economic system—in contrast to the "science push" model. Where potential demand and an appropriate knowledge base are integrated with the right institutional set up, they provide the background for dynamic innovation activities. The development and fast spread of conservation agriculture (CA) in Brazil is a good example of these factors coming together in one place at the appropriate time.

Innovation can also be induced by a sudden change in context (e.g., war, drought, unpredicted change in market demand, advent of a road, etc.) that causes farmers and others to adjust quickly. Some will be better able to do so than others, and the resilience and linkages of a group or network that can help its members through such turbulent times can be very important in effective adjustment.

THE CASE FOR CHANGE

From the above we see increasing recognition that innovation process models that are: (1) single source, and (2) linear, are overly simplistic; and that this kind of process seldom produces technologies that become widely adopted by farmers in least developed countries. There have been many reasons for the failure of the Transfer of Technology (ToT) approach: new technologies often involved factor inputs (cash, labor, or land) that poor farmers simply did not have access to in the required amounts; and "receiving environments differ from those in which technologies have been developed, being more complex, more diverse, less controllable and more risk-prone" (Chambers, 1997). A further problem has been the lack of communication and interaction between researchers and intended users.

The general failure of the ToT model to benefit poor farmers provided a major stimulus to the development of other models of innovation processes that are more complex and nonlinear.

In addition, there are fast-moving factors requiring adaptation by farmers, traders, private enterprises, and governments requiring a more agile research and development process, such as:

- The globalization of agricultural production and trade;
- New opportunities provided by information and communication technology;

- Impacts of biotechnology on agricultural production and processing;
- Commercialization agendas in national development strategies that attempt to increase the contribution of agriculture to national Gross Domestic Product;
- Environmental (e.g., climate change, degradation of ecosystems, genetic erosion, water supply crises) and social (e.g., conflict, population growth, inequality, migration) issues.

These global, national, and local level changes require a research and development approach that is able to support rapid adaptation, while the complex, risk-prone, and diverse nature of rural environments requires a flexible, decentralized type of research that builds on the involvement of farmers and other actors in developing and disseminating technologies and processes (Box 11.3).

BOX 11.3 Innovation and Transformation

The transformational nature of technological innovation involves a shift in traditional relationships in society (Juma and Yee-Cheong, 2005).

Diversity requires locally-specific technologies and practices (Waters-Bayer et al., 2006).

THE INNOVATION SYSTEMS MODEL

In the innovation systems (IS) model, which is the main focus of this chapter, innovation is seen as being "neither research nor science and technology, but rather the application of knowledge (of all types) to achieve desired social and/or economic outcomes" (Hall et al., 2005). Innovation in agriculture often requires a combination of changes in technology *and* infrastructure (hardware), knowledge, skills and information (software), and organization of agricultural systems (orgware) (The World Bank, 2012).

The IS concept embraces not only the science suppliers, but the totality of actors needed for innovation to take place, and the *interaction* of actors involved in innovation. In particular, it highlights the contribution of the private sector to innovation. It extends "beyond the creation of knowledge to encompass the factors affecting demand for, and use of, knowledge in novel and useful ways" (The World Bank, 2006). The IS concept is derived from direct observations of industrial countries and sectors with strong records of innovation, and has been used predominantly to explain patterns of past economic performance in developed countries (Freeman, 1987). Nevertheless, it is closely related in some ways to the "multiple sources of innovation" model (Biggs, 1991), which preceded it in the literature on agricultural innovation in less developed countries.

In 2006, the World Bank observed that: "The innovation systems concept is derived from direct observations of countries and sectors with strong records of innovation. The concept has been used predominantly to explain patterns of past economic performance in developed countries and has received far less attention as an operational tool. It has been applied to agriculture in developing countries only recently, but it appears to offer exciting opportunities for understanding how a country's agricultural sector can make better use of new knowledge and for designing alternative interventions that go beyond research system investments."

In the 10 years since that statement there have been a number of projects that have attempted to apply the principles of the IS concept in agriculture in developing countries as a way of addressing challenges or opportunities, or (in a more restricted interpretation of the concept) as a vehicle for promoting new technologies. It has thus progressed from being a mainly analytical model to being a development approach. Some of these initiatives are summarized later in the chapter.

According to Anandajayasekeram (2011), systems thinking evolved over time in two different directions: (1) as a framework for organizational analysis, and (2) as a framework for technology development and dissemination, both leading to the IS concept that not only involves research, but also a wide range of other activities, actors, and relationships associated with the creation and transmission of knowledge, and its productive use.

The IS model sees innovation as an interactive process involving organizations and individuals who possess different types of knowledge. It recognizes the importance of the "particular social, political, policy, economic and institutional context" within which the process takes place (The World Bank, 2006). In some instances, initiatives have the development of innovation capacity as a key objective, whereas in the linear "transfer of technology" model the primary objective was often to maximize the number of adopters of new technologies. This is in recognition of the fact that as circumstances change, farmers and others need to be able to respond effectively to those changes with appropriate technical, social, or organizational innovations. A good example is climate change, where conditions are changing with increasing rapidity (see chapter: Climate Change and Agricultural Systems).

The World Bank (2006) analyzed a range of agricultural innovation case studies to arrive at the set of defining features for AISs presented in Table 11.1.

The IS model is more holistic than previous models, in that it gives more emphasis to private sector service providers, and also emphasizes the important influence of the enabling environment (policies, social and economic structures, infrastructure, and institutions) on innovation (called the "framework conditions" in Fig. 11.1).

TABLE 11.1 Defining Features of Agricultural Innovation Systems

Defining Feature	Agricultural Innovation System
Purpose	Strengthening the capacity to innovate throughout the agricultural production and marketing system
Actors	Potentially all actors in the public and private sectors involved in the creation, diffusion, adaptation, and use of all types of knowledge relevant to agricultural production and marketing[a]
Outcome	Combinations of technical and institutional innovations throughout the production, marketing, policy, research, and enterprise domains
Organizing principle	New uses of knowledge for social and economic change
Mechanism for innovation	Interactive learning
Degree of market integration	High
Role of policy	Integrated component of the approach, enabling framework
Nature of capacity strengthening	Strengthening interactions between actors; institutional development and change to support interaction, learning, and innovation; creating an enabling environment.

[a] *In practical terms, actors are limited to those required to meet the agreed goals of the platform. The partnership should be dynamic, with partners coming and going according to need.*
Source: The World Bank, 2006. Enhancing Agricultural Innovation: How to Go Beyond the Strengthening of Research Systems. Washington, DC: The World Bank.

However, it does not give the same level of emphasis as previous development models to the involvement of resource-poor families in the development process. Explicit action needs to be taken by initiatives that use an IS approach to include the poor and other vulnerable or disadvantaged groups. This is because they may not have the resources to be able to take advantage of innovations, or the confidence or visibility to be included in innovative processes, and often cannot, without support, take the risks that joining the innovation process implies. As described below, IS are often driven by their stakeholders, rather than a project that can devote resources to involving the poor. Many of the stakeholders would prefer not to be burdened by the poor, who might contribute least to the achievement of common objectives.

The IS concept, as applied to agriculture in developing countries, has received less attention as an operational tool, but in recent years it has been enthusiastically embraced by some international donors searching for a more effective approach to development. The Integrated Agricultural Research for

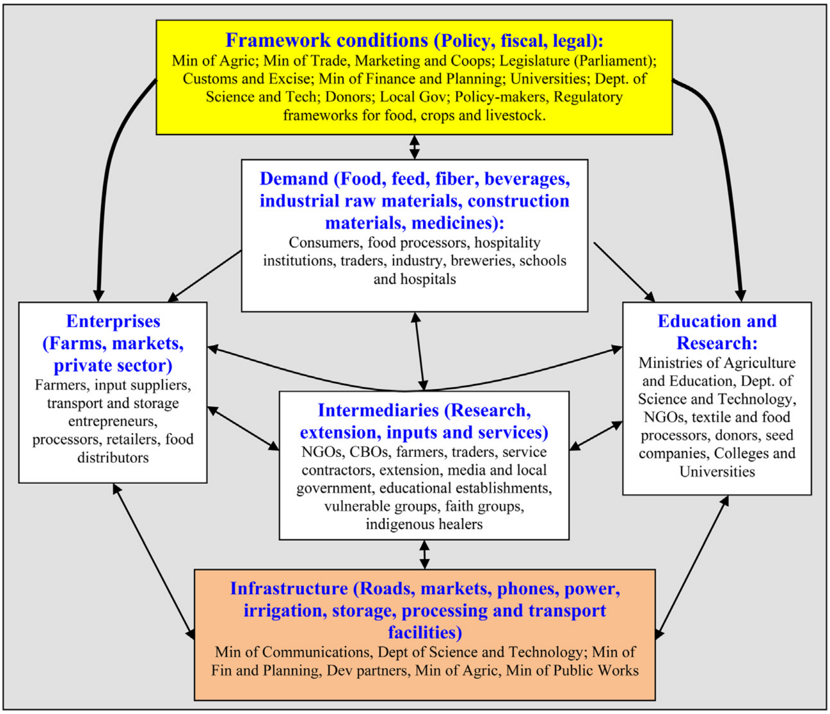


FIGURE 11.1 Stakeholder analysis of key stakeholders in the Lesotho national agricultural innovation system. The figure shows the linkages between all actors that would be needed for a fully functional AIS, but in reality many of these are weak or nonexistent. *From Pound, B., 2008. Second Institutional Analysis Visit to Lesotho. Chatham: Natural Resources Institute (Pound, 2008).*

Development (IAR4D) process, which has its roots in IS and in integrated natural resource management (NRM), and is implemented through innovation platforms (IPs), was tested in the sub-Saharan Africa Challenge Programme (SSA-CP) (The SSA-CP was coordinated by the Forum for Agricultural Research in Africa (FARA). The program focused on generating impact in smallholder agriculture in a particular region, sub-Saharan Africa, through a process termed integrated agricultural research for development (IAR4D)) in western, eastern, and southern Africa using a randomized control trial design to compare the impact of IAR4D and conventional top-down methods of technology delivery. The IAR4D methodology under test envisaged that proper implementation of the concept has the following characteristics: (1) a functional linkage point between farmers, private sector, and service organizations; (2) integration of productivity, NRM, markets, and policy; (3) an efficient modality for organizing farmers; (4) an effective mechanism for knowledge transfer to farmers; (5) action research oriented toward problem solving and impact; and (6) bottom-up organizational development (CGIAR ISPC, 2011). According to Adekunle (2013), IAR4D

TABLE 11.2 Improvements of IAR4D Over the Conventional Delivery Model According to Adekunle (2013)

Actor	Wins
Farmer	More food; more income (80%)
Private sector	More profits/more jobs
Research and extension	Greater impact; justifying more investment
Consumers	Better quality and safer product

applied in this way at the SSA-CP benchmark sites has proved superior to the conventional linear delivery model in addressing technological, institutional, and infrastructural challenges, and providing benefits to the main stakeholders, as shown in Table 11.2.

The World Bank (2006) analyzed a number of case studies and concluded that innovation can follow two main trajectories, shaped by the context in which they emerge, and the way that the context evolves. The *orchestrated trajectory* is typically where a government organization initially coordinates and stimulates a development initiative. The *opportunity-driven trajectory* is where a group of stakeholders (such as farmers and processors) recognize an opportunity and work together to benefit from the opportunity. Both trajectories can pass through a number of phases to arrive at a *dynamic system of innovation*, in which there is a high degree of public and private interaction and collaboration.

Fig. 11.1 depicts a hypothetical AIS for Lesotho, developed during a workshop with government, nongovernmental organization (NGO), and University of Lesotho participants. The classic AIS framework developed by Arnold and Bell (2001) is used, with the relevant Lesotho institutions assigned to each box (domain). In reality (and in line with the situation in many countries), although the organizations mentioned all exist, the linkages between them are often weak or nonexistent. This is an example of an AIS at national level, but the same framework can be used to identify stakeholders for a commodity value chain or enterprise development at a more local (e.g., district) level. However, the focus at the national level is usually a strategic one (to discuss and facilitate strategies to promote innovation), while at the local level the focus is on linking and mobilizing actors to address specific challenges or opportunities (Anandajayasekeram, 2011).

While it is possible to depict the national innovation system elements and their hypothetical interactions in a diagram such as Fig. 11.1, it is much more difficult to operationalize the system and the linkages shown. Most countries have agricultural policies and a strategy (e.g., a 5-year plan) for agriculture, and these are becoming increasingly influenced by the IS perspective—often with the encouragement of donors. At a national level, there may be taskforces drawn from different organizations (government ministries, donors, universities, farmer's unions, and others) with the remit to implement agricultural strategy, but these are usually much narrower than the very wide set of stakeholders in Fig. 11.1. In particular, private enterprise and consumers are rarely part of such taskforces, and there is rarely an in-depth analysis of the framework, and infrastructural conditions, and the limitations which these pose on the successful operation of the AIS.

The DFID Research into use project assessed the status of the different components of the AIS in Zambia (Research into Use (RIU), 2008) at the time. As shown in Fig. 11.2, they gave a rating (positive, mixed, or negative) for each "domain," and defined what the principal strengths and weaknesses were, and what a relatively short-term project could realistically influence or

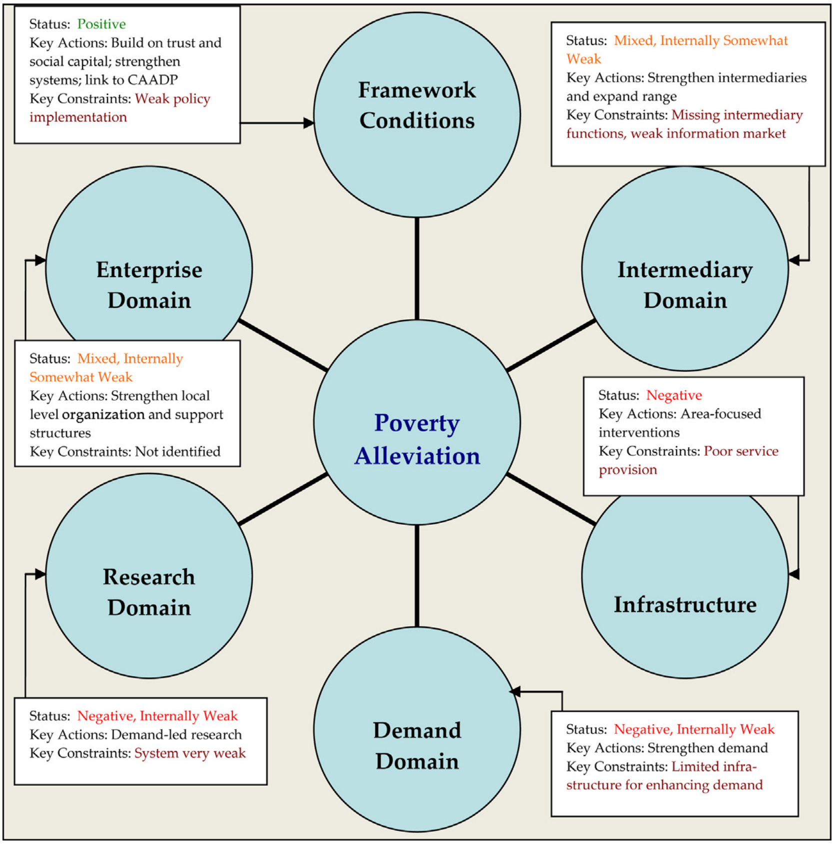


FIGURE 11.2 Assessment of the innovation system domains in Zambia. *From Research into Use Country Assessment and Strategy Development Team, 2008. Draft Zambia Country Assessment Report. Research into Use.*

change within the lifetime and resources of the project. For example, although it was acknowledged that infrastructure is part of the innovation system, major infrastructural deficiencies could not be addressed or influenced by the project, so ways had to be found to work within those deficiencies, such as supporting local markets.

Such whole country assessments are rare, and the framework and infrastructural limitations to making the innovation system work in practice are rarely comprehensively addressed, as even in a 5-year plan, the typical 3-year donor project, or the timespan between elections, it is difficult to make significant progress.

As a donor project, the RIU initiative had limited geographic scope, and a limited time horizon. The situation might be different for a government with more resources and a longer timeframe that could make significant improvements to the enabling environment, thereby raising the efficiency of the AIS.

As Hall et al. (2005) note, "the capacity to innovate can no longer be thought of in terms of the creation of human and physical scientific and technological resources alone. Instead, it must be thought of in terms of the *policies and practices* that promote learning and innovation in networks of organizations. While agricultural research organizations will remain important players, they are not sufficient on their own. Furthermore, *policies and practices* must be put in place to promote the flexibility and adaptability of innovation systems." They also note that the policy focus should be broader than agriculture alone, to include trade, rural development, industry, research, the agriculture and food policy environment, and education, with integration and coordination between these policy domains.

The task of operationalizing the innovation system at the local (e.g., district) level is more manageable, with its reduced geographical and institutional landscape. The practical mechanism of choice for operationalizing the innovation system, at this level in particular, has been the *innovation platform*, described below.

THE INNOVATION PLATFORM: A MECHANISM FOR OPERATIONALIZING THE INNOVATION SYSTEM AT LOCAL (AND NATIONAL) LEVELS

The IP is a tool for linking innovation system domains, and coordinating relations among actors to identify priority areas for intervention within any of the various domains, enhance access to technology, information, and markets, and to facilitate learning and innovation. Thus, an IP has been defined as "...a dynamic, multi-stakeholder partnership working to develop and use technologies and processes to improve livelihoods" (Tittonell et al., 2012).

A second definition, by an ILRI workshop, holds that: "Innovation platforms are equitable, dynamic spaces designed to bring heterogeneous actors together to exchange knowledge and take action to solve a common problem" (Cadilhon, 2013).

They are, therefore, a forum for discussion and negotiation, and a facility for collective or coordinated action. They bring diverse stakeholders together into an active partnership, to achieve a common goal through a range of activities to which the partners contribute, and from which they benefit. The main functions are:

- *Coordination*: Lead, coordinate and facilitate the relationship between member organizations to define and address the common goal of the platform;
- *Information and capacity building*: Identification of capacity strengthening and information needs of the partners. Assist the flows of information, knowledge (including training), and materials;
- *Diagnosis and assessment*: Understanding of different stakeholders' (e.g., retailers, farmers) needs/circumstances in relation to the common goal, which could include stakeholder mapping and understanding the framework conditions;
- *Experimentation*: Testing, demonstrating, and adaptation of technical and organizational options to specific site and farmer conditions;
- *Advocacy*: Championship of the common goal, engagement with actors on policy and resource mobilization;
- *Monitoring, evaluation, and learning*: Follow-up of activities implemented, results achieved, challenges in the functioning of the platform, learning lessons, and sharing experiences.

Any platform is likely to have a particular focus, with national platforms likely to have a more strategic focus interested in policy and strategy, while more local platforms are more likely to focus on commodities and market opportunities. This is often likely to be within the context of commodity value chains. Different actors in the platform will have different interests, and different skills and resources relating to the area of focus. In order to carry out the various functions described above, the partners need to have defined roles and responsibilities. Therefore, the platform needs a formal or informal structure with the capability to convene partners, agree roles, mobilize resources, and make decisions.

Not all platforms address all of the functions listed above, and they do not necessarily link all of the domains. However, to be effective, they should identify and work with those domains, functions, and stakeholders that are relevant to their own focus. A dynamic platform will change incrementally or dramatically over time due to changing opportunities or other circumstances, and the stakeholders and their roles will also change accordingly. Such changes should come from within, be owned by stakeholders from within the platform, and not be orchestrated by external interests such as research organizations.

CHARACTERISTICS OF INNOVATION PLATFORMS

Operationally, the characteristics of IPs include:

1. *Multistakeholder partnerships* to address a need or opportunity. The partnerships embrace the totality of actors involved in the value chain or enterprise, from planning and preparation through to production, postharvest, and marketing. The mix of stakeholders depends on the challenge or opportunity to be addressed. A dynamic partnership will change its composition over time, as the situation progresses. Once the innovation system is mapped, then the relevant players for the commodity and the stage of development of the value chain can be brought together to form *innovation platforms* to support the technological, infrastructural, and organizational development of the commodity or enterprise. Fig. 11.3 depicts a generic value chain from planning and production through to retailing and consumption of the different products. At each stage there will be actors that need to interact to make the value chain operate effectively and equitably, and at each stage research and development organizations from the state, NGO, and private sectors can support the value chain actors with materials, services, knowledge, and information. The IP brings all of these stakeholders together to interact and provide their contributions to the overall development and success of the value chain—to the benefit of all stakeholders.

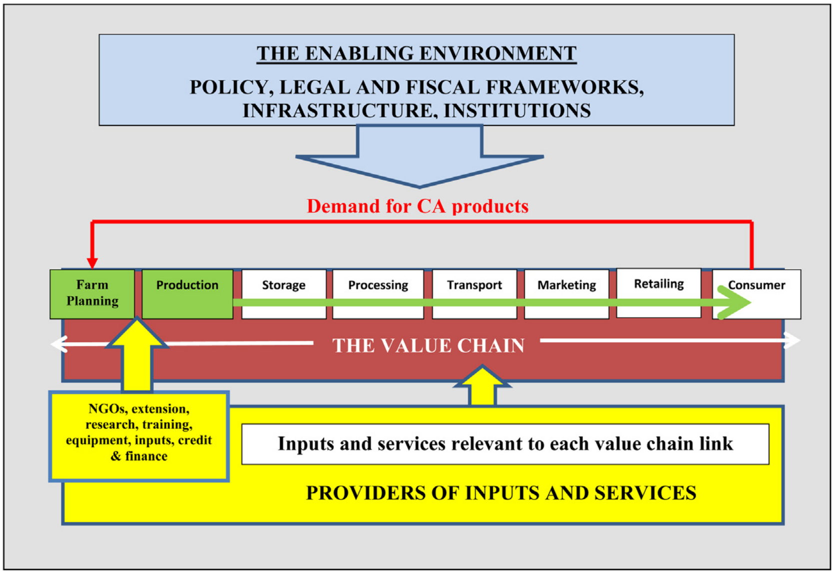


FIGURE 11.3 Generic commodity value chain.

2. Forming, maintaining, and managing partnerships require *facilitation/ coordination skills*, and the resources to bring stakeholders together to discuss, negotiate, share information, and make decisions. Trust is an essential ingredient of success, as any partnership has the potential for asymmetry (i.e., an imbalance of power, voice, or benefits) and conflict.
3. Local institutions may need empowerment through *building their organizational or technical capacity*, and the development of *links* to input supplies, markets, and technical assistance.
4. A major difference with conventional research is that the IS approach recognizes that *innovation can arise anywhere*. It is not the preserve of formal research organizations. Farmers, Community-Based Organizations (CBOs), NGOs, and private enterprises can be the source of the innovation, and in many cases can develop the innovation independently of formal government structures (see Box 11.4a). In other

BOX 11.4a Nigeria: Spontaneous Development of Gari Processing

Processing cassava into gari for food and income is practiced by many Nigerians in rural areas. To harness the opportunities offered by the increasing market demand for gari, farmers devised several technical, social, and institutional innovations.

Gari markets began to emerge as middlemen from urban centers besieged rural markets to bulk purchase gari from farmers. Simultaneously, enterprising farm households discovered that higher cash income can be earned from urban markets, thus circumventing the middlemen. Gari processors also began to spring up in urban centers, purchasing roots directly from farmers.

Several prevailing factors catalyzed gari marketing:

1. The favorable natural environment;
2. Wide sociocultural acceptance of gari in local food systems;
3. Income-generating potential of gari;
4. Government stimulus of the market;
5. Improved processing technology to reduce drudgery.

The innovations are of four types

1. Technological innovations (improved varieties, fuel saving technologies, adding palm oil to improve color, mechanization of processing, reduction of the fermentation period, adjusting processing for specific market requirements);
2. Social innovations (establishment of cooperative societies, improving access to market, diversifying markets, emergence of private ancillary service providers);
3. Economic innovations (investment in equipment, partnerships to pool finances, use of informal local credit services);
4. Institutional innovations (contractual arrangements between parties, including gari in the strategic food reserve program, government provision of a N50 billion loan to farmers).

Adapted from Ekwe, K.C., Ike, N., 2006. Sustaining gari marketing enterprise for rural livelihood: farmers indigenous innovations in South Eastern Nigeria. In: Paper presented at the Innovation Africa Symposium, Kampala, 21–23 Nov 2006. Umudike, Nigeria: National Root Crops Institute (Ekwe and Ike, 2006).

BOX 11.4b Ghana: Government-Led Cassava Initiatives

Cassava is a major staple in West Africa, and is grown in most agroecological zones of Ghana. Cassava can also be processed into gari and into starch, which is the raw material for other industrial products. The government sought to use Ghana's comparative advantage as a cassava producer to transform the cassava industry into a major earner of export revenue in industrial starch through the "Sustainable Uptake of Cassava as an Industrial Commodity." This initiative revolves around the creation of market linkages to provide market access for small- and medium-sized enterprises, new product development, quality assurance, and the management of supplier – buyer business relations.

The critical actors are:

- Scientific research institutes;
- Policy institutions (especially the Ministry of Food and Agriculture);
- Business promotion organizations (the National Board of Small-Scale Industries);
- Producer/processing organizations.

A major lesson learned was that market access does not happen by itself, but needs strategic support and the building of trust.

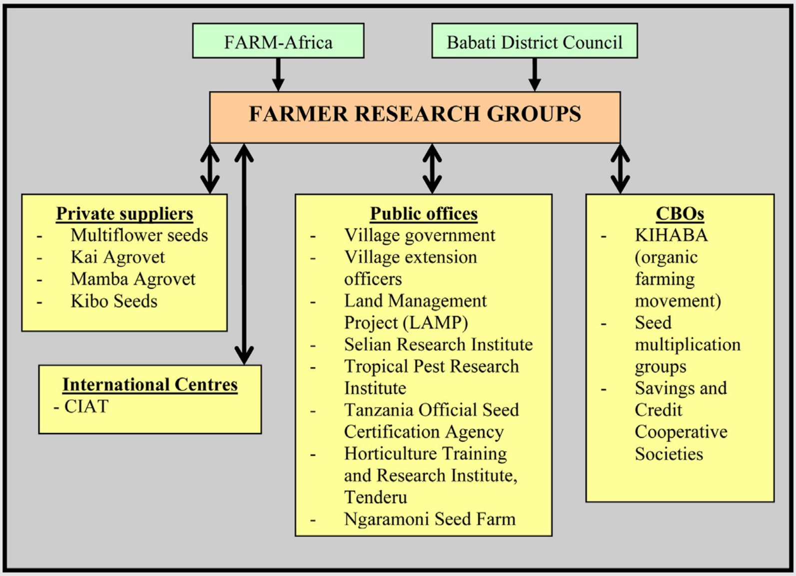
Adapted from Essegbey, G., 2006. The innovation of the cassava sector: the Ghana experience. Science Technology Policy Research Institute, Council for Scientific and Industrial Research, Accra, Ghana (Essegbey, 2006).

cases, innovation is stimulated and coordinated by government or donor initiatives that bring the relevant stakeholders together and support them through the innovation process (see Box 11.4b).

5. In other situations, the innovation process can be coordinated by an NGO or extension program that provides capacity building and empowerment for farmer groups, and *links the farmer groups to local government, research, and private agencies* that can support production and marketing (see Box 11.5).
6. Normally, the term "innovation" at the farmers' level has been used to refer to farmers' adoption of new technologies coming from outside, rather than the *new technologies, management practices and institutions that farmers and their communities have developed themselves*. Many local innovations are not of a technical nature, but rather are socioeconomic and institutional innovations, such as new ways of gaining access to resources, or new ways of organizing marketing activities (see Fig. 11.4) (Waters-Bayer et al., 2006; also see Box 11.6).
7. Research is important, but not always central—and one needs to consider other *bottlenecks to the use of innovations and to the process of innovation*. We have seen that the livelihoods framework (see chapter: Farming-related Livelihoods) is useful in analyzing where these constraints might be important through consideration of the social, human,

BOX 11.5 Tanzania: Sustaining Innovation by Farmer Research Groups

In Tanzania, an NGO (FARM-Africa), working closely with district and village government, has established a number of Farmer Research Groups to stimulate local innovation for improved crop productivity and profitability. The groups were successful due to linkages with national and international research organizations, government seed certification and training centers, and input suppliers.



The initiative is of particular interest for the ways that the Farmer Research Groups ensured their long-term access to these linkages, and a sustainable capacity to continue to investigate novel technologies of local relevance.

This they achieved through:

1. The establishment of *community-based seed multiplication schemes*, which provide income that can then be used to finance further experiments;
2. *Community agricultural input supply shops*, established by farmer research groups in response to the need for local access to the technologies identified;
3. *Savings and Credit Cooperative Societies* (SACCOS), which enable members to accumulate capital for the purchase of inputs.

(*Continued*)

BOX 11.5 (Continued)

Farmer research groups manage input shops in rural areas to ensure that villagers have access to improved seeds (including those multiplied by their members), fertilizer, and pesticides. A savings and credit scheme helps those who previously could not afford to purchase improved inputs.

The production increases have resulted in farmers being able to store grain at harvest, and either sell it at a better price later on, or use it to reduce food insecurity. They have become financially independent of external donor and government agencies.

Adapted from Pound, B., Massawe, K., Fazluddin, F., 2007. Innovation partnerships for effective adaptive research and technology uptake. In: Paper presented at the workshop "Enhancing agricultural innovation" organized by the World Bank and held in Washington, March 22nd–23rd 2007. Chatham: Natural Resources Institute (Pound et al., 2007).

financial, natural, and physical assets available to communities, and the legal, institutional, and political influences on them. Recently, regional research organizations like ASARECA (Association for Strengthening Agricultural Research in Eastern and Central Africa) have put emphasis on the policy reforms needed to support agricultural innovation. A major bottleneck that their DONATA project (see below) encountered was the lack of understanding by government, NGO, and private sector organizations of the process of multistakeholder collaboration, and how that could lead to new alliances and the breaking down of traditional mistrust between producers, traders, and suppliers.

FIGURE 11.4 Innovation for agriculture might include disciplines outside the agricultural sciences. Here low-cost water tanks are developed with farmer groups in Nepal for supplementary irrigation of high-value vegetables. Farmers in this case were supported with advice on production and marketing of the vegetables, as well as training in tank construction and the use of water. The "innovation" covered the whole value chain from production to consumption. *From Pound, B., Shakya, P.B., 2004. Final consultancy completion report: uptake pathways and scaling-up. Hill Agriculture Research Programme (DFID-Nepal). Chatham, UK: Natural Resources Institute (Pound and Shakya, 2004).*

BOX 11.6 Case study: Network Promoting Farmer-Led Innovation Processes

Tigray local improved beehive.

(*Continued*)

BOX 11.6 (Continued)

Ethiopian farmer discusses his agroforestry innovation with Ministry of Agriculture officials.

PROLINNOVA is an NGO-initiated international network active in 20 countries in Africa, Asia, and Latin America that fosters farmer-led processes of participatory innovation in agriculture and NRM. It focuses on recognizing the *dynamics* of indigenous knowledge, and enhancing the capacities of farmers (including pastoralists, fishermen, and forest dwellers) to innovate so that they can adapt to change. Farmers are seen as the main actors in developing their own site-appropriate systems and institutions of resource management to achieve food security, sustain their livelihoods, and safeguard the environment. The essence of sustainability lies in their capacity to innovate for both private and public good.

Working with a farming community starts not with problem analysis, but with appreciative enquiry, seeking the strengths within the community. This includes looking for positive deviancy: "crazy" people who have created locally new and better ways of doing things using the available resources. The entry point to farmer-led participatory innovation is thus embedded in local

(*Continued*)

BOX 11.6 (Continued)

realities, and is driven by farmers' interest and energy. Discovering how and why farmers innovate makes the outsiders appreciate what farmers are already trying to do to improve their situation; understanding the rationale behind local innovation transforms how they view local people. This experience stimulates interest on both sides to enter into joint action, and lays a basis for a more equal partnership in ARD than if one starts by introducing external technologies.

The PROLINNOVA network encourages partnership between smallholders, extension agents, development workers, university teachers, and researchers who are open to recognizing that farmers are knowledgeable and creative. These actors collaborate—building on local ideas and bringing in ideas from outside—in an innovation process that integrates local with external knowledge. They start by seeking answers to farmers' questions: what the group or community wants to explore further. Drivers of local innovation generally include the need or desire to solve a local problem, take advantage of a new opportunity, or adapt to changes in the economic or natural environment. Local innovations are more likely to be suitable for smallholder farming because of their frugality: they are typically inexpensive and do not require intensive use of external inputs. They usually fit well into the local agroecological and socioeconomic conditions.

The network seeks to integrate participatory innovation approaches into institutions of research, extension, and learning. It uses experiences with farmer-led research on the ground as a basis for multistakeholder reflection on the policy change needed to enable this approach. It seeks to increase farmers' influence in decision-making about ARD, including management of funds. A key way for farmers to decide what research is done, and how, is through deciding on the use of research funds. The PROLINNOVA network has therefore been helping to establish Local Innovation Support Funds so that farmers can "call the tune." The vision of PROLINNOVA is a world in which women and men farmers play decisive roles in ARD for sustainable livelihoods.

Some impacts that have been observed in the areas where PROLINNOVA[b]. partners are working include: locally appropriate and better ways of doing things; farmers organizing themselves around ARD at the community level; better links between farmers and support organizations, including sources of relevant information; more local spaces created for experimentation and learning, e.g., farmers forming their own research clubs, and organizing farmer symposia and local innovation fairs. Where innovation by women was recognized and women were encouraged to lead experiments, this led to their greater confidence and assertiveness, also to lead in other activities within the community.

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[b] More about the impacts of PROLINNOVA and similar approaches to promoting local innovation can be found in: Study on impacts of farmer-led research supported by civil society organizations (http://aas.cgiar.org/publications/study-impacts-farmer-led-research-supported-civilsociety-organizations#.VPmlJ2YoXzI), also see www.prolinnova.net.

BOX 11.7 Uganda: "Enabling Rural Innovation": Nyabyumba United Farmers' Organization

The Nyabyumba farmers group of Kabale district, Uganda, was formed in 1998, with 40 members. The group, supported by the NGO Africare, focused on producing improved potatoes from clean seed provided by the National Agricultural Research Organization (NARO). In 2000, the Nyabyumba group formed a farmer field school (FFS) to improve their technical skills on potato production and increase yields. In 2003, equipped with the necessary skills for producing a high quality and quantity of potatoes, the group decided to increase their commercial sales, and requested support from Africare, NARO, PRAPACE (Regional Potato and Sweet Potato Improvement Network in East and Central Africa), and CIAT.

Through this consortium of partners, the Nyabyumba Farmers' Group received training in identifying and analyzing market opportunities, and developing a viable business plan for the potato enterprise. From the market study the group identified *Nandos*, a fast food restaurant based in Kampala, and the local wholesale markets in Kampala. The group has set up a series of committees to manage, plan, and execute their production and marketing process. To maintain a constant supply, the farmers have set up a staggered planting system to ensure that there are up to 50 tons of potatoes available each month.

To increase the competitiveness of production the group has conducted research supported by NARO to determine the most suitable nutrient levels of NPK fertilizer, and time of dehaulming potato plants that produces a big tuber size, with higher organic content, firm skin, and higher yields, as required by the buyer. The farmers group has expanded to a membership of 120 members, 80 of whom are women. They have supplied 190 metric tonnes of potatoes to *Nandos*, bringing their income to UgSh60,000,000 or approximately US$33,000.

Adapted from Kaaria, S., Abenakyo, A., Alum, W., Asiimwe, F., Best, R., Barigye, J., et al., 2006. Enabling rural innovation: empowering farmers to take advantage of market opportunities and improve livelihoods. In: Paper presented at the Innovation Africa Symposium, CIAT, Kampala, November 21–23, 2006 (Kaaria et al., 2006).

8. The innovations systems approach is related to some previous approaches, such as the commodity systems approach and the analysis of value chains, both of which, like the AISs approach, consider the whole chain from *producer through to consumer* (see Box 11.7).
9. The *public sector* has a central role to play through developing legal and regulatory frameworks, and providing an enabling policy, trade, infrastructural, and support environment that encourages innovation (see Fig. 11.5).
10. The innovations systems approach is *not inherently pro-poor*. As with other approaches, real impact on poverty and gender imbalances will only result if special attention is given to meeting those challenges (see Fig. 11.6).

FIGURE 11.5 Multistakeholder partnerships can improve community use of natural resources.

FIGURE 11.6 In Bihar, India, there are many landless people with few income options. The East India Rain-fed Farming Project searched for income-generating occupations for the landless that also contributed to the overall wellbeing of the community. These include blacksmithing and the use of common property resources, such as "Sal" (*Shorea robusta*) leaves as plates, the use of grasses to make ropes, and split bamboo to make mats and baskets.

PRACTICAL EXPERIENCES WITH INNOVATION PLATFORMS

Because the use of IPs is new, most experiences to date are project-based and backed by donors who are interested in "proof-of-concept"—i.e., does it work? The following three examples are all from Africa, but use IPs for different purposes. In the case of the Dissemination of New Agricultural Technologies in Africa (DONATA) it is for the dissemination of new food crop technologies, in the case of Agroecology Based Aggradation – Conservation Agriculture (ABACO) it is for the testing and adoption of CA, while for Africa-RISING the purpose was to coordinate a complex set of research protocols and the scaling-up of successful interventions.

Dissemination of New Agricultural Technologies in Africa

This large project funded by the African Development Bank and managed by FARA (Forum for Agricultural Research in Africa) operated in 35 countries in southern, western, and eastern Africa. The east Africa component was overseen by ASARECA, who published a book about their experiences using IPs for the dissemination of agricultural technology (Kimenye and McEwan, 2014). In eastern and central Africa, 48 IPs were established in six countries (20 for the promotion of orange-fleshed sweet potato (Orange-fleshed sweet potato is rich in vitamin-A (a common nutrient deficiency in sub-Saharan Africa)) and 28 for the dissemination of quality protein maize (Quality protein maize (QPM) has higher lysine and tryptophan amino acids than conventional maize. These essential amino acids are beneficial to the diets of humans and other monogastric animals)). These provided a rich set of experiences across a wide range of environments and situations.

The following preliminary principles on the establishment, maintenance, and use of IPs emerged from the analysis of their findings:

- *IP composition*: A diversity of actors is critical to support learning, innovation, technology generation, and dissemination processes. The right mix of people and organizations needs to be identified and brought on board, according to the objective and functions of the IP. The DONATA experience shows that the promotion and dissemination of crops with high nutritional value attracted nonconventional actors to the platform, e.g., health and education professionals. Value chain and stakeholder analysis should drive the identification of the actors. Such analysis should be iterative, and therefore the IP membership dynamic should be able to respond to changes in, e.g., market opportunities, macroeconomic conditions, and the political and policy context. The IP approach also aims to achieve a greater impact with the technologies it is disseminating—so composition could include organizations which could support this scaling process. All partners (at both the individual and organization levels) need to see a benefit in order to remain committed; incentives may not only be financial, but include increase in knowledge, status, recognition, and becoming part of a wider community of practice or movement for change.
- *Tools and processes*: A range of tools and processes can support the establishment and functioning of the IP. Value chain analysis is critical to understand the relevant commodity, its challenges and opportunities. Stakeholder and SWOT analysis can help members to analyze issues jointly, so as to enhance a feeling of belonging, responsibility, and transparency, as well as empowering partners. Joint monitoring tools and activities also strengthen joint accountability. Roles and responsibilities of individual members need to be agreed and understood.

- *Capacity and competencies for supporting innovation processes and IP functioning*: Identify a suitable champion for the platform, and where necessary strengthen his or her facilitation and other soft skills. The IP needs a motivated champion who can mobilize and broker the partnering arrangements, and facilitate interactions among the IP members, balancing the need for participatory processes with clear direction when required. This requires skills and experience in leadership, coordination, and facilitation, together with sensitivity and awareness to tackle or harmonize power asymmetries, and negotiate through conflicts which may need to be resolved. A systematic proactive approach is needed to encourage joint learning, out of which new innovations may emerge. A safe "space" for this learning and reflection process can encourage a more honest appraisal of what needs to be done differently.
- *Lead organization*: The lead organization needs to coordinate and advocate for the IPTA at the institutional level, especially for favorable policies and for resources.
- *Governance and management*: It is crucial to take time to establish democratic, participatory, governance and management processes. Experience has shown that both formal and informal institutional and partnering arrangements can be effective governance structures and management procedures; these should be clearly understood, accepted, and respected by all members of the platform. It is advisable to employ the principle of subsidiarity, so that decisions are made at the level of those who will implement them.
- *Communication*: The flow of information is one of the key elements for successful functioning, and for innovation and growth of the platform and its enterprise. Therefore, take time to put in place processes and channels that can enhance the flow of information, including feedback from different stakeholders.
- *Innovation and dynamism*: IPs should deliberately and proactively innovate as a means of addressing challenges or threats, and to exploit emerging opportunities. In this regard, IPTAs should have explicit actions that encourage innovation, e.g., proactively seeking opportunities for improving the benefits for members.
- *Sustainability*: For sustainability, platforms should be founded on a sound business model, and efforts should be made to employ business management principles, including record keeping, and making use of various economic analyses, such as demand and supply analysis and cost-benefit analysis. In addition, the ability to document and disseminate verifiable evidence of successes and outcomes from IP interventions and processes is a powerful means of gaining support for scaling-up and sustainability.

It took time (in some cases 1–2 years) for the relevant organizations to understand and accept the IP concept, and agree to try it alongside their conventional R&D methods. However, in many cases the IPs have made a big difference to the availability of planting materials for sweet potato and

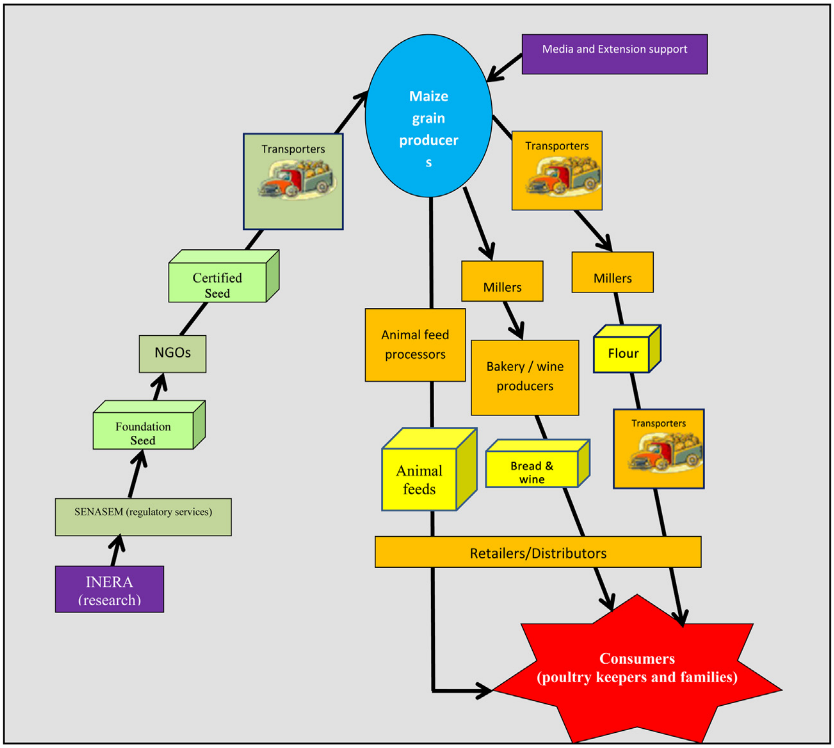

FIGURE 11.7 Democratic Republic of Congo: quality protein maize value chain.

quality protein maize, and also in promoting the value chains associated with these commodities (including the involvement of farmers—often women—in the processing of the harvested crops into a range of products for sale, thereby adding value and generating income). Fig. 11.7 shows the value chain for quality protein maize that eventually evolved around the IPs in the Democratic Republic of Congo. The left-hand strand of the value chain relates to seed supply (a major constraint in most countries) which *pushes* production, while the right-hand side shows the range of products being marketed to consumers which is *pulling* production.

Agroecology-Based Aggradation – Conservation Agriculture

ABACO is a EU-funded research project investigating the use of CA (Conservation agriculture (CA) consists of a package of several agricultural practices based on three principles: minimum soil disturbance, soil cover, and crop rotation) by smallholder farmers in sub-Saharan Africa. The introduction of CA in new areas often requires a fundamental change in the farming system, and a change in the behavior of stakeholders (Kassam and

Friedrich, 2011). Weak institutions resulting in, e.g., inefficient supply of agricultural inputs, inadequate extension services, limited access to finance, and contradictory policies, obstruct the potential livelihood benefits of CA (Nkala et al., 2011). Furthermore, CA can increase gender and social disparities in some cases, because of social and institutional factors (Beuchelt and Badstue, 2013). In order to address the persistent bottlenecks to CA, IPs have been used in recent years to develop, adapt, and promote CA practices at local levels (e.g., Tittonell et al., 2012).

However, CA IPs have tended to focus on a solution (i.e., CA), rather than the underlying constraints, such as declining soil fertility, insecure property rights, conflicting demands on farm resources, or lack of inputs and services. When IPs are focused on technology development and dissemination, there is a risk that they revert to the ToT model.

It is preferable that rather than a narrow promotion of CA, IPs should focus on underlying shared complex problems (e.g., land degradation, changing climate and climate variability, weak institutions, and market failures), which form obstacles to sustainable agricultural intensification and agricultural sector development. The focus on the problems enables IPs to widen their mandate, to bring in innovative solutions that are not prescribed. IPs should (see Fig. 11.8):

- Experiment with possible solutions to the underlying problems;
- Facilitate access to a variety of technologies from which farmers can choose;
- Create an enabling environment that facilitates sustainable intensification;
- Facilitate connections between actors at all levels;
- Improve access to services, credit, transport, markets, knowledge, technologies, seeds, and agricultural inputs;
- Identify strategies that link income generation with land rehabilitation.

Africa RISING in Ethiopia

This USAID-funded, ILRI-managed research project brings together seven CGIAR institutes, Ethiopian agricultural research organizations, NGOs, local government, and farmers to test and scale-out technologies and processes that assist with the sustainable intensification of agriculture in the highlands of Ethiopia. To assist the research and scaling agenda, IPs have been established at the district (woreda) level. The IPs include all the actors mentioned, with facilitation by a local organization (i.e., not the donor-supported research project). During the present, mainly research phase, the focus of the IP is on coordinating the research and ensuring it is predominantly demand driven. The IP interacts with parish (kebele)-level farmer research groups that are involved with the testing of specific interventions. It is anticipated that, as the emphasis shifts from research to scaling-out and benefiting from the interventions, the IP will evolve to support the commercialization

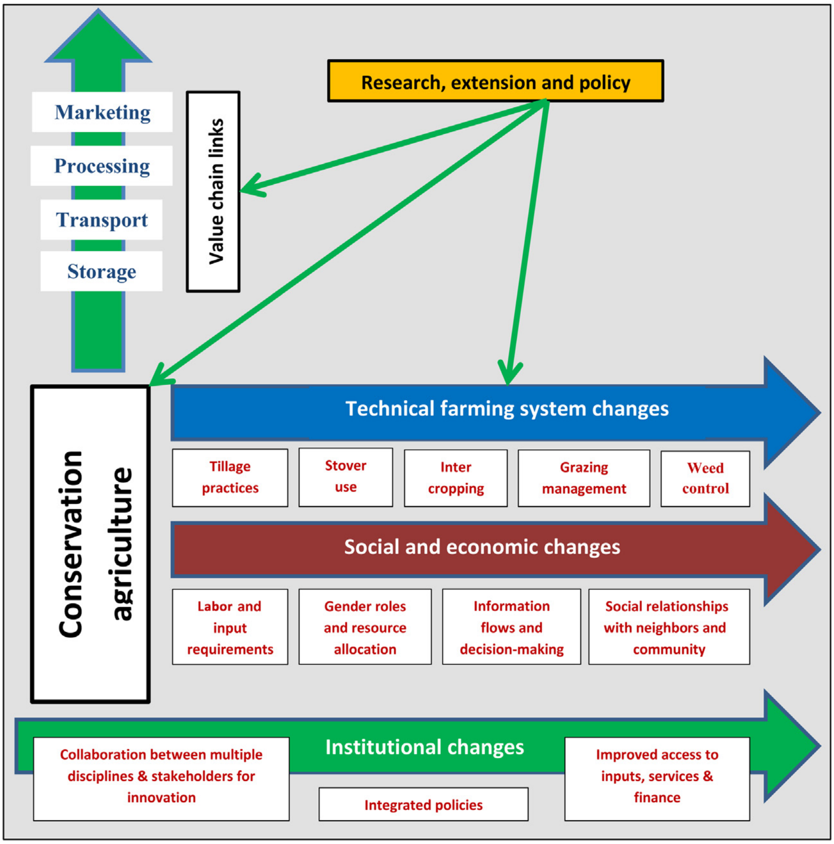

FIGURE 11.8 Technical, social, economic, and institutional changes brought about by a conversion from conventional to conservation agriculture.

(information supply, storage, transport, processing, and marketing, as well as the organization of collective input supply and sales) of commodities and products. Private sector organizations and service providers are expected to join the IP as the value chains become more established. Interesting features of these relatively new IPs are the emphasis on participatory monitoring, the evaluation of the IPs as a learning and management tool (Damtew and Duncan, 2015), and the election of "champions" within the IP members with responsibility for specific aspects of the IPs (M&E champion, gender champion, communications champion). The district-level IPs link to farmers through kebele-level IPs and Farmer Research Groups which have representatives on the district IPs. There are plans to establish a national-level IP to represent all the district IPs at the relevant national research, extension, training, and commercial organizations.

CAPACITY DEVELOPMENT NEEDS FOR AGRICULTURAL INNOVATION SYSTEMS

The case studies in Chapter 9, Research on Livestock, Livelihoods, and Innovation, highlight the importance of "hands on" learning by farmers. This is consistent with theories of adult learning (Kolb, 1984), and with the FFS approach (Gallagher, 2003). Interactive, iterative processes involving potential users may be a necessary condition of effective innovation; in contrast, traditional approaches to agricultural extension tend to treat farmers as passive recipients of technical knowledge. This may be effective in making farmers aware of technologies, without leading to their adoption, and may be another reason for limited adoption of the outputs of formal research (Fig. 11.9).

While there is no consensus on the precise nature of innovation capacity, its broad features include a combination of:

1. Scientific, entrepreneurial, and managerial skills;
2. Partnerships, alliances, and networks linking different sources of knowledge and different areas of social, economic, and policy activity;
3. Routines, organizational culture, and traditional practices that encourage the propensity to innovate;
4. Supportive policies, incentives, and governance structures; and
5. The mechanisms and encouragement to continuously learn and use knowledge more effectively (http://www.innovationstudies.org).

FIGURE 11.9 A farmer in highland Ethiopia demonstrates good sprouting of an improved variety in her new diffused light storage facility. These two complementary innovations have reduced seed potato rotting, and increased germination, yield, and profits substantially, enabling the sustainable intensification of her limited farm acreage.

The World Bank (2007) maintains that research capacity should be developed in such a way that, from the beginning, it nurtures interactions between research, private, and civil society organizations. An effective AIS requires a cadre of professionals with a new skill-set and mind-set that encompasses markets, agribusiness, intellectual property law, rural institutions, rural microfinance, facilitation, system analysis, and conflict management.

Implications for national research and advisory services include the need to reskill in the areas of facilitation, communication, entrepreneurship, conflict management, value chain analysis, and market research. Reward systems also need to change, to reflect the changed emphasis from academic papers to developmental outcomes. Also implied is much closer working between research and extension on the one hand, and government, civil society, and the private sector on the other. The World Bank (2007) also calls for the reform of university curricula to include innovation system principles and case studies (Table 11.3).

TABLE 11.3 Human Capacity Needs for Implementing Agricultural Innovation Systems Approaches, and Some Mechanisms for Developing That Capacity

Human Capacity Needs for the Implementation of Innovation Systems	Some Mechanisms for Enhancing Human Resource Capacity
• Management of dynamic partnerships • Governance of partnerships • Facilitation • Negotiation and conflict management • Communication • Sourcing, managing, interpretation, and "packaging" of information • Entrepreneurship and business skills • Systems thinking • Value chain analysis • Market evaluation • Research methods, including participatory and impact-oriented methods (action research) • Research leadership • M&E, impact assessment, and learning • Mobilization and local organization development • Rural finance • Demand identification/articulation and priority setting *Adapted from* Kibwika et al. (2007)	• Partnerships (e.g., through competitive grant schemes) • Exchanges (N − S, S − S) attachments and internships • Undergraduate and postgraduate degree studies • Vocational training • On-the-job learning • Short courses • Distance learning (e.g., professional PhDs) • Conferences and workshops • Reflection and learning events • Job rotation • Mentoring and coaching • Joint activities (e.g., joint monitoring visits, PRAs, etc.) • Curriculum reform and the adoption of course delivery methods that stimulate problem solving abilities *Adapted from* Pound and Adolph (2005)

THE ENABLING ENVIRONMENT FOR INNOVATION SYSTEMS

There is a danger that multistakeholder IPs will be promoted without addressing key higher-level constraints to effective pro-poor innovation, such as the policy, legal, and fiscal environments, and infrastructure such as roads, mobile phone coverage, storage facilities, and market places. These are more difficult to change, and tend to be overlooked in donor-sponsored initiatives to enhance agricultural innovation. The importance of *policies* was identified by practitioners of FSR, as well as more recently by proponents of IS. However, the innovation system concept stresses the need to look beyond just research policy, and to ensure that a wide range of policies is in place to address the "incentives, triggers and support structures needed to stimulate and sustain creativity" (Hall et al., 2005).

The other aspect of the enabling environment is effective institutions and organizations (private, NGO/CBO, and government) that can support and promote IS. In the innovation system literature *institutions* are defined as "the sets of common habits, routines, practices, rules or laws that regulate the relationships and interactions between individuals and groups" (Hall et al., 2005). For example, projects or initiatives that aim to support NARIs (National Agricultural Research Institutes) to adopt or promote participatory innovation processes have commonly found that the processes are not sustained much beyond the end of the initiative. Inhibiting factors have included entrenched habits, practices, and rules, such as a widespread attitude that participatory on-farm research is messy, does not conform to scientific and statistical norms, and is not a good basis for an academic career pathway.

RISKS AND BENEFITS OF ADOPTING AN INNOVATION SYSTEMS APPROACH

There is a risk that organizations will adopt this approach *instead of* previous approaches, such as farming systems, sustainable livelihoods, agricultural knowledge and information systems, and participatory approaches. This would be a shame, as each of those approaches is still valid, and their concepts should still be brought to bear when considering rural development situations. The IS approach should rather be *complementary* to these other, still valid, approaches.

A further risk is that the need for technical specialists will be disregarded in favor of those with soft skills. Again, that would be a mistake, as technical specialists are still needed to investigate and provide understanding of complex technical aspects of innovations.

In contrast, the benefits include greater efficiency due to the "joined-up" thinking in the production-to-consumption cycle as people work together to address opportunities, and the emergence of creative solutions to problems facing rural communities from a range of sources.

IMPLICATIONS FOR AGRICULTURAL DEVELOPMENT

Already, major donors such as the World Bank and DFID are advocating the adoption of the approach, and subregional organizations such as ASARECA are incorporating IAR4D as the underlying research paradigm for their programs. In addition, it is expected that there will be a reform of university and training college curricula to include IS approaches. Such courses should include soft skills, such as participatory rural appraisal tools and facilitation skills, as well as instilling an understanding of entrepreneurship and business management, alongside technical agricultural knowledge and practice.

The implications of the IS approach for donors and governments are clear. Formulation of intervention programs should be done in the specific context of the respective countries and localities, and these must emphasize strong linkages among the critical stakeholders. The investment in such programs must not only result in tangible outputs such as improved genetic materials, technologies, and products, but also the intangibles such as enhanced skills, knowledge, and mutual trust, and an improved enabling environment for farming, processing, distribution, and marketing of agricultural products. The roles of government research and extension staff will change from developing and delivering technical solutions to facilitating and coordinating a range of actors to establish and maintain IPs, and support them in addressing constraints and building strong, productive, and equitable partnerships.

Innovation in agriculture often requires a combination of changes in technology *and* infrastructure (hardware), knowledge, skills and information (software), and organization of agricultural systems (orgware) (The World Bank, 2012). Development actors have adopted some of the terminology and a subset of these components (in particular the IPs), but there is still a strong emphasis on research and technology, and a tendency to continue with a ToT approach, superimposed on IPs. It is to be hoped that future initiatives will embrace the IS approach in its entirety, and address underlying framework and infrastructural constraints to effective rural development.

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Chapter 12

Outreach to Support Rural Innovation

Vicki Morrone

INTRODUCTION

Outreach is the focus of this chapter; it is defined as a process in which individuals, organizations, and teams extend knowledge and offer opportunities to those seeking change so they can improve their livelihoods. Outreach can be offered using various approaches, depending on the audiences engaged in the process, the ultimate goal of the extension workers, and available resources. The approach largely depends on the capacity of the leaders or facilitators of the educational process, and relationships with the stakeholders, such as smallholder farmers.

Historically, a common approach to promote technologies to target audiences was via the Training and Visit System, commonly known as T&V system. It was promoted by the World Bank and was shown to require considerable resources, but at the same time, the system was an effective means to promote technology transfer of relatively simple technologies, such as fertilizer use on hybrid rice. For this approach to be successful, it requires an environment of stable markets, adequate infrastructure, and social capital with strong linkages among research, extension, and farmers (Benor and Harrison, 1977). These conditions rarely exist in developing countries, now or in the past.

The complex and rapidly changing environment that shapes smallholder farmers' livelihoods negates the value of protocols or blanket recommendations, often disseminated through top-down delivery. This historical approach typically offered a single technology to address a problem, and is referred to as a "supply-driven approach." There are many instances today where extension continues to focus on single solutions and the promotion of technologies through subsidies or interest-free credit. This extension approach does not address the tremendous variability across and within communities. Further, it discourages local innovation and farmer-led solutions,

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often ending in less desirable outcomes and abandonment of technologies once subsidies are depleted.

In contrast to a supply-driven approach, farmers can be supported by extension to work together to problem solve and design their own solutions. An example is shown in Fig. 12.1. In Zimbabwe, farmers and extension workers have collaborated through a participatory action approach to define and address their agricultural challenges (Chambers 1994b). In this case, soil pH was found to be a problem, as acid soil limits crop growth. Through establishing a revolving credit club, farmers were able to afford soil amendments such as lime. Farmers experimented with combinations of lime, manure, and fertilizers to identify the best approaches. Joint planning meetings with agrodealers, extension educators, and farmer groups allowed for development of quality relationships that led to better understanding of each groups' goals. Forming an innovation platform (see Chapter 11) is a more formalized way to support this type of collaborative, systematic problem-solving and fine-tuning of technical advice for local conditions by all involved. In the Zimbabwean example, farmers and extension educators worked together to choose "best bet" or plausible technologies. Several rounds of testing were undertaken. Annual meetings were held to consider the findings and plan how to use the technologies on local farms. Working collectively with an approach that is scientifically sound and relevant to the local context typically increases the success rate. Examples will be provided throughout this chapter that demonstrate such approaches that are part of an agricultural knowledge innovation framework (See Fig. 12.2).

Dissemination of targeted technologies through a "pipeline" of researchers—extension workers – farmers has been a traditional means to support farmers' adoption of new technologies and has led to remarkable yield gains in some circumstances. The Green Revolution in Asia is a clear example of yield gains in addition to some shortcomings. This agronomic approach has been inadequate to address many of the complex realities of smallholder families,

FIGURE 12.1 Zimbabwe participants in a revolving credit club.

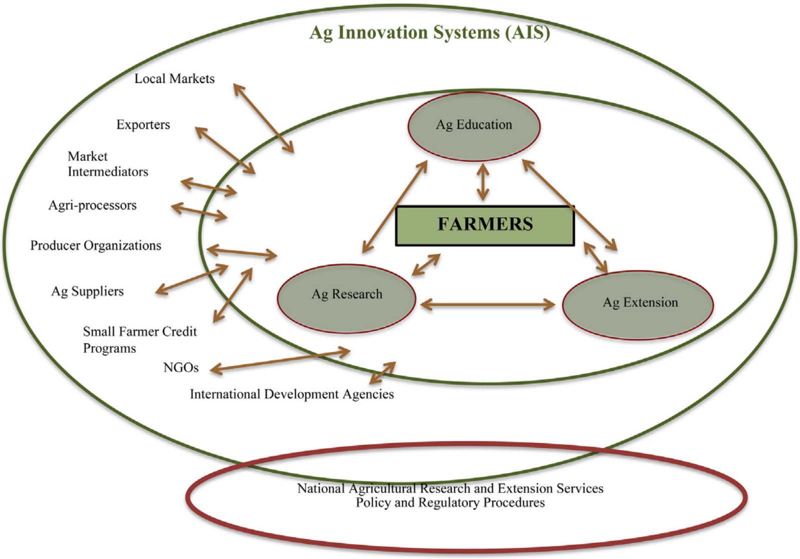

FIGURE 12.2 Extended agricultural knowledge and innovation systems.

and has fallen notably short of protecting the environment. To find long-term solutions will require reform in how extension is conceptualized (Rivera and Alex, 2004). Throughout the developing world, new models for community-led extension and learning are emerging which offer customized long-term solutions for individuals and groups, rather than country-wide solutions.

Central principles in extension that will be explored in this chapter include:

1. Improving relevance through demand-driven and decentralized extension;
2. Facilitation of human and organizational capacity for innovation;
3. Scaling out to reach more people; and
4. Sustainability of outreach.

AGRICULTURAL KNOWLEDGE AND INNOVATION SYSTEMS

A widely-used model for agricultural knowledge generation and dissemination is referred to the Agricultural Knowledge and Innovation Systems (AKIS) paradigm (Röling and van de Fliert, 1994). This approach places farmers and communities at the center of a triangle that has three nodes: university, research, and extension. This model has been updated from the agricultural knowledge and information systems triangle used historically, integrating innovation within the context of agricultural knowledge (Fig. 12.2). Without the necessary resources, inputs and market access, new technologies and knowledge will not achieve the anticipated results. This figure demonstrates how agribusiness, as well as development groups, must contribute to the process to improve farmers' opportunities to engage new technologies and innovations that will lead to increased yields and more sustainable production.

The previously published iteration of the AKIS model (2012) has been criticized because of its somewhat linear conceptualization of delivering technology to the three sectors that include farmers, non-government organizations (NGOs), and the private sector from the three nodes of agricultural information: research, extension, and university. Note that this model does not take into account the logistics or infrastructure necessary to implement the sought changes. Collaborative learning and promotion of local innovation and partnerships have been incorporated into this model. The three core institutions of education, technology generation, and extension advisory staff need to be interwoven and interlinked with the private sector and other catalysts of innovation, promoting farmer-centered learning and the continuous exchange of information among all parties. Promoting such an approach allows farmers to adopt, adapt, and implement changes into their farming practices.

A participatory research and extension process is at the foundation of AKIS, integrating stakeholders to identify problems, prioritize, and chart a way forward. Experts in technologies assist them to understand the principles that support the approaches, interactions, and possible challenges. This type of engagement is essential to create ownership and build bridges among development organizations (e.g., NGOs, extension, and researchers), community governance structures (e.g., village councils headed by village chiefs or chairpersons), and other parties such as agricultural industry and regulatory institutions. A successful interaction of this nature requires a strong facilitator, and joint collaboration to achieve common goals.

There are emerging examples of alternatives to traditional extension, including privatized or public–private hybrid models, and decentralization of extension services (see Fig. 12.2). These have been tried in different permutations in Bolivia and New Zealand (Bently et al., 2003). Concerns have been raised about the potential of market-driven extension systems that do not prioritize the environment or pay sufficient attention to sustainable production techniques (Hall et al., 1999; Kaaria et al., 2006). Striking a balance through technologies that address economic and environmental qualities is obviously ideal, but can be difficult to achieve. As noted by Tilman et al. (2002), farmers alone cannot address negative impacts on the ecosystem, but they can point to relevant aspects to guide in the selection of appropriate solutions. To ensure successful meetings with farmer-relevant and scientifically sound practices, environmental policies that incorporate realistic farming systems need to be in place. This is typically difficult when addressing the needs of smallholder farmers, that have claim to small amounts of land, thus little power (IFAD, 2013).

There is a shift in the goals of extension, which increasingly, consider the impact of agriculture on the environment, as well as on the livelihoods of producers. Awareness is heightened of the necessity of providing farmers with tools to understand the trade-offs between environmental services and production. Such decision tools can also facilitate identification of synergies (also see Chapter 4). Beyond providing environmental education to farmers, there are incentive programs across the globe, with varying levels of success. Some programs provide farmers who implement environmental practices with cash incentives, similar to the Conservation Reserve Program (CRP) in the United States. There are other programs that reward farmers via land tenure rights at various scales, depending on the farmer's level of environmental action. Then, there are rewards that focus on infrastructure provisioning for the farmer's community. As expected, each approach has advantages and disadvantages in terms of effectiveness to stimulate environmental nurturing and maintain ongoing impact. Some of the reward programs are very labor intensive to implement and monitor, and because the reward is based on ranking the farmer, biases can be triggered, while other reward programs or incentive programs have been effective only when community leaders are well respected and honest (Lipper and Neeves, 2011). As noted by Kerr (2014), payment for ecological services directly to farmers may gain the expected outcome during the payment period, but how is that sustainable? Is a payment program required for eternity in order to maintain proenvironmental actions by individual farmers? He suggests that collective action by farmers will support one another, help enforce the action, and provide collective incentive to maintain the environmental practices. The outcomes or returns from the environmental actions will be visible sooner, with a greater number of replications of the practices, providing visibility of the value of the action complemented by evidence-based outcomes. This approach will require less evaluation and implementation time, and thus will be more efficient. But most importantly, this will offer a degree of sustainability, due to a larger population implementing the practice and that population encouraging and aiding one another to accomplish what may be difficult to achieve, compared to individual farmers investing in such a program.

In "developed" parts of the world, such as the European Union (EU) and United States, there are programs that offer farmers economic incentives along with technical support to implement practices that benefit the environment. Typically, the program is based on the action of an individual farmer versus a community or watershed. In the United States the federal government directs the US Department of Agriculture, which houses the Natural Resource Conservation District offices located in each state. These offices offer farmers education, guidance, and direction to manage resources, mainly water and soil, for land that is environmentally sensitive, such as near a waterway, a marshland, or which has highly erodible soil. This program pays farmers to take the environmentally sensitive land out of farming production, and maintain it with a nonharvested plant cover to reduce erosion and nutrient leaching, and to minimize chemical inputs. Each state is allocated funding, to promote and support environmental practices, i.e., provided to farmers through a cost-share program. The issue with this program is that farmers' incentive to enroll acres in the conservation program is impacted by the current market price for cash crops such as corn (maize), wheat, and soybean. When these crops' market prices rise farmers remove acres from the program to allow production to realize the increased profits. Yes, farmers must make a living and have a profitable business. This is yet another justification to develop models and calculators to identify economic value of environmentally supportive practices, reward the farmers for their effort, and return the environmental savings to the farmer through property tax reductions. With such a program, I believe that reduction in property taxes would support these types of practices and inspire farmer commitment. In 2013, the price of corn rose 30% (just over US $7.00 per bushel), thus farmers were removing acreage from the program so they could grow higher-valued crops on even marginal land. This demonstrates that there are problems with all approaches to provide incentive programs to promote environmental actions, and there is never one sure approach.

In the EU, there is a similar approach to the US CRP program, with a few important differences. Farmers receive payments to support their ecological efforts, but if they do not follow the common agriculture policy then their payments are reduced. Rural areas are supported by the government to protect the environment with foci on biodiversity preservation, implementing practices to offset the impacts of global climate change, and water management (Cordier, 2015). The EU acknowledges the great variation of ecologies across its union, and each country uses their own experts to operate their system and develop best practices, as well as being in charge of enforcement. These environmental programs in the United States and the EU focus on environmental farming programs that are not based on peer support or collective action as Kerr suggested, but often these farmers are implementing practices on very large areas of land, often thousands of acres/hectares. The overriding ecological principles taught and promoted to farmers worldwide hold similar messages; to preserve what is there, as it is not easily replaceable, and to improve what is damaged as best as possible, while maintaining an economic livelihood. Extension of knowledge that promotes understanding of principles can equip farmers with "rules of thumb" or decision support tools to assist them to select modes of management that are suited to their unique environment while allowing them to make management decisions that best fit their business. This is an approach that is more likely to help farmers meet multiple objectives. In contrast, standard, one-way-fits-all technologies, such as blanket fertilizer recommendations, are not robust or sustainable, as noted by Mutegi et al. (2015) where blanket fertilizer recommendations are made for a wide range of ecological variations in Malawi. Country-wide, financial incentives are usually a preferred method of reward. But, whether a country's government or supporting entity can invoke such a program depends on affordability and organizational capacity.

Central to the vision of participatory AKIS is that extension plays the role of facilitator, one that nurtures farmers to share ideas, and ask questions. This shifts the role of extension staff from advisors on technical issues to acting as catalysts, helping in conflict resolution, and assisting communities in identifying key priorities, opportunities, and methods to resolve problems. The goal of AKIS is to reach a wide range of individuals, not only crop farmers, but also livestock producers, foresters, traders, seed buyers, sellers, and consumers. Reed (2008) describes this as a process that needs to have clear farmer-identified objectives, from the outset. It should not overlook the need for highly skilled facilitation, maybe the most difficult role to fill. There is growing recognition that training for extension educators should prioritize the facilitation process, as well as being able to articulate the mechanism and process to implement agricultural technologies. Farmer priorities and scientific knowledge can be integrated to provide a more comprehensive understanding of complex and dynamic socioecological systems and processes. Perhaps recognizing the complexity of the issues from the beginning will lead to more realistic expectations of outcomes.

An iterative process of learning is important, with built-in evaluation steps that include midcourse corrections. Attention to process will promote co-learning and enhance the relevance of outcomes. The value for all team members, and notably farmers, have "buy-in" and are part of identifying priorities, not just implementing development activities is essential. This practice complements technological innovation, and together they will strengthen the rate of success. Participants will have been part of the development throughout the process, embracing the risks and discoveries as a way forward, as Reed (2008) noted.

There are many resources available today to support participatory research and extension. A notable collection (from 2005) is available on the internet from CIP-UPWARD. This three-volume resource book, "Participatory Research and Development for Sustainable Agriculture and Natural Resource Management," sets out theory and case studies from 30 countries that describe successes and challenges while fully engaging with stakeholders. See http://www.idrc.ca/EN/Resources/Publications/openebooks/181-7/index.html.

This valuable resource was developed from a project that was based on commitment to assist extension advisors in their understanding of process dynamics, and to move beyond perfunctory implementation of a participatory methodology. Some observers contend that extension should play a facilitator role by focusing on enhanced communication among and between farmers and other stakeholders rather then promotion of an explicit technology or methodology (Hagmann et al., 1999). Others have emphasized the centrality of rural innovation, seeing extension as the catalyst that brings together different players and supports new ventures and entrepreneurship. In the synthesis presented in the UPWARD source book, four elements were identified as crucial for participatory agricultural development:

1. Assessment and diagnosis: problem diagnosis and participatory assessment of resources, needs, and opportunities;

2. Experimenting with technology options: joint agenda setting, testing a range of options, on-farm research, and collaborative evaluation;
3. Facilitating local innovation: institutional and policy innovations, negotiation and conflict management, supporting community organizations, local capacity development; and
4. Dissemination and scaling-up: document findings, promote networking and horizontal linkages for information flow, outreach to a broad audience.

This approach to reach farmers is widely-accepted in the world of development, but requires a large leap for educators on the ground. Since the onset of colonialism, academic and practical education have been promoted as doctrine rather than through experimentation. Facilitating local innovation is the major topic of Chapter 11, whereas dissemination and scaling-up is the theme of the final section of this chapter.

RELEVANCE OF EXTENSION

There is growing consensus by donors, development agencies, and community educators on the need for an increase in demand-driven extension services. This is presented as the first principle for effective outreach, where locally defined priorities guide extension programming. As illustrated in Table 12.1, there are multiple approaches that can be used to improve client orientation, and integration of demand and supply in extension. Engagement of end-users can be seen as a continuum, depending on how a technology or change can be implemented to be successful, as well as the users' circumstances and resources available for them to implement the change. Not all technologies may be successful if modified or adjusted to meet farmers' circumstances. Therefore, there is not a blanket approach to effective information sharing, but rather these three factors need to be considered before choosing the best approach.

Expressing local demand can be problematic, as farmers often have different access to resources and their land has different characteristics requiring various approaches that impact which support services can be most beneficial, highlighting the opportunity for flexible innovations that can be adopted by institutions. Demand-driven extension examples include those built around farmer organizations, decentralized extension services that rely on local contracts, and market-linked extension. This approach may include fixed technologies that are appropriate to be promoted through a market-value chain, such as treadle pumps for small-scale irrigation, and diesel-powered maize mills based in village markets. Other technologies require considerable adaptation to meet local environmental conditions, and complementary investment in education for local capacity building. Conservation agriculture or CA if often promoted as a solution to reduce erosion and build soil health. It is often too prescriptive requiring extensive adaptation,

TABLE 12.1 Fundamental Principles and Examples of Relevant Outreach

Guiding Principles	Extension Models
Farmer-led extension	
• Farmers as empowered learners • Respect for local knowledge • Farmer organizations to identify common needs	• Farmer field schools (see Box 12.4) • Decentralized, demand-driven extension • Participatory action research and extension • Farmer organizations
Experiential learning	
• Biological principles taught, not set recommendations • Knowledge generation through action learning	• Farmer field schools, e.g., Agroecological curriculum • Farmer research groups or Local Ag Research Committees (CIALs) • Participation in mother-baby action research and extension
Facilitation	
• Extension as facilitators and knowledge brokers • Involve stakeholders from many different sectors	• Innovation platforms • Community food hubs • Participatory action research and extension • Farmer research groups (CIALs)
Iterative learning	
• Build working relationships among researchers, extension, NGOs, farmers, and other stakeholders • Transparent and joint priority setting • Systematic evaluation and reflection steps	• Demand-driven extension from farmer organizations and local nongovernmental organizations, for information • Community round table discussions • Farmer-to-farmer exchanges (reciprocal visits) • Demand-driven extension from farmer organizations and local contracts • Market-linked value chains (see Box 12.2)
Sustainability of extension	
• On-going support from public and private sectors jointly • Integration of demand and supply of extension information • Farmer/stakeholder inclusion in country-wide program planning	• Local private providers of technical information • NAADS development of country-wide services (Box 12.3) • Complementary work between government and NGOs to promote technologies • Joint collaborations amongst various ministries and private sectors • Collective work plan development

depending on the state of the soil, agricultural policies, farmer production practices, and priorities (e.g., preferring to use plant residue for animals, or preferring not to use herbicides), and farmers' access to resources such as compost, manure, and seed varieties.

Practicing participatory approaches is more than asking the farmer or end-user to engage in dialogue about priorities. Extension advisors also need to facilitate the learning process, shifting away from a focus on simply communicating technical outputs (Table 12.1). The process of facilitation can include knowledge sharing through discussion and personal examples, but sometimes the more difficult task is to bridge dialogue between users' needs and possible solutions to ensure that all parties are given the opportunity to contribute to the engagement, and address the issue at large. When farmers can modify technologies to better meet their expectations, then the agricultural facilitators focus on supporting local learning, building quality relationships, and developing an iterative process that has "built-in" evaluation and reflection steps; e.g., how well did it perform for each farmer, what yields are being achieved, is erosion less than before? The foundation for this extension approach offers respect to each farmer as a co-learner in the change process. It engages the learner who is interested in understanding about principles rather than set recommendations. It extends the learning platform to all attending, including the "teacher." An outreach process to address information or technology gaps needs to be approached from this "inside-out" view. The end-users are offered a chance to provide input into the development of the program, and collaboratively improve the results.

A client-oriented extension approach has been criticized by those who contend that this process is too time and resource-consuming, and difficult to implement. Issues have also been raised about equity, as questions arise about who is "at the table" to set locally defined priorities. It is challenging to ensure access to all community members, and to negotiate the diverse agenda of multiple stakeholders. (See Chapter 10 for further insights into equity and access issues.) There are often differences in perspectives amongst community members, NGO staff (who may be acting as facilitators for farmer organizations), extension advisors, and other educators. Some community members may value longer-term returns, such as soil improvement, while other community members—perhaps at the edge of survival—may necessarily focus on immediate returns. Concerns about shifts in labor requirements may vary with agricultural responsibilities and priorities, depending on gender, age group, and economic status. But at a wider perspective, respect for local knowledge, culture, and traditions are of paramount importance when facilitating negotiations for a community-led extension plan. Bringing communities to the table as a directing body is difficult to do, with the required sensitivity and insight into appropriate protocols. A factor often overlooked is ensuring that all community members have the means and opportunity to come to the table, and to engage equally in the planning process. Too often it is the chosen few who are popular with extension, or have a greater voice, who are informed of the opportunity to share ideas and develop a collective plan. Participatory approaches attempt to bring all together, such as through the Participatory Extension Methodology described by Chambers (1994a), encouraging all to attend and then create subgroups of the attendees based on differences such as age, marital status, employment type, or whatever differences are pronounced of that particular group.

ENHANCING CLIENT-ORIENTATION AT DIFFERENT SCALES

Regardless of the scale of operation, extension must address local aspirations set by the end-users and governing bodies. At a district-wide level, this is a difficult task, given the diversity of people, expectations, and resources typically being addressed. This is a major reason that NGOs, and NGO partnerships with public and private sectors, have emerged as globally significant, and have been successful in promoting community development with locally-based values. Many nonprofit organizations target communities rather than regions, and have achieved notable successes in rural development, including areas where public institutions have failed to deliver to a wider audience, or scaling-out as well as scaling-up to effectively capture a wider audience. Despite the values of NGOs serving as technical outlets and development promoters, there are challenges inherent in such NGO-led developments, including a potentially narrow scope of operation, or changeable priorities which may be due to the technical knowledge available within that NGO, or the source and conditionality of funding. For example, a specific target group may be the focus of an NGO (e.g., children under five or widows), or they may opt to focus on a particular technical area (e.g., agroforestry or nutrition), rather than development as a whole. Additionally, the NGO may only work in one district, or a limited number of communities. This narrow focus created by NGO's can cause communities not served to become resentful while served communities feel privileged, often resulting in less than favorable results. Regardless of which organizing body leads development, there will always be drawbacks, but maximizing the outreach and providing an increase in collaboration across government and private sectors can lead to reaching more people (Table 12.1). The question is, "How many people is enough?" When you are one of the persons not included, it is not enough. Developing approaches that offer information exchanges and encouragement to engage in farmer-to-farmer approaches can help address the need to reach more people with a wider coverage. This approach is also one of the few ways to achieve sustainable extension outcomes, and improve transparency in policy and objectives. Actions such as these are built on and support civil society.

A number of innovative examples are explored here, addressing the conundrum of how to meet local needs at different levels, and in various scenarios. These include integrated projects that expand over time, as well as more targeted, market-linked approaches (Table 12.2). An example of the former is a Malawi community fuelwood tree project that linked indirectly to the private sector, while focusing on community-level natural resource management (see Box 12.1). The tree project's goal was to offer

TABLE 12.2 **Innovative Outreach and Scaling Approaches to Support Agricultural Knowledge Dissemination**

Agriculture Knowledge	Technology System	Strengths	Challenges
Time sensitive market information and pest monitoring	Cell phone text or audio	Timely	Requires infrastructure, mobile phones, and fair access
		Reach a large audience	
		Can be made regional specific	No way to check if user followed through
		Can offer feedback by phone text	
General information that may be culturally sensitive (STD prevention)	Radio drama broadcast	Entertainment value reduces tension	No way for feedback or questions
		Many can listen on one device Affordable and familiar	Seen as a casual innovation, so is it used to learn?
		Strong country-wide infrastructure Easily rebroadcastable	Must meet many levels of knowledge
On-site analyses of crop and soil health	On-site soil test kit	Increase contact/ access to SHF	Difficult to reach a large number of farmers
	Hand-held device for diagnostics of plant health	Provides immediate feedback on soil health.	Diagnostics may be expensive and kit supplies need to be replenished
		Farmer and extension can discuss observations and ask questions	Technical expertise needed—solid background to answer questions
		Easy to get feedback and revisit for follow-up	
Simple messages and campaigns in support of behavioral changes	Screen print media (tshirts, cloth, posters)	Popular to wear art	Need graphic art work
		Many people see it	Slow to be available (comparing) High price/message
		Repeat views, reinforces message	
Deliver inputs with message	Voucher system with technical drawing (cartoon like sketches)	Can be used for the poorest of the target population	Need a good graphic artist
			Technology messages that can be communicated through drawings

BOX 12.1 Supply and Demand for Fuel-wood Trees in Malawi

In Malawi, as in many developing countries, rural families depend on wood for cooking and heating. Deforestation and soil erosion are of growing concern in the populated areas of southern and central Malawi, as populations increase and farmers seek larger land holdings to farm. In 1996, the University of Malawi's Department of Rural Development initiated a survey that documented the limited supply versus demand for firewood in the rapidly growing capital city of Lilongwe. Community clubs were formed to support fuelwood tree production. Linkages with extension and local businesses were established from the onset of the project, including financial support from the Tobacco Exporters Association of Malawi (TEAM). The tobacco industry relies on wood to cure burley tobacco; thus, there is a consciousness of the need for trees in the countryside from the environmental and economic perspective. Rural and urban residence rely on wood for cooking and heating. Thus this limited supply is in high demand.

University lecturers hired students, who gained real-world experience by working with the farmers' clubs, and with extension educators of the National Agroforestry team. The clubs received education through training sessions and farmer-to-farmer visits for information on performance of tree species and seedling establishment techniques. TEAM provided long-term support for the project, including funding for the local collection of seed from superior trees. The Malawi chapter of the Rotary Club supported these efforts by providing some economic support to pay the students, and participated in community field days, further empowering the participating community members. This supported project-growth from three farmer clubs in year 1, to 25 clubs by year 5, reaching over 1200 farmers. Participating households each planted an average of 100 trees, and over time the project has become integrated into the country's extension program, offering Malawians throughout the country the opportunity to learn how to establish their own wood lots and conserve local tree seeds. This project continues today, supported by the National Extension System.

An impact assessment found unexpected benefits from educational opportunities associated with the project. These included experiential training in participatory extension for agricultural university undergraduates who participated, and it expanded primary education for youth who collected seeds and sold them to the club members, as they were able to afford school fees. Environmental education was enhanced on the role of trees in biodiversity, soil, and water conservation as relevant, at the community level.

communities a way to produce trees to reduce dependency on indigenous forests, providing a renewable source of firewood, and to offer a means for families to earn income.

The sustainability of the Malawi Tree Project was ensured through the involvement of multiple stakeholders from the beginning, to plan, implement, and adjust as needed. Farmers' feedback was ensured through interview surveys. Results were shared with educators, community leaders, and agribusiness organizations (TEAM) to ensure continuation of support and recognition of the value to extend this type of effort beyond the initial project area.

Multiple links with local businesses can be developed through solicitation of financial support and seeking management advice from a business community service organizations, as described in the case study. In this example, a cash crop with an environmental impact (tobacco on fuelwood trees) was linked to a business organization (TEAM) that contributed to community-led, sustainable resource management. Initiated at the agricultural university, over time this became a joint venture between the Ministry of Agriculture and a private development organization. The communities with more vulnerable landscapes were targeted first, but gradually all communities interested were offered the chance to invest in trees for fuelwood and other purposes such as poles, selling firewood, and soil conservation. The initiative continues today throughout the country, supported jointly by a private development group promoting ecological agriculture with complementary extension outreach by the Ministry of Agriculture and Forestry.

When natural resources are limited and in great demand, conflicts can arise due to different interests and priorities. This was the case for the Malawi Tree Project, in a few of the farmers' clubs. The selection of tree species for village nurseries brought out different agendas amongst the participants. For example, some village chiefs were interested in promoting a single species for production of poles to sell. Other community members were interested in multiple species to address a range of needs, from fuelwood to poles, soil fertility, and fruit production. To resolve this issue, facilitation of community discussions and an evaluation process were undertaken each year, and the results shared with all stakeholders, especially with the participating farmers. Sharing this information promoted a wider understanding of individual and group objectives and opportunities. These strengths of the project enhanced long-term success, and demonstrated how extension can support scaling-up through attention to conflict resolution and communication, in addition to addressing technical needs.

The market-value chain (A value chain is a systematic approach to integrate every step of the process, from field to market, through production and processing for sale of a product) approach is another innovative means to form public–private partnerships and address all steps essential to complete the process. This is a systematic approach to integrate every step of the process, from field to market, through production and processing for sale of a product that has been highly successful in linking specific groups of smallholder farmers to market opportunities. This approach is gaining popularity among farmer groups and development coordinators, as success is realized in a more sustainable and comprehensive way to move product. In Zambia, extension from private and public sectors have supported smallholder production of paprika as an export crop (paprika is used as a natural food colorant); see Fig. 12.3. Support came in the form of

FIGURE 12.3 Private extension crop advisors work with University staff to support paprika production.

technical guidance, low interest loans for purchase of seed, and inputs and facilitation to establish postharvest stations for grading, drying, and shipping paprika for export. This project was successful in its first 10 years, but then due to the development of cheaper markets the buyers "moved on" to a cheaper source. This demonstrates the importance to continually evaluate the product and service offered to help ensure its continued value, often requiring on-going evaluation and modification of product to maintain and even expand the markets.

In Southern Malawi a seed producing area used a market chain approach to produce and sell certified seed of modern varieties of bean and pigeon pea. In this example, farmer groups were supported through NGOs, researchers, and private enterprise collaborations. Education in production and business techniques, on-farm research, and market information was provided to assist farmers to tackle this market niche (Box 12.2). Often the challenge is to identify and engage all the partners to fill the links in the value chain, while addressing the needs of a dynamic global market.

DEMAND-DRIVEN MODELS

Centralized and bureaucratic approaches to extension have been critiqued as lacking in flexibility, and in responsiveness to farmers. Experiments in new approaches for extension to improve responsiveness include an emphasis on decentralization, and a "demand-driven" structure. These are occurring in various countries. The village extension system of Laos demonstrates this approach, as described in an interview with Mr. Somaxy Sisanonh (Reported in the BeraterInnen News, January 2004. See http://www.lbl.ch/fileadmin/10_International/PDF/RDN/RDN_2004/BN_1-04_The_Village_Extension_System.pdf (2/16)), the director of Central Extension and Training

BOX 12.2 Local Seed Production Has Markedly Improved the Livelihoods of Farmers in Chingale, Malawi

Producing seed—whether certified or quality declared—requires training in production, harvest management, seed selection, and storage to meet quality and quantity standards. Seed was a high value product for Chingale farmers working with an NGO (World Vision), and marketed to government and NGOs interested in high quality legume seed, which is often not available from the formal sector. World Vision initiated training in farmer empowerment and business education in the late 1990's. Partnerships were developed with national and international agricultural research institutes, and private sector grain legume marketers. Farmers gained knowledge in seed production techniques and access to new varieties. By 2003, Malawi farmer groups from Chingale had marketed 30–50 metric tons of legume seed annually, allowing these entrepreneurial farmers to build modest houses, and upgrade thatched houses with tin roofs. This collaborative effort with farmers is similar to the work of Setimela et al. (2004).

Development in Laos. "Through this system, it is the responsibility of village leaders to organize extension and choose experienced farmers to be extension workers who are supervised by village authorities. These village extension workers address the topics of greatest interest to local households, whether those interests are livestock, crops, or another agricultural specialty. The responsibility of the Laos government extension service is to provide technical backstopping and to facilitate networking of village extension workers in order to promote the spread of innovations." Many extension groups favor this approach across the world; it is just that the roadblock is often effective implementation. This approach, like the others discussed in this chapter, has challenges that require more time, greater training of extension workers, and typically more capital up-front; all often limiting factors in international development, unfortunately. Perhaps these approaches are more costly, but they empower stakeholders or farmers with the knowledge to understand how things work, not just how to do them. The saying, "knowledge is power," describes how the person, once referred to as the learner, now the experimenter, can own their ideas and approaches as they gain understanding of how a system works. They can take the system and modify it to function under their circumstances, developing a sustainable implementation of a technology. Despite the additional time and cost often required by this extension-approach, it offers the added value of empowerment to the end-user. Not only can they modify a technology to function under unique circumstances, but also the farmers can be empowered to embrace other challenges (future), and have the confidence to adjust technologies and systems to serve their needs.

Another example of the demand-driven approach was initiated by farmers insisting on their needs being addressed to obtain affordable

BOX 12.3 Farmers Promote Use of Waste Water for Irrigation in Pakistan

Today, in Faisalabad, Pakistan, waste water is widely used for irrigation by smallholder farmers. This was not always true, but farmers formed a committee to address the water shortage and teaming up with health officials, found a solution. Naturally, this was a concern for public health and safety when the farmers suggested using waste water on food crops. Effluent (treated waste water) from canals was in large supply and low in salinity and provides some nitrogen to the crops. and appeared to be more affordable. The cost/ha/irrigation of canal water was about $25, in contrast to $10 per season/ha to irrigate using waste water; water that was lower in salts and high in nitrogen. Groups of farmers and public health leaders collectively formed the Learners Alliance to bring stakeholders together to discuss options for alternate water sources and, collectively, test waste water outlets, address water quality regulations, and understand water management challenges. This alliance provided a venue to integrate farmers' needs and concerns, while addressing health risks to people and animals.

This initial group was the impetus to motivate government officials in health and agriculture to investigate the safety and feasibility of using waste water that was readily available and affordable to farmers dependent on water for irrigation. Today, a majority of the farmers in this province irrigate with waste water that is tested periodically for safety. This system allows farmers to grow three crops instead of one crop per year. Since the water is lower in salts and higher in nitrogen, higher crop yields are achieved and water demand by crops is met (Clemett and Ensink, 2006; Weckenbrock et al., 2011).

water for irrigation. In Faisalabad, the third largest province in Pakistan, the farmers that depend on irrigation found that waste water was superior to chemical-treated water in terms of quality for their crops and cost. The preferred, untreated, water provides nitrogen to the crops, and contains less salts than treated water, while costing less since it is effectively using a process to manage a "waste-product". Farmers teamed up with health leaders to organize and seek change (see Box 12.3).

Another example of farmer-driven demand is in Uganda, where over half the country is involved in a bold initiative to reorganize their extension service (see Box 12.4). A central aspect of the Ugandan demand-driven extension system is the aggregation and expressed need of local people. What is the process that a farmer's demand is articulated, who facilitates it, and how are the identified knowledge gaps prioritized? Government extension, NGO facilitators, and farmer organizations are the key players involved in facilitating the articulation of farmers' demands and priorities (Esbern, 2004). There can be conflicting expressions of farmer demand, where local priorities interpreted by one group may be interpreted differently by another group. Furthermore, a process for regional aggregate demand requires prioritization by multiple local farmers' groups who request technical information and

BOX 12.4 Demand-driven Advisory Services in Uganda

Uganda has launched institutional reform in provisioning of services to limited-resource farmers. Local farmer groups are involved in contracting out information requirements, with the goal of integrating demand and supply. This radical reorganization of extension is called the NAADS. A review was conducted in Soroti, one of the first districts where NAADS was initiated (Friis-Hansen, 2004). The number of farmers reached by NAADS was impressive, and many had made significant educational and economic gains. The study also highlighted the importance of earlier investments in farmer education in the district, most notably farmer field schools (FFSs). The NAADS were shown to have been most successful in meeting the needs of market-linked production systems.

A list of guiding principles developed by the government of Uganda NAADS program can be viewed at http://www.naads.or.ug/files/downloads/The%20NAADS%20Act%202001.pdf. These guidelines include a commitment to change extension services across all sectors. Information is sourced from private and public advisors, whoever can best fulfill a local contract for extension services. Priorities generated by farmer forum groups are set at parish levels, and then at subcounty level. The NAADS have undertaken this ambitious experiment in reform, including significant reform of current extension services, decentralizing of funds in some cases, and “building in” a demand component to extension services. Success has been variable, and critiques include the lack of clear guidelines on how to organize and document local priorities. NAADS describes their successes as being due to working directly with families to help them engage in a self-identified farming enterprise. Through the secretariat funds, farmers are given opportunities to request educational materials and technical guidance to establish their business. This is a notable value chain-linked approach requiring technical and tangible inputs, and thus is not appropriate for all households (some are in a better position to take advantage), and local community goals may not always be coherent or in agreement, according to a recent review by NAADS on this approach (NAADS, 2013).

guidance (Obaa et al., 2005). Unfortunately, this initiative has led to dissatisfaction among some groups that have found the prioritization process to be slow, cumbersome, and too market driven.

Critiques of this process focus on how to speed up the priority setting process and improve flexibility. Discussion in national and international forums has also centered on the prioritization of cash crops and livestock, which may have led to bypassing some subsistence cropping systems that a majority of the rural people are dependent upon for their personal food supply. This transparent process of critique and engaged discussion at many levels showed strong commitment by Uganda’s National Agricultural Advisory Service (NAADS), which has led to a process of continual improvement. As noted by Naidoo (Bashaasha et al., 2011), to effectively match public services to individual preferences there is a need for increased accountability, fewer levels of bureaucracy, and better knowledge of local costs. Some argue that decentralization of services such as extension removes structure, which invites corruption due to lack of supervision and accountability, or perhaps the difficulty of demonstrating accountability accurately with the many players at the table needed to facilitate the process.

A challenge in developing more demand-driven extension is that many farmers are not familiar with articulating demand or their needs, and have little political clout so they do not feel "entitled" to express these needs. There has been little to no precedence for this type of farmer engagement with extension. This is a clear problem in the on-going experiment with demand-driven extension such as in Uganda (see Box 12.4). Indeed, it is vital to acknowledge that agricultural information often does not reach many farmers, as resources are limited on the side of over-stretched public extension staff and many never meet with the majority of their clients. At the same time, farmers face severe cash and time constraints, and are unable to pay for advisory services. Local payment is suggested for extension services is intended to promote sustainability. But, the very poor, who face cash and resource constraints and are on the brink of survival, barely managing to purchase seed, cannot consider hiring extension workers. The question remains how to provide support for farmers who may not have the time or resources to participate in educational meetings, let alone to pay for services.

Production of cash crops for local, regional, and international markets is one pathway that has been used to generate funds to support technical advice, often linked to the market's expectations, such as variety type or meeting packaging requirements. For farmers with limited market access, and those with few resources to invest in cash crops, a publicly funded mechanism such as a voucher system may be the most logical and beneficial approach to ensure this sector of farmers has access to inputs. Coordinated action and cooperation among farmers encourages those with more to assist those with less. This approach may be one of the most viable means to aggregate demand, identify priorities, and improve extension services to a wider range of small-holder farmers, especially in extreme rural areas (Leeuwis and Van den Ban, 2004).

FACILITATION OF LOCAL CAPACITY

Building capacity through adult education around agricultural development challenges is at the foundation of extension. Opportunities with private, as well as public sector institutions can enhance local capacity, but require personnel engagement. The modified AKIS framework shown in Fig. 12.2 illustrates the diversity of organizations that can be involved, but in all cases attention to building human resources and education is key. An example was presented earlier in Box 12.1 of university lecturers in Malawi collaborating with extension educators and private sector agroindustry to support local

FIGURE 12.4 A youth club is planning how they will plant the trees in a school wood lot in Bunda, Malawi. The original project was not focused on youth but this group of young men sought out the program leaders and requested to participate and have their own wood lot to help offset their school-fees.

villagers in learning how to address fuelwood needs and resource conservation through agroforestry. The holistic approach has ensured sustainability of the project, with close attention to provide educational opportunities to all participants. This was a popular program, serving families that depended on the sales of firewood in the capital city, 15 km away. Fig. 12.4 (Bunda youth) shows a group of young men insistent on participating in this project. The program did not intend to address youth, out of concern they would participate in lieu of attending school. Women formed clubs to grow trees for their home use and to supplement their income (Figs. 12.5 and 12.6), working collectively to share the work load required to grow the seedlings. Trees were large enough for harvest (coppiced) after 2 years of growth (Fig. 12.7).

Tree varieties were selected that grow quickly in that area, have relatively few disease problems, and have moderate burning qualities. The fact that this project is integrated in the National Extension Program and continues even in the most remote areas of the country demonstrates the continued demand for firewood, and the need to grow trees to conserve remaining indigenous trees.

ACTIVE LEARNING

Building an environment for active learning is one of the more innovative pillars of extension. For this to occur, it is important to fully respect the local knowledge of stakeholders, and to realize that all participants face multiple time demands. Maintaining this perspective will support the building of

FIGURE 12.5 One of the 15 Community Fuel Wood Tree Clubs. This women's club choses tree varieties to grow in their own wood-lot. The seedlings were grown in a cooperative way, collectively building the fence to protect from goats and sharing the workload for gathering compost and daily watering.

FIGURE 12.6 Club members share the work load to care for the tree seedlings. They use the same technique to start tobacco so it was a familiar practice for them.

FIGURE 12.7 A tree club member presents her fuel-wood lot (*Senna siamea*), proudly displaying the growth attained in only 2 years.

quality relationships with all, from start to finish. Experiential learning builds on indigenous knowledge, promotes science-based education, and engages participants in testing research questions. This approach reinforces principles and engages farmers in discovery.

The FFS is a form of extension promoted around the world to support discovery learning. Farmers are encouraged to observe the natural world, often within the confines that relate to their priorities and resources, and conduct experiments in their own fields. Insect and plant interactions were the initial focus of FFSs, with farmers participating in weekly educational sessions and testing principles through field studies. As with all outreach approaches, there are various levels of stakeholder engagement, depending on who is leading or facilitating the group. Ideally, farmers are not only given the opportunity, but also encouraged to engage in trial, discussion, and modification of approaches and technologies on offer. This approach requires a more concerted effort by the educators, and thus a greater time commitment. With demands by programs, organizations, grants, and projects, time

BOX 12.5 New Directions for Farmer Field Schools (FFS)

FFSs train farmers in biological principles and other principles critical to human development, and empower them to design integrated crop management strategies that are relevant and specific to their farming practices. An exciting new development in FFSs involves linkages with primary education in Southeast Asia (see http://www.communityipm.org/down-loads.html). The Rural Ecology and Agricultural Livelihoods (REAL) program was initiated in Cambodia, Thailand, Vietnam, Bangladesh, Laos, Indonesia, and the Philippines, through the cooperation of Education and Agriculture Ministries (Praneetvatakul et al., 2007). At the core of the REAL approach is the student-centered study of local agriculture and rural livelihoods through real-world experiments. Information collected in rural environments is used as a basis for integrated, activity-based learning about mathematics, science, art, and culture. It facilitates intergenerational learning, and creates a bridge between community members, teachers, parents, and children. If ecological literacy is at the heart of a relevant curriculum, as claimed by educational theorists such as Orr (1992), then a REAL approach shows how ecological literacy can be implemented. As explained by Chutima, a fifth grader from Central Thailand, participating in an IPM program in her school gave her the opportunity to gain knowledge about the life-cycles of insects, and the skills required to follow environmentally sound practices in vegetable production (Bartlett and Jatiker, 2004). Most importantly, she learned how to learn.

is often a limiting factor, thus the educator is limited in what can be offered to the participants or the number of farmers that can be reached. The Food and Agriculture Organization (FAO) has long considered itself the primary implementer of FFSs around the world, but there are additional approaches to this outreach system. This approach is detailed by FAO at http://www.fao.org/ag/ca/ca-publications/farmer_field_school_approach.pdf.

Active, inquiry-based learning promoted by the FFS approach is highly suited to the knowledge-intensive nature of adapting farm management technologies to local conditions. Sustainable agricultural practices, in particular, are supported by an enhanced understanding of biology, as noted in Chapter 5 of this book. Initially focusing on integrated pest management, the growth of the FFS movement has led in surprising directions, with curricula as diverse as living soils, livestock health, human nutrition, and learning about scientific approaches. From Southeast Asia there are exciting examples of synergistic collaboration between FFSs and primary education. The future of agriculture is in the hands of the next generation. Providing experiential learning opportunities in farm settings is an important investment to reach the hearts and minds of future farmers (see Box 12.5). The FFS approach to engage farmers groups in active learning has also been criticized for its high costs and required human inputs. One needs to consider the approach that FFSs use to encourage learning. The person providing the guidance is functioning as a facilitator, not a teacher. This person encourages farmers to learn through understanding, questioning, and testing the procedure or technology. Essentially, many of the technologies discussed in FFSs have been "taught" to farmers by educators through a step process. The approach used in a FFS is not explaining HOW to implement a practice, but to show the farmers how they can investigate whether the technology is right for their system (Larsen and Lilleør, 2014). This is a life skill that can be learned in a FFS setting, offering greater value than learning a single technology and once learned can be used in any situation requiring a "feasibility assessment" by the end-user.

The overall goal of a FFS approach is that the participating farmers take what they have learned and share it with neighbors. Not so much how to do something but using a different approach to address a challenge by seeking ways to resolve the issues, learn how the technologies work, and then modify them to remedy the problem. With this approach, it is not the teacher who is responsible for idea and knowledge dissemination, but the farmers who participate in FFSs, learning how-to systems and technologies work, and modify them to work under their circumstances. This difference in approach leads to a greater number of community members impacted through the "grape vine" effect.

A typical FFS involves a significant time commitment on the part of farmers, and a talented facilitator who has strong biological training, as well as understanding of active learning techniques. This level of educational investment is not available through many extension systems, but where it is, there is evidence that the return on the investment is multifold and long-term. In Uganda, the experience with NAADS advisory services was initially successful in regions where FFSs were first initiated. This provided a large number of educated farmers who were effective at identifying knowledge gaps and participated with NAADS in agricultural development (Friis-Hansen, 2004).

SCALING-UP AND OUT

A primary goal of agricultural advisors is the generation of knowledge to serve a wide audience, but the issue remains of how to scale from a small number of beneficiaries to many. Or from a farmer-led perspective, how can we support local change at many locations, and still meet individual preferences? There are trade-offs here, as participatory engagement and extension in one area requires time and resources, often exceeding program capacity. Consequently, there needs to be a change in mind-set by program implementers and donors of what is required for successful technology transfer and adoption by the end-users. Teaching an approach or technology will create awareness, but will not ensure adoption. Adoption can be achieved only when the end-user has invested time and has experience of how to use and modify the innovation, as noted by Anandajayasekeram et al. (2007) when considering if this approach will replace classic extension in Kenya.

Farmer organizations can play a key role to enhance the effectiveness of extension efforts to reach a wider audience and be more effective.

Information and communication technologies can also play a role. There are mass media and innovative approaches using cell phones that appear to greatly impact the ability to communicate to farmers and for farmers to easily obtain information that can promote economic opportunities. A recent study by Aker and Mbiti (2010) indicates that nearly 60% of the population use (own or have access) to a cell phone in sub-Saharan Africa. An estimate of 50% of rural individuals share access to a phone, and of course the cell phone capacity greatly varies. But phones have become more affordable, solar units are entering the market, and there is more competition in many countries, making it affordable for many more. Aker and Mbiti (2010) point out that while farmers have great access to information, the infrastructure to support this information needs to be in place. For example, a farmer calls various markets and finds one that is paying more for seed, but is unable to feasibly deliver the grain because there is no passable road. However, another value for farmers is that they have gained increased access to information through cell phones that can improve their livelihoods, such as invitations to extension meetings, notification when a certain pest is emerging so the farmers begin to scout their fields for that pest, or the farmers can provide yield data the day it is taken by sending it to the researchers as a text, thus increasing data accuracy. Additional benefits noted in this study, that are not as dependent on infrastructure and can improve one's life, include personal safety, ability to receive or send money, and even a way to learn to read, and practice by sending texts to friends and family. The cell phone offers many more farmers access to information, and a convenient and affordable way to inform many, at the same time. This is a true asset to promote scaling-out. But now we now have to connect the pieces together to maximize its value.

Scaling-out requires many approaches and partners working in accord. Table 12.2 provides examples of scaling-out approaches for dissemination of agricultural information, and presents challenges and opportunities associated with each. An objective they have in common is that the intended users gain relevant knowledge that is accessible. Consideration of the delivery of the messages is important, including the entertainment value. Engagement will aid audience focus, and retention of the information. Social media is growing rapidly in importance, although cell phone penetration is not universal. There are differences by gender and age in terms of cell phone access that should not be overlooked. A simpler technology that provides messages to many is in the form of radio dramas. While radio dramas are a popular form of entertainment and learning, the ability to engage with the individual is lacking, so there is no way to check if the listeners interpret the information correctly. Because of the lack of ability to identify the individual, there is not a way to conduct any follow-up. Perhaps using cell phones by members in the audience to evaluate message effectiveness is a step in the 21st century direction. Cell phones are becoming an important media through which to provide SMS (text) "real time" market information and technical advice. However, the lack of supporting infrastructure is a real concern. For example, if a farmer uses her cell phone to receive the latest market prices and makes business decisions accordingly, the market prices delivered to the phone via text must be accurate. Additionally, internet connectivity is highly unreliable, as is cell phone coverage in some areas. Coverage and access is improving for cell phone connectivity and price, expanding opportunities to connect with farmers, markets and even health-care providers.

Another outreach approach being explored involves mini-projectors that operate on battery and are solar rechargeable. Recent technology is making it feasible for extension and communication teams to create simple videos, using local actors to discuss and act out an extension message, such as on the value of orange-fleshed sweet potato for family nutrition and food security insurance. The acting quality may be variable, but community members enjoy an "evening show" that features neighbors. The discussion that follows provides a way to clarify messages and start a conversation in the community (Cai et al., 2015).

Scaling-out technologies can be supported by extension workers, government, and NGOs, through improved communication technologies, but still the most important point is that the extension message is relevant to the user, is achievable and at least useful in some way. The ratio of extension workers to farmers is lower than ever, often due to budget shortfalls and increases in populations. Such technologies as the cell phone to maximize outreach capacity are valuable to allow coverage, but it also means that extension workers need to maintain a level of knowledge to effectively use and explain the technologies. This new demand for professional development is costly and must be maintained on a continuous basis. I suspect this is another challenge to consider when integrating any new outreach tools in extension. The technologies used in the delivery can enhance the capacity to reach a larger number of stakeholders, which is extremely valuable to maximize coverage and even provide a convenient mechanism for follow-up, but all educators must be versed in their use, and they too must have access.

As farmers demand better service and needs change with new farming opportunities and challenges, extension workers need to adjust messages, approaches, and solutions to meet their stakeholder's needs and resources. This is a very demanding requirement during times of innovation, less predictable weather and climate, and growing populations making it critical that we work collaboratively if we are to realize benefits and not pitfalls.

There are also lessons to be learned from farmer-led movements. In Nicaragua a people-led movement was started to promote literacy. Community members who were literate helped their neighbors learn to read (Snapp and Heong, 2003). In Pakistan, farmers who needed water for irrigation began to use waste water, as treated water was not readily available and was expensive. A community action team, led by farmers was formed to address the questions, and now farmers rely on waste water that is tested for safety to irrigate their crops. Today nearly 80% of farmers in this region access waste water that has been treated at least minimally before it is used to irrigate their crops (Weckenbrock et al., 2011; and see Box 12.3). Another

BOX 12.6 Reaching Millions of Farmers to Reconsider Pest Management Practices

High rates of pesticide use in rice production are a significant concern in Southeast Asia. This motivated a team of entomologists, extension advisors, and public media specialists to improve farmers' understanding of pest dynamics. Initially, the project surveyed farmers in Vietnam to document local perceptions about insect damage and management strategies used to control pests. These practices were compared to biological findings on pest thresholds for damage and rice–insect interactions. A contradiction was exposed between the view of entomologists that early leaf damage had minimal impact on yield, and a common belief of these rice farmers that insecticide sprays should be used to control early leaf damage. This led to costly, early season spray applications, and to secondary pest problems arising from indiscriminant killing of insects early in the season, including leaf folders, whorl maggots, grasshoppers, and beetles as well as beneficial insects that would help to keep many of these insects in check.

Radios are a primary source of information and entertainment in villages around the globe. To capitalize on this popular media type, a large-scale radio campaign was launched to expose these contradictions of rice-pest management. Actors used scenarios to challenge farmers to test the following "rule of thumb" on a small area of their field: "Spraying for leaf feeder control in the first 30 days after transplanting (or 40 days after sowing) is not necessary." Farmers were encouraged to try a simple experiment: compare a rice field section during the first 30 days following transplanting the rice with no insecticide application to a section with normal pest management practices. In follow-up workshops farmers shared their results. Over 85% of farmers who participated found the yields of the two plots were identical. The farmers' own experiments helped them to resolve the conflicting information, and beliefs changed. Thirty-one months after the campaign started, excessive insecticide use dropped by 53% (Escalada et al., 1999).

demonstration of farmers being proactive to improve farming and food conditions is farmers who worked with a scientist to understand pest management in their rice fields. The farmers tested some approaches suggested by a scientist to monitor pests and reduce pesticide applications. As a result, pesticide use was reduced by 50% on rice in Southeast Asia while still achieving pest management, impacting over two million farms. Millions of farmers in Vietnam and Thailand were reached with a message that challenged their current practice in pesticide application and encouraged their experimentation (Box 12.5) (Huan et al., 1999). These examples illustrate the effectiveness of a campaign based on in-depth listening and understanding of the audiences, including carefully targeted messages that engage farmers to test approaches suitable to their circumstances.

The learning cycle described in Box 12.6 continues today. Members of the rice-producer team have broadened their scope beyond insect pest management to also consider fertilizer and seeding rates. Research on integrated

BOX 12.7 Slow but Steady: Fuel-conserving Stoves

Niger is an arid country located in West Africa, in the Sahelian region. Firewood is the primary source of fuel for cooking in the rural areas, and collection takes up to 5 hours per day, per family. Stoves are made from three rocks or bricks that are covered by a locally-sourced clay stove reduce wood consumption by up to 50%, compared to an open fire. The stoves are made from local mud, which is also used to construct homes. The families constructed stoves with guidance from a Peace Corps volunteer and a local teenager who assisted with the project. This young man saw an unmet need, as families adopted the mud stove but sought technical assistance in order to seal the stove so it would last over the rainy season. Following construction, he would conduct a use assessment, and then offer to return to seal the stove with cement. He charged a small fee to seal the stove, offering a needed service and earning some income. He also followed-up with a postsurvey, and checked in with the family at the same time to ensure the stove was satisfactory. This provided district-wide sustainable support for the implementation of mud-stove construction. The steady growth of adoption of fuel-conserving stoves (mud and metal design) has spread to many other countries in recent years, showing that a consistent, long-term extension effort that meets a real demand can make a real difference. In Malawi, fuel-conserving stoves are being adopted in combination with a multipurpose shrub, pigeon pea, for a winning combination of food and homegrown fuel (Orr et al., 2015).

management of rice indicated that a cost savings of about US$85.00 per hectare was possible through judicious, coordinated reductions. This outcome was the genesis for a campaign called the “Ba Giam Ba Tang” or “Three Reductions.” Farmers across the Mekong Delta in Vietnam and other regions are testing the role of economics when they reduce rates for three inputs simultaneously on their farms. The pioneer of this multidisciplinary effort, IRRI entomologist Dr. K.L. Heong, pointed out in a recent interview “We should be training extension workers to communicate more effectively, to deliver correct information to farmers and to motivate them to evaluate it objectively. We can’t afford to leave pesticide education to those who profit by spreading misinformation about these chemicals.” (See http://www.irri.org/media/press/press.asp?id=79.)

Farmer organizations are one means to enhance sustainability, as such associations provide institutional continuity and, in some cases, financial support. Another way is through local entrepreneurs who provide technical knowhow, or act as an information brokering service. Examples include individuals who obtain training or develop a technical innovation, and then offer services to other farmers for a small fee. This is illustrated through a case study of mud-stove construction in Niger (Box 12.7).

Sustainable extension requires integrated social and technological development. An example comes from West Africa, where thousands of farmers

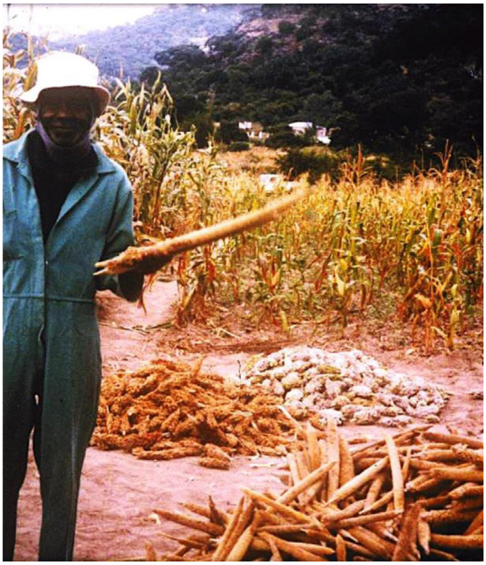

FIGURE 12.8 Targeting microdoses of 4 kg P/ha fertilizer to planting hills has greatly enhanced this farmers millet crop.

FIGURE 12.9 The inventory credit system "warrantage" has proved to be a successful institutional innovation in West Africa that reduces risk, enhances returns and insures credit access.

have adopted "microdosing" of fertilizer in sorghum and millet production (Fig. 12.8). This technology targets fertilizer to planting hills at very low rates, 4–10 kg/ha. It was shown to be technically feasible through a network of on-farm trials carried out across five countries (Hassane and Sidi, 2014). However, no farmer uptake occurred until extension and NGOs became involved in institutional innovations, most notably the "warrantage" credit inventory system (Fig. 12.9). These village-based grain banks support credit access and more reliable economic returns through sponsoring sales when grain prices are high. This has been critical to farmer adoption. What remains to be seen is how rapidly this social and technical "integrated innovation" will spread. Farmers continually assess the socioeconomic returns to agricultural technologies, and adopt, adapt, or disadopt technologies as incentives change.

Agricultural change is not only influenced by climate and biophysical resources, but, most importantly, by the economic and social context. These complexities require extension educators and development agents to identify ways to effectively engage with policymakers and other key actors in the social environment to support agricultural needs, and ensure they have the capacity to reach all levels of society. As discussed earlier in this chapter, access to a technology is only as good as the infrastructure that supports it.

CONCLUSIONS

Approaches and methodologies used to invoke changes are undergoing rapid change due to necessity. Slowly we realize that for development to be sustainable, it must be able to meet the individuals' needs. Historically, agricultural information often followed a technology transfer mode, with a linear flow of information from researchers to farmers. This was not effective at meeting the needs of poor farmers, nor did it take into account the complexity at local levels. In contrast, the emerging outreach models described within this chapter emphasize relevance and local capacity building. Notably, these are decentralized and demand-driven extension systems, where priority setting involves village leaders, farmer organizations, and market linkages. With this approach, the role of extension advisors is to act as facilitators and advocates, to catalyze innovations, and to develop local capacity and institutions. Farmers are being encouraged to engage in the process rather than be passively educated or informed. This approach requires the interaction of many stakeholders, including farmers, extension workers, traders, private industry, NGO advisors, entrepreneurs, and researchers, and a value chain for innovations. Furthermore, this broad vision of extension encompasses engagement with governmental regulators, policymakers, and members of the media to support this approach to change.

Effective agricultural change requires the courage to try new models and modes of operation, recognizing that one approach may work for a certain group or program, but not another. For this reason, often the most effective methodology is one that focuses on the goals and abilities of a specific group, and collectively identifies a feasible solution. Promoting rigid protocols to achieve a predicted outcome is seldom effective. An example of this is the recent push for farmers in many countries in Africa to adopt and practice Conservation Agriculture. The promotion of this technology initially followed a prescriptive farming approach that required changes with the perspective of all or nothing. In many cases farmers are still expected to implement each step as prescribed by the promoter, often an NGO or ministry extension provider. This delivery is often not successful in the eyes of the deliverers, since all steps were not established, as prescribed. This “all or nothing” approach is easier to teach and makes data collection easier but it is not feasible for many of the farmers to adopt each step as it interferes with their farming goals, such as using some of the crop residue for animal feed. As noted by Giller et al. (2009, 2012), extension of a technology requires close attention to farmers’ values, access to resources and social norms. Taking all of these factors into account requires attention to the entire agricultural knowledge and information system, and support for local adaptation and innovation. It may not be the simplest or tidiest approach, but time and time again, it is proving to be an effective way to improve farmer’s livelihoods and food security.

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Chapter 13

Climate Change and Agricultural Systems

Richard Lamboll, Tanya Stathers, and John Morton

INTRODUCTION

Climate change matters for agriculture, and *vice versa*. Agricultural lands occupy over one third of the earth's land area (Smith et al., 2008). Agriculture is a mainstay of many developing country economies, and millions of people's livelihoods. There is renewed attention to achieving global food security after the 2008 food crisis, but additional, multiple demands are being placed on agriculture. Beyond increasing productivity, food production, and food security, these include: promoting rural employment, value addition, growth and poverty reduction in developing countries; supporting nonprovisioning ecosystem services (e.g., water regulation, pollination); and now being resilient to climate change, while reducing relative and absolute contributions to greenhouse gas (GHG) emissions.

Since 2008, the issue of climate change has loomed much larger in debates on agricultural and rural development, and agriculture has featured more strongly in discussions of climate change. Agricultural and development organizations and rural communities across the developing world have started to acknowledge climate change, identify and analyze its impacts on their livelihoods, and to develop adaptation options which work in their specific contexts.

The Fourth and Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment Reports produced headline findings: on projected climate impacts on the world's major food crops and global food security; the multiple vulnerabilities of rural people in developing countries; the complexity of the impacts they are experiencing and will experience; and the profound difficulties of modeling them (Easterling et al., 2007; Porter et al., 2014; Dasgupta et al., 2014).

Agricultural Systems. DOI: http://dx.doi.org/10.1016/B978-0-12-802070-8.00013-X

Comprehensive chapters reviewing GHG emissions and opportunities for mitigation (Smith et al., 2007; Nabuurs et al., 2007; and most recently Smith et al., 2014a) have concluded that the agriculture, forestry and other land use (or AFOLU) sector is responsible for just under a quarter of anthropogenic GHG emissions. There are substantial opportunities for both supply-side (e.g., reducing deforestation, reducing GHG emissions from livestock), and demand-side (e.g., reducing food waste) mitigation measures, although there are also multiple barriers to implementation.

Climate change itself is not a new phenomenon. Agricultural and pastoral communities across the world have been adapting to such change since they began farming and herding livestock, but the anticipated rate and scale of change is projected to increase to levels that make autonomous adaptation very difficult. Developmental challenges are already considerable across much of the world, and climate change and increased variability are anticipated to compound these.

While mitigation actions are key for reducing the rate of GHG emissions, and thus the future rate of global warming, the inertia of the climate system means that no matter what emission reductions we make now, we are in an "era of committed climate change" (Field et al., 2014).

This chapter will explore agriculture and climate change, by reviewing projected impacts, the opportunities for mitigation and adaptation, and the importance of an innovation systems approach in responding to climate change. While much of the data and projections we review are global in nature, our focus, in line with that of this book, is on smallholder agriculture in developing countries, and most of the examples, following our own experience, are from sub-Saharan Africa (SSA).

CLIMATE CHANGE: DEFINITIONS, CAUSES, AND LINKS WITH AGRICULTURE

The IPCC (2014) defines climate change as "any change in climate over time, whether due to natural variability or as a result of human activity." The overwhelming consensus, confirmed by the IPCC, is that human influence has been detected in changes to many climate parameters, and that "it is extremely likely [IPCC reports use a systematized language to express the underlying evidence for, and agreement on a finding as a level of confidence, and to express the assessed likelihood of an outcome or result. The interested reader is referred to IPCC, 2014 (the synthesis SPM) footnote 1, and references therein] that human influence has been the dominant cause of the observed warming since the mid-20th century." The IPCC has further concluded that current warming of the global climate system is "unequivocal," and that many of the observed changes in climate since the 1950s are "unprecedented."

What is the process of anthropogenic climate change? While solar radiation passes through the earth's atmosphere, and warms the earth system, greenhouse gases (principally CO_2, but also methane and others) emitted by human activity (chiefly burning of fossil fuels, but also others, including agricultural activities; see Fig. 13.1) reradiate lower-wavelength radiation that would otherwise be reflected back into space, causing additional warming. This results in higher temperatures at the sea and land surfaces, changed patterns of atmospheric circulation, and a variety of changes in rainfall distribution, snowcaps and glaciers, storm intensity, and sea level.

The IPCC (2014) notes that "each of the last three decades has been successively warmer at the earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere (medium confidence)." At a *regional* scale, there is low confidence in the detection of changes in

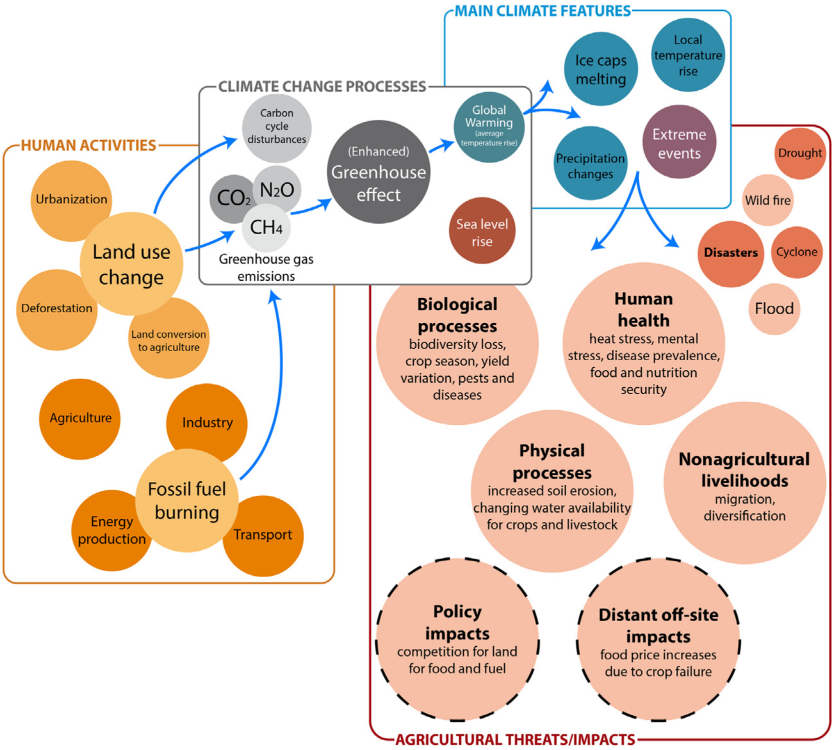


FIGURE 13.1 Climate change global processes and effects on agriculture. *Modified from GRID-Arendal. http://mrqawwasscience.weebly.com/uploads/1/0/8/5/10857298/_9233697.jpg?559.*

rainfall to date, but when considered at the fine-scale of countries, there is greater confidence in trends of increasing or decreasing rainfall, or shifting of rainfall patterns across the year. From 1900 to 2010 the global average sea level rose by almost 20 cm, and current sea level rise is faster than the mean rate during the previous two millennia. There is likely to have been an increase globally in extreme rainfall events, and concomitant floods, and in extreme sea level events such as storm surges.

Up to 2035, the global mean surface temperature change relative to the period 1986–2005 will likely be in the range of 0.3–0.7°C (medium confidence), but "near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and sub-tropics than in mid-latitudes (high confidence)" (IPCC, 2014). Beyond 2035, projected increases in temperatures, as reviewed in the IPCC reports, vary according to the scenarios in which they are modeled. These scenarios are now systematized into representative concentration pathways (RCPs), depending on the proportions of GHGs in the atmosphere they assume for the future. This depends on the extent to which the world's people and economy can reduce our net GHG emissions. The RCP 2.6 shows the effects of strong and effective mitigation policies, and RCP 8.5 the impacts of "business as usual," or continued fossil fuel use without mitigation (UK Met Office, 2015). For the period 2081–2100, the increase in global mean surface temperatures relative to 1986–2005 is projected to likely be between 0.3°C and 1.7°C for RCP 2.6, and between 2.6°C and 4.8°C for RCP 8.5.

Overall, global projections of temperature change mask regional variations which are profoundly important for agricultural system response. Projections for changes in precipitation also vary regionally, in complex ways, in both the near- and longer-terms. Warmer air holds more moisture, and therefore leads to changes in rainfall patterns. Uneven warming around the world results in shifts in weather regimes. Whilst globally temperatures are rising, some areas are experiencing increased rainfall, others decreased. There are changes in the scale and frequency of extreme weather, such as heavy rainfall, prolonged dry spells, droughts, and heat waves (Table 13.1).

Longer-term climate projections show serious implications for food production and food security globally, but especially in the tropics (Porter et al., 2014). Across developing countries farmers report, in the present and recent past, damaging changes in climate, especially shifts in the timing of rains, and increases in climate variability and extreme events. Scientific attribution of these to global processes of climate change remains, in the context of limited data and understanding of the processes involved, very problematic, but "the lack of documented impacts attributable to climate change should not be read as evidence for the absence of those impacts" (Hansen et al., 2015). There is therefore an imperative to assist smallholder farmers to adapt to the impacts of climate change, which in turn gives rise to an imperative to better understand adaptation.

At the same time, GHG emissions attributable to agriculture are growing. The per capita emissions of smallholder farmers in developing countries are negligible compared to those of citizens of the wealthier countries of the north. It is practically futile and ethically questionable to expect smallholder farmers to work to contribute to climate change mitigation—reducing the sources or enhancing the sinks of GHGs (Allwood et al., 2014)—without additional incentives. Those incentives are now emerging, including in the form of climate finance.

IMPACTS OF CLIMATE CHANGE

Observed and Projected Climatic Changes

Rising levels of greenhouse gases are having a warming effect on the earth's climate. There is high confidence that warm days and nights, and heat waves, will continue to increase across Africa, Asia, Latin America, and the Caribbean, but there is much less certainty regarding rainfall trends or incidences of heavy precipitation and dry spells (Table 13.1).

Temperatures in Africa are projected to rise faster than the global average, and these unprecedented temperatures are expected to occur 10–20 years earlier in West Africa than in the rest of the world (Niang et al., 2014). Under RCP 8.5, mean annual temperatures across the continent are expected to be $>2°C$ higher by 2046–65, and $>4°C$ by 2081–2100, compared to a late 20th century baseline. Precipitation projections are more uncertain than those for temperature. Projections suggest it is very likely that mean annual precipitation decreases over northern and southern Africa, while central and eastern Africa are projected to be likely to see increases in mean annual precipitation. Increased rainfall is expected in October–December and March–May seasons in east Africa, indicating a change to historical trends. There is less certainty regarding West African precipitation projections. Increased rainfall will not necessarily be beneficial, rainfall may become more variable and less predictable, and especially in East Africa projections of increased average rainfall are associated with increases in heavy precipitation events (and thus potentially destructive soil erosion and floods).

Asia is also projected to be very likely to experience warming, and precipitation increases are very likely at higher altitudes by the mid-21st century, and over eastern and southern areas by the late 21st century (Hijioka et al., 2014). The influence of climate changes on tropical cyclones is likely to vary by region, but future increases in precipitation extremes related to monsoons are very likely in East, South, and Southeast Asia.

Central and South America are also projected to experience warming (Magrin et al., 2014). Increased precipitation is projected for south eastern South

TABLE 13.1 Observed and Projected Changes in Temperature and Precipitation Extremes Across Selected Areas of Africa, Asia, Latin America, and the Caribbean

		Increase in warm days and/or decrease in cold days		Increase in warm nights and/or decrease in cold nights		More frequent and /or longer heat waves and/or warm spells		Increase in heavy precipitation		Increase in dry spell duration and/or dryness and/or area of drought	
		Obs	Proj	Obs	Proj	Obs	Proj	Obs	Proj	Obs	Proj
AFRICA	West Africa	↑ ~	↑	↑	↑	~	↑	↑	- ~	↑	~
	East Africa	~	↑	↕ ↑[1]	↑	~	↑	~	↑	↕	↓
	Southern Africa	↑	↑	↑	↑	↑	↑	~	~ ↑[2]	↑	↑↓
	Sahara	~	↑	↑ ~	↑	~	↑	~	~	~	~
ASIA	North Asia	↑	↑	↑	↑	↕	↑	↑	↑	↕	~
	Central Asia	↑	↑	↑	↑	↑ ~	↑	↕	~	↕	~
	East Asia	↑	↑	↑	↑	↑ ↕	↑	↕	↑	↑	~
	Southeast Asia	↑ ~[3]	↑	↑ ~[3]	↑	~	↑ ~	↕	~	↕	~
	South Asia	↑	↑	↑	↑	~	↑	~[4]	- ~	~	~
	Western Asia	↑	↑	↑	↑	↑	↑	↓	~	~	~
	Tibetan Plateau	↑	↑	↑	↑	↕	↑	~	↑	~	~
LATIN AMERICA AND THE CARRIBBEAN	Amazon	~	↑	~	↑	~	↑	↕	↑	↕	~
	Northeastern Brazil	↑	↑	↑	↑	~	↑	↕	-	~	↑
	Southeastern South America	↕	↑	↑	↑	↕	↑	↑ ~	↑ ~	~	~
	West Coast South America	↕	↑	↑	↑	~	↑	↕	↑ ~	~	~
	Central America and Mexico	↑	↑	↑	↑	↕	↑	↕	~	~	↑

Key: Symbol denotes the direction of the trend. ↑, increasing trend; ↓, decreasing trend; ↕, varying trend; ~, inconsistent trend or lack of data. The shading of the symbol denotes the level of confidence in the findings; red (underlined black in print version), high confidence; orange (dark gray in print version), medium confidence; blue (light gray in print version), low confidence. Obs, observed changes since the baseline period of 1961–90; Proj, projected trends for 2071–2100 compared with respect to 1961–90 reference period. [1]in Southern tip; [2]in southeast regions; [3]in Malay Archipelago; [4]in India.

Source: Adapted from Climate Development Knowledge Network (CDKN), 2012a. Managing climate extremes and disasters in Africa: lessons from the IPCC SREX report. 24 pp. CDKN, www.cdkn.org/srex; Climate Development Knowledge Network (CDKN), 2012b. Managing climate extremes and disasters in Asia: lessons from the IPCC SREX report. 24 pp. CDKN, www.cdkn.org/srex; Climate Development Knowledge Network (CDKN), 2012c. Managing climate extremes and disasters in Latin America and the Caribbean: lessons from the IPCC SREX report. 24 pp. CDKN, www.cdkn.org/srex.

America, the northwest of Peru and Ecuador, and western Amazonia, while decreases are projected for northern South America, eastern Amazonia, central eastern and north eastern Brazil, the Altiplano, and southern Chile. There are high uncertainties regarding the rainfall projections for Amazonia and the South American Monsoon System region.

Impacts of Climatic Changes

Changes in climate have caused impacts on both natural and human systems across the globe. Examples of relatively recent climate-induced changes to natural systems include: retreat of glaciers across East Africa, Asia, and the

Andes; reduced soil moisture in areas of China and the Sahel; and decreasing tree density in western Sahel and semiarid Morocco (Field et al., 2014).

Climate-induced changes to human systems are more complex to analyze because of their interaction with other socioeconomic drivers of change, and the dynamic, context-specific, and often rapid, responses which occur. Individuals within a community and different communities within one location will be affected in different ways by climate change as factors such as wealth, education, gender, age, class/caste, health, culture, location, population density, livelihood choices, and governance affect each individual's or community's vulnerability (Olsson et al., 2014).

Observed and Projected Impacts of Climate Change on Agricultural Systems

Some of the difficulties of attributing current trends in agricultural systems to climate change have been mentioned above. Smallholders' livelihoods typically involve mixtures of crops, livestock, and off-farm income sources interacting in multifaceted ways. Climate change will continue to impact simultaneously on many dimensions of smallholders' livelihoods, and understanding and projecting these dynamic interactions and outcomes is highly complex, and context-specific (Dasgupta et al., 2014). Additionally, as negative impacts start becoming evident, interventions usually rapidly occur to help address them which then interfere with long-term climate impact analysis.

Crops: most assessments and projections of the impacts of climate change on agricultural systems have focused on how yields of major food and cash crops in different locations will be affected. Most studies suggest that climatic changes have to date, and will continue to have, a negative impact on maize and wheat yields at low latitudes, but slightly less so for rice and soybean (Rosenzweig et al., 2014; Porter et al., 2014). Some studies suggest that in higher latitude and altitude areas there have been positive yield impacts.

Historical data analysis from African maize trials suggested that each growing degree day with an average temperature above 30°C led to yield decreases of 1% under optimal rainfall conditions (Lobell et al., 2011). The physiology of some crops, such as wheat, rice, barley, cassava, and potato (referred to as C3 crops) means they may realize some yield benefits as a result of the fertilization effect of increased carbon dioxide (CO_2) levels in the environment, while other crops such as maize, millet, sorghum, and sugarcane (referred to as C4 crops), whose physiology is less responsive to CO_2, are unlikely to realize any benefits.

A meta-analysis of the literature estimated an expected 8% negative yield impact by 2050 in both South Asia and Southern Africa, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane

(Knox et al., 2012). However, crop yield projection analyses are highly complex, and are often made using broad generic and oversimplified assumptions about farmer management, varieties, soil types, rainfall patterns, etc. Crops, varieties, and plant developmental stages differ in their sensitivity to changes in temperature and precipitation. In Uganda, cassava and sweet potato were found to be less vulnerable to projected climate changes, while sorghum, beans, plantain, maize, rice, and coffee, were increasingly vulnerable, with coffee (particularly the *Arabica* type) being the most vulnerable of all the focal crops (USAID, 2013). Changes in the timing and overall amounts of precipitation, as well as the incidence of extreme heavy rainfall events, radiation levels, and rising concentrations of carbon dioxide, will also influence crop development, yields, and survival. Alterations in climate also indirectly affect biotic factors such as diseases, pests, vectors, and weeds which interact with and impact on crop productivity. Interannual variation in yields is projected to increase (Porter et al., 2014).

Additionally, some projections suggest the potential crop land in developing countries will also decline by 110 million ha by 2080, and in SSA land suitable for double and triple cropping is particularly likely to decrease due to moisture stress, shorter growing periods, and increased variability (Fischer et al., 2002). Also, globalization and the marginalization of traditional agricultural systems has already eroded genetic and cultural diversity, which is important for breeding programs producing crops and livestock appropriate to the new conditions. Increased temperatures are predicted to result in further varietal losses, with serious genetic resource consequences for future environmental adaptation, associated disease and pest resistance, and other important traits (Thornton et al., 2009).

Production is only part of the agricultural cycle, and what happens at and after harvest is equally important, and can also be impacted on by climate change. Higher temperatures may: facilitate crop drying, but also increase heat stress during harvesting and threshing; lead to more rapid reproduction of insect pests and diseases on stored produce and higher carry-over of pests from field to store and between years; reduce efficacy of some grain protectant pesticides; increase risk of mycotoxin contamination, reduce safe storage and shelf-life periods and product quality (Stathers et al., 2013b). Postharvest losses of cereal grains in SSA are already estimated at US$4 billion/year (World Bank et al., 2011), and climate change will heighten the need to reduce unnecessary loss.

Livestock: climate change can impact on livestock in a range of ways including: quantity and quality of feeds; heat stress; water; livestock diseases and disease vectors; biodiversity; systems and livelihoods; and indirect impacts (Mader and Davis, 2004; Baylis and Githeko, 2006; Thornton et al., 2009; Morton, 2012). Different livestock systems (e.g., a mixed rain-fed system vs a landless monogastric-based system) will be affected by climatic changes in very different ways (Rivera-Ferre et al., 2016).

Food security: climate change-related global yield decreases and increased yield variability are likely to lead to an increase in food prices and the number of food-insecure people (Skoufias and Quisumbing, 2005; Bloem et al., 2010; Porter et al., 2014). Studies suggest projected changes in temperature and precipitation will lead to food price increases of between 3% and 84% by 2050 (Hertel et al., 2010; Calzadilla et al., 2013; Lobell et al., 2013; Nelson et al., 2013). Increased food prices will affect the many agricultural producers in low income countries who are already net food buyers, as well as other poor consumers who spend a high proportion of their income on food.

Health and other aspects: the health of the farming household, including the ability to work in agriculture, will also be affected by climatic changes, including temperature rises, floods, and exposure to infectious diseases (Sahu et al., 2013; Smith et al., 2014b). Increased food insecurity as a result of reduced crop yields will have numerous health impacts, including on child stunting (Nelson et al., 2009; Lloyd et al., 2011). The stress of increased food insecurity, disease, and migration can result in severe anxiety for afflicted households.

Climate change will also impact water resources, forests, and wild fauna and flora on land and in oceans, infrastructure, human migration patterns, trade, and tourism. Measuring impacts can be difficult, as many are things that are not normally given monetary values or traded, such as human lives, cultural heritage, health, and ecosystem services (Dasgupta et al., 2014; Adger et al., 2014). Impacts in the informal or undocumented economy may be very important in some areas, but are generally uncounted.

Direct and Indirect Impacts

The actual and potential impacts of climate change are often disaggregated by researchers into direct, indirect, and cumulative impacts. Direct impacts occur at the same time and place as the climate change, while the indirect impacts occur later in time, or at a more removed distance. Cumulative impacts are those which result from the incremental direct impacts added to other past, present, and foreseeable impacts, and may result from minor individual direct impacts which at the collective level become significant over a longer period of time. Examples of such impacts on smallholder agricultural households are given in Table 13.2. Most of these impacts have negative outcomes on smallholder agricultural households, highlighting how crucial it is that investments and policies which support them in adapting to climate change are prioritized.

Uncertainty

Numerous research studies discuss the potential impacts of climate change on different aspects of natural and human systems. However, it is vital to note that studies and models relating to the future are complex, and

TABLE 13.2 Examples of Direct and Indirect Impacts of Climate Change Likely to Affect Smallholder Agricultural Households

Direct impacts	● Increased uncertainty for planning and implementing agricultural activities; ● Increasing water scarcity; ● Increasing destruction of terraces, stream embankments, and risks of drowning from heavy rainfall events and floods; ● Reductions in crop yields and associated agricultural incomes; ● Change in crop pest and disease ranges; ● Increased difficulties in drying crops before storage; ● Loss of livestock due to water and food shortages, heat, and disease; ● Increased risk of heat exhaustion during agricultural activities and heat-related mortality.
Indirect and cumulative impacts	● Increased agricultural extensification into forests, wetlands, grazing and fallow lands, and associated loss of biodiversity; ● Increased seasonal and permanent migration amongst agricultural communities; ● Increased transformation and diversification of farming systems in terms of crops and varieties grown, crop: livestock mix, livestock types, etc.; ● Changes to postharvest practices for protecting and storing crops; ● Reduced food consumption and increased use of more climate-resilient food crops; ● Increased food insecurity, malnutrition, erosion of assets and inability to rebuild them, and shift from transient to chronic poverty; ● Increased food purchases by farm households, or food aid supply by governments or NGOs; ● Increased food prices; ● Disruption and transformation of socioeconomic structures; ● Unintended negative consequences of climate change policies, e.g., biofuel production and concern over food insecurity by mid- and high-income countries, leading to large-scale land acquisition in Africa and elsewhere; ● Increased stress, anxiety, mental illness, gender-based violence, susceptibility to infection, and malnutrition; ● Erosion of natural, human, and financial assets.

Source: Data from World Bank, 2012. Turn Down the Heat: Why a 4°C World Must Be Avoided. 106 pp. Washington, DC: World Bank; Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., et al., 2014. Food security and food production systems. In: Field et al. (Eds.). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 485−533. Cambridge and New York: Cambridge University Press; Olsson, L., Opondo, M., Tschakert, P., Agrawal, A., Eriksen, S.H., Ma, S., et al., 2014. Livelihoods and poverty. In: Field et al. (Eds.). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 793−832. Cambridge and New York, NY: Cambridge University Press; Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., et al., 2014. Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y. O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1199−1265. Cambridge and New York, NY: Cambridge University Press; Dasgupta, P., Morton, J.F., Dodman, D., Karapinar, B., Meza, F., Rivera-Ferre, M.G., et al., 2014. Rural areas. In: Field et al. (Eds.). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. WG II 5AR to IPCC, pp. 613−657. Cambridge and New York, NY: Cambridge University Press; Smith, K.R., Woodward, A., Campbell-Lendrum, D., Chadee, D.D., Honda, Y., Liu, Q., et al., 2014b. Human health: impacts, adaptation, and co-benefits. In: Field et al. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 709−754. Cambridge and New York, NY: Cambridge University Press (Smith et al., 2014b); Adger, W.N., Pulhin, J.M., Barnett, J.M., Dabelko, J., Hovelsrud, G.D., Levy, G.K., et al., 2014. Human security. In: Field et al. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. WG II 5AR to IPCC, pp. 755−791. Cambridge and New York, NY: Cambridge University Press. ISO, 1989. Hot Environments − Estimation of the Heat Stress on Working Man, Based on the WBGT-Index (Wet Bulb Globe Temperature). *International Standard ISO Standard* 7243:1989 E, 2nd edition International Organization for Standardization, Geneva, Switzerland, p. 16.

inherently involve multiple uncertainties. First, there are uncertainties around climate models, emissions scenarios, climate data, and assumptions. Second, different crops, varieties, crop stages, and livestock respond differently to changes in temperature and/or rainfall. The farm management practices, different crop or varietal mixtures, planting times, pest and disease incidence, soil types, etc., all affect yields, as does the degree of diversity amongst smallholder agricultural systems in any particular area. Factoring the interaction of all these aspects into crop models is extremely complex. Some models are factoring in the uptake of likely adaptation strategies, while others are not.

Climate change impacts will not be felt evenly, and will vary depending on the farming household's location, size and composition, crops, animals, water sources, assets, livelihoods, health, farming experience, service provision, neighboring communities, and networks (Dasgupta et al., 2014; Olsson et al., 2014). Interactions between the projected climate and the existing natural and human systems and their responses to climate and other drivers of change (e.g., rapid population growth, ecosystem degradation, urbanization, and improved access to education and health care) are extremely complex to speculate on. However, climate change is expected to disproportionally impact on many of the world's poorest regions, which have the least economic, institutional, scientific, and technical capacity to cope and adapt (World Bank, 2012). Climate change is occurring, and although there are uncertainties regarding precise impacts in a particular location, this is not a reason for inaction.

CLIMATE CHANGE MITIGATION AND AGRICULTURE

Agriculture is a significant cause of global warming, but it can also play an important role in contributing to climate change mitigation.

How Agriculture and Land Use Change Contribute to Greenhouse Gas Emissions/Global Warming

Agriculture, forestry, and other land use (AFOLU) activities lead to the emission of CO_2 (e.g., deforestation, peatland drainage), and non-CO_2 GHG emissions (e.g., methane (CH_4) from livestock and rice cultivation, and nitrous oxide (N_2O) from fertilizer) (Smith et al., 2014a). Agricultural production accounts for about 10–12% of total global anthropogenic GHG emissions (5.1–6.1 Gt CO_2-eq/year between 2000 and 2010) (Smith et al., 2014a). When deforestation and the burning of biomass (often associated with agriculture) are included, together with other land use activities, the contribution to total annual global emissions from the AFOLU sector increases to about 24% (Smith et al., 2014a).

Three main sources of agriculture-related GHG emissions exist: (1) direct agricultural production, (2) deforestation, peat loss, and fires, and (3) the agricultural supply chain and on-farm machinery (Dickie et al., 2014).

Direct Agricultural Production

Agriculture is the largest contributor to anthropogenic non-CO_2 GHGs, accounting for 56% of such emissions in 2005 (US EPA 2011 cited in Smith et al., 2014a), and about 47% and 58% of total anthropogenic emissions of methane and nitrous oxide, respectively (Smith et al., 2007). Nitrous oxide and methane have a global warming potential 296 times and 23 times that of CO_2, respectively. The main sources of emissions are: enteric fermentation in the digestive systems of ruminant livestock (cattle, sheep, and goats), biomass burning, rice cultivation, and soil management (including manure left on pasture, synthetic fertilizers, manure management, crop residues, and manure applied to soils) (Table 13.3). Agricultural non-CO_2 emissions grew by 0.9% p.a. between 1990 and 2010 (Smith et al., 2014a).

Deforestation and Other Land Use Change

Deforestation and other land use change (LUC), such as conversion of peatlands to agricultural lands, agricultural waste burning, and grassland burning, are major sources of GHG emissions (between 3.5 and 7.8 Gt CO_2e p.a.). Agriculture is a key driver of LUC in most parts of the world, but LUC-linked emissions are heavily dominated by a few countries, including Indonesia and Brazil (Dickie et al., 2014). There are marked differences between countries in terms of types and amounts of emissions. For example, the highest AFOLU emissions are directly from agricultural production in China, India, and the United States, from deforestation in Indonesia, and roughly equally from both categories in Brazil (Fig. 13.2).

Agricultural Supply Chain and On-Farm Machinery

These emissions account for about 1.9–3.5 Gt CO_2e p.a. However, most are fossil fuel emissions which are recorded in other sections of national inventories (e.g., transportation, energy). Fertilizer production and energy used for irrigation and cold chains are the most significant sources of agricultural supply chain emissions.

Food System Emissions

The contribution of food systems, as a whole, to global warming is being increasingly recognized. Quantified estimates vary widely, with the contribution of food systems to anthropogenic GHG emissions being put at anything between 19% and 57%, and the proportion of food system emissions coming from agricultural production anywhere between 47% and 86% (Vermeulen et al., 2012; GRAIN, 2013).

TABLE 13.3 **Global Agriculture, Forestry, and Other Land Use Emission Data ($MtCO_2eq$ year)**

Agriculture Category	1961	1990	2000	2005	2010 (% +)
Enteric fermentation: ruminants (e.g., cattle, sheep, goats) emit CH_4 as a by-product of digestion	1375	1875	1863	1947	2018 (44%)
Manure left on pasture: N_2O emissions	386	578	682	731	764 (17%)
Synthetic fertilizer: N_2O emissions from fields where nitrogen fertilizer applied	67	434	521	582	683 (15%)
Rice cultivation: CH_4 emissions from anaerobic decomposition in flooded fields	366	466	490	493	499 (11%)
Manure management: storage systems emit CH_4 (if wet), N_2O (if dry)	284	319	348	348	353 (8%)
Crop residues: residues left in fields are a source of N_2O	66	124	129	142	151 (3%)
Manure applied to soils: source of N_2O emissions	59	88	103	111	116 (3%)
Total++	2604	3883	4136	4354	4586
Net deforestation		4315	4296	3397	3374
Combined		8198	8432	7751	7960

+ , % of agriculture total; ++, Excluding emissions from biomass burning and drained organic soils.
Source: Modified from Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., Smith, P., 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. Environ. Res. Lett. 8, 1–11 (Tubiello et al., 2013).

Agriculture, Forestry, and Other Land Use Mitigation Options

It is increasingly being recognized that agricultural mitigation options need to take into account other ecosystem services from the AFOLU sector, and that demand-side options need to be considered together with supply-side options.

Supply-Side Mitigation Options

There are a variety of supply-side measures (see Table 13.4), which can contribute to mitigation. These may be grouped into three categories: (1)

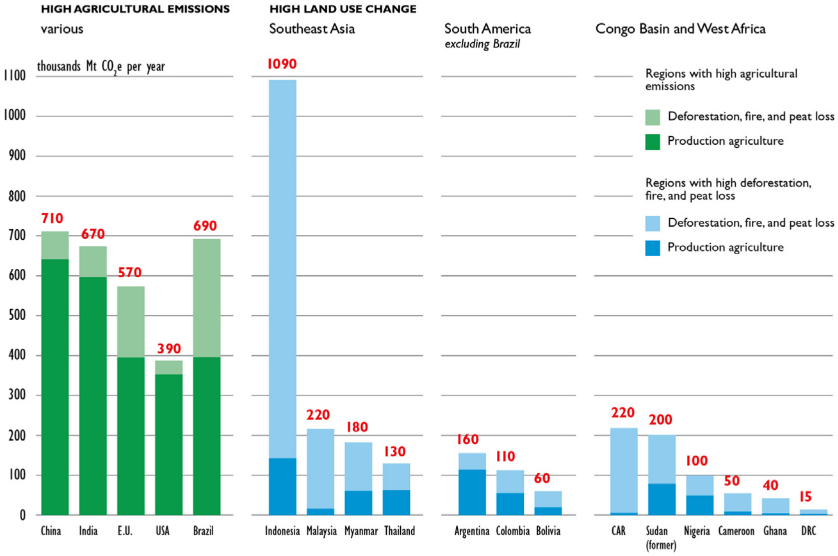


FIGURE 13.2 Examples of annual agriculture and land use change emissions. *From Dickie, A., Streck, C., Roe, S., Zurek, M., Haupt, F., Dolginow, A., 2014. Strategies for mitigating climate change in agriculture: abridged report. Climate Focus and California Environmental Associates, prepared with the support of the Climate and Land Use Alliance. www.agriculturalmitigation.org.*

reducing/preventing emissions from the AFOLU system by conserving existing carbon in soils or vegetation that would otherwise be lost, or by reducing emissions of methane and nitrous oxide; (2) sequestering additional carbon in above-ground biomass, in cropland soils, or in grassland soils; and (3) substituting biological products for fossil fuels.

This last, however, is controversial in the context of developing countries, because of threats to food security in Africa, threats to biodiversity through the conversion of forests to biofuel (e.g., palm oil) plantations, and the risk of reducing carbon stocks and releasing carbon to the atmosphere (Smith et al., 2014a). For example, analysis of direct LUC resulting from the conversion of semiarid woodlands in Brazil and India to *Jatropha curcas* as a perennial biofuel crop found that there was no detectable change in above-ground carbon stocks at the sites in South India, where *jatropha* replaced *prosopis* woodlands. In contrast, large losses of above-ground carbon stocks were detected in Central Brazil, where *jatropha* replaced native *caatinga* woodlands. These losses represent a carbon debt that would take 10–20 years to repay (Bailis and McCarthy, 2011).

The effectiveness of an intervention will depend on context. Dickie et al. (2014) suggest that there are only a limited number of countries and sectors that can, by 2030, provide meaningful reductions, with practices that would

TABLE 13.4 **Summary of Supply-Side Mitigation Options in the Agriculture, Forestry, and Other Land Use Sector Based on Smith et al. (2014a)**

	CO_2	CH_4	N_2O
Forestry			
Reducing deforestation: Conservation of C in forest vegetation and soil by controlling deforestation, protecting reserves, and controlling disturbances such as fire and pests. Reducing slash and burn agriculture.	√		
Protection of peatland forest, reduction of wildfires.		√	√
Afforestation/reforestation: Improve biomass stocks by planting trees on non-forested agricultural lands.	√		
Forest management: Management for sustainable timber production including extending rotation cycles, reducing damage to remaining trees, reducing logging waste, soil conservation, fertilization, using wood more efficiently.	√		
Wildfire behavior modification.		√	√
Forest restoration: Protecting secondary and other degraded forests whose biomass and soil C are less than their maximum value, and allowing them to sequester C, rehabilitation of degraded lands, long-term fallows.	√		
Land-based agriculture			
Cropland management			
Plant management: High input carbon practices, e.g., improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology.	√		
Improved N use efficiency.			√
Nutrient management: Fertilizer to increase yields and residue inputs (especially in low-yielding agriculture).	√		
Changing N fertilizer application rate, fertilizer type, timing, precision application, inhibitors.	√		√
Increased use of biological N fixation.	√		√
Tillage/residues management: Reduced tillage intensity, residue retention.	√		
Water management: Improved water availability in cropland, including water harvesting and application.	√		
Decomposition of plant residues.		√	
Drainage management to reduce emissions, reduce N run-off leaching.			√
Rice management: Straw retention.	√		
Water management, mid-season paddy drainage.		√	
Water management, N fertilizer application rate, fertilizer type, timing, precision application.			√

(*Continued*)

TABLE 13.4 (Continued)

	CO_2	CH_4	N_2O
Rewet peatlands drained for agriculture: Ongoing CO_2 emissions from reduced drainage, but CH4 may increase.	√		
Set-aside and LUC: Replanting to native grasses and trees. Increase C sequestration.	√		
N inputs decreased resulting in reduced N_2O.			√
Biochar application: Soil amendment to increase biomass productivity, and sequester C.	√		
Reduced N inputs will reduce emissions.			√
Grazing land management			
Plant management: Improved grass varieties/sward composition, e.g., deep rooting grasses, nutrient management.	√		
Animal management: Appropriate stocking densities, carrying capacity management, grazing management.	√		
Stocking density, animal waste management.			√
Fire management: Improved use of fire for grassland management. Fire prevention. Improved prescribed burning.	√		
Livestock management			
Feeding: Improved feed and dietary additives to reduce emissions from enteric fermentation.		√	
Breeding: For high productivity(lower emissions per unit of product) or reduced emissions from enteric fermentation.		√	
Manure management: Manipulate storage conditions, anaerobic digesters, biofilters, dietary additives.		√	
Manipulate livestock diets to reduce N excreta, soil applied and animal fed nitrification inhibitors, urease inhibitors, fertilizer type, rate and timing, manipulate manure application practices.			√
Integrated systems			
Agroforestry: Mixed production systems can increase land productivity and efficiency in the use of water and other resources, and protect against soil erosion as well as serve carbon sequestration objectives.	√		
Other mixed biomass production systems: Such as double-cropping systems and mixed crop-livestock systems, can increase land productivity and efficiency in use of water and other resources, as well as carbon sequestration.	√		
Reduced N inputs will reduce emissions in all integrated systems.			√
Integration of biomass production with subsequent processing in food and bioenergy sectors: Integrating feedstock production with conversion, typically producing animal feed that can reduce demand for soya, and can also reduce grazing requirements. Using agricultural and forestry residues for energy production.	√		

be beneficial to producers and to yields and, on this basis, suggest priority focus areas should include:

- Reducing emissions from enteric fermentation, particularly targeting management of Brazil's cattle population and India's dairy herd.
- Improving nitrogen fertilizer management and production, particularly in China, by increasing the efficiency of nutrient use on croplands, and improving efficiencies in fertilizer production.
- Reducing methane emissions from rice cultivation, particularly in Southeast Asia.
- Managing manure, particularly improving manure storage in industrial livestock systems.
- Sustainable intensification (see also "Concepts and Broad Approaches to Addressing Climate Change in Agricultural Development" section and chapter: Farming Systems for Sustainable Intensification): increasing attention is being paid to options that reduce emissions intensity by improving the efficiency of production (i.e., less GHG emissions per unit of agricultural product).
- Sequestering carbon in agricultural systems. Beside the much-discussed strategy of sequestering carbon in forests, there are three other broad options: management of soil carbon in cropping systems, agroforestry, and improving carbon storage in grazing lands. However, mitigation, yield, and economic impacts of sequestration are not well understood for all practices. There are also concerns about the process being reversible (Powlson et al., 2011), and the availability of carbon sources, particularly where systems are low-yielding and there are competing demands for these sources (e.g., where crop residues may be used either for livestock feed or organic manure). However, increased soil carbon brings important cobenefits (e.g., soil fertility and water retention). Croplands across SSA could be an important target, because soil carbon content is particularly low and links to food security, poverty reduction, and productivity gains are strong.

Demand-Side Mitigation Options

Demand-side options (Smith et al., 2014a; Dickie et al., 2014) include reducing losses in the food supply chain, particularly for developing countries in production, storage, and transport. This reduces energy use and GHG emissions from agriculture, transport, storage, and distribution, and reduces land demand. Another option is to reduce or replace consumption of food items with high GHG emissions per unit of product, with food items with low GHG emissions (Fig. 13.3). Such demand changes, often mentioned in connection with reducing the consumption of meat, and also other food items, can reduce energy inputs in the supply chain and reduce land demand. Ruminant meat has high emissions per unit of product, though pig and

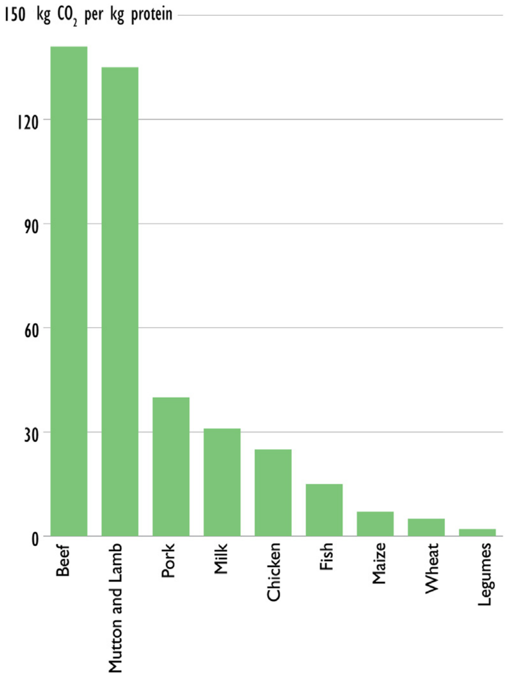


FIGURE 13.3 The carbon intensity of food products. *From Gonzalez et al. 2011 in Dickie, A., Streck, C., Roe, S., Zurek, M., Haupt, F., Dolginow, A., 2014. Strategies for mitigating climate change in agriculture: abridged report. Climate Focus and California Environmental Associates, prepared with the support of the Climate and Land Use Alliance. www.agricultural-mitigation.org.*

poultry meat bring other problems, such as competition for human feed, deforestation for feed cultivation, and dysfunctional flows of nitrogen. Emissions per unit of product will vary hugely with the system in which it is produced, and such a calculation needs a careful life-cycle analysis. The overall social and environmental costs and benefits associated with particular dietary trends also need to be assessed. As traditional diets are replaced by diets higher in refined sugars, refined fats, oils, and meats, dietary trends will become a major contributor to an estimated 80% increase in global agricultural GHG emissions from food production, and to global land clearing, as well as serious health issues (Tilman and Clark, 2014).

Mitigation Opportunities and Challenges Vary With Location

Mitigation options will vary significantly by location due to a number of factors, including: variation in local natural resources and ecology; the livelihoods context of the land use decision-makers (social, human, financial, natural, and physical capitals); the nature of local marketing systems;

the willingness of national and local governments to support and regulate mitigation practices; transparency and accountability of governance and institutional arrangements; knowledge, technology, and innovation system capacity at local and national levels (based on Dickie et al., 2014; Smith et al., 2014a).

Action Required to Achieve Mitigation in Agriculture, Forestry, and Other Land Use in Developing Countries

The majority of GHGs being emitted from the AFOLU sector are from developing countries. The large number of smallholders in developing countries manage complex and diverse farming systems, integrated with nonagricultural livelihood strategies, often with limited access to resources and vulnerability to a range of climate-related and other stressors (Morton, 2007). To contribute at scale to climate change mitigation through agricultural/ natural resource management practices requires that farmers have sufficient incentives (financial or nonfinancial) to act, and the capacity to do so.

Farmers may be motivated through achieving significant cobenefits (e.g., in the form of sustainable productivity increases or adaptation to climate variability or change); or direct/ financial incentives, e.g., through climate finance. The former can be managed at a local level through improving access to sustainable agriculture and adaptation measures, although this will require strengthening of agricultural innovation systems (AISs)—see section Strengthening AISs to respond to climate change, and Chapter 11, The Innovation Systems Approach to Agricultural Research and Development. Some standards and certification programs, e.g., the Climate, Community and Biodiversity Alliance, support cobenefits, including poverty reduction, enhanced biodiversity, and soil health.

Direct financial incentives may be delivered through a number of potential mechanisms. Carbon markets have provided a means for buyers of carbon credits to finance payments to farmers for using practices which reduce emissions and/or sequester carbon. However, opportunities for agriculture have been hindered by limited markets (mainly the voluntary carbon market), low returns to farmers, high transaction costs, and the need for advance funding (Wollenberg et al., 2012). Under the Reduced Emissions from Deforestation and Forest Degradation (REDD+) initiative, agriculture is included as a driver of deforestation, and is eligible for finance. Support from actors further up agricultural supply chains may be an option in some contexts (e.g., premiums or market access from social and environment certification standards in tea, coffee, cocoa, and sugar cane supply chains). However, few examples exist, and more initiatives are needed to show how they will work in practice.

An enabling environment for agricultural mitigation, and especially equitable agricultural mitigation, requires: international and national policy support, e.g., through Nationally Appropriate Mitigation Actions (NAMAs);

robust monitoring, reporting, and verification methods; and public finance for capacity strengthening at various levels. Smallholders need information about mitigation options, and associated benefits and risks. Mitigation initiatives also need safeguards to reduce unintended negative impacts (Wollenberg and Negra, 2011).

Although most developing country GHGs are primarily emitted from the AFOLU sector (Hoffmann, 2013), growing populations, urbanization, increasing per capita incomes, and changing demands for food, mean that the contribution of other parts of the food system is set to increase. Early interventions could help, or allow developing countries to avoid being locked into high carbon pathways and contribute to a green economy (GE) (UNCTAD, 2009; Hoffmann, 2013).

AGRICULTURAL ADAPTATION TO CLIMATE CHANGE

Humans adapt their agricultural practices to climate change in many ways, including by harnessing the adaptation processes of domesticated species and ecosystems. Adaptation to climatic changes is not new, it has been happening throughout history alongside adaptation to other drivers of change (e.g., demographics, pests and diseases, markets). However, the rate and scale of future climatic changes are expected to increase, causing impacts too great for autonomous adaptation. Given this prognosis, we need to ensure that adaptation decisions and actions taken now do not undermine the ability to respond to potentially larger impacts in the future (Howden et al., 2007).

While mitigation actions are crucial for reducing the rate of GHG emissions, and thus the future rate of global warming, the inertia of the climate system means that no matter what emissions reductions we manage to make now we are in an "era of committed climate change" (Field et al., 2014), and people from all countries irrespective of their capacity to do so, will still have to adapt to climate changes (Lemos et al., 2007). The influence of feedback loops and unexpected changes, and the complex and dynamic social and ecological responses to these changes across a range of influential scales, spaces, and time phases, make the subsequent impacts and outcomes complex and difficult to assess.

Various categories are used in conjunction with adaptation (see Box 13.1).

The heterogeneous nature of farming systems and livelihood strategies, and the high level of uncertainty regarding how climatic changes will be expressed, highlight the need for localized innovation, experimentation, and solutions, as opposed to generic blanket-recommendations. The focus of much agricultural adaptation discussion is on technical solutions that can help agricultural communities and agrifood systems become more resilient to climate change. However, the learning process by which farmers, their service providers, and other agricultural stakeholders find out about, interact with, test, and then start to use these potential adaptation technologies is

BOX 13.1 Categories of Adaptation

Adaptation is typically thought of as:

- Either *autonomous* or *planned* (with some suggesting that due to the scale of future climate change autonomous adaptation will become inadequate);
- *Responsive or anticipatory*;
- *Incremental* (where the aim is to maintain the essence of existing systems) or *transformational* (where the aim is to change the fundamental attributes of existing systems, this could include migration, farm relocation, or change in emphasis from cropping to livestock-based livelihoods, or *vice versa*).

Source: *Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptation climate change insufficient. Proc. Natl. Acad. Sci. USA. 109(19), 7156–7161.*

equally as important for resilience building as the technology itself, and deserves increased attention.

In some situations, incremental farm-level changes are sufficient for adapting to current climatic changes. In other situations, organizational or institutional changes may be needed, such as farmer organization strengthening, value chain arrangements, and access to credit or climate finance. In some cases, transformational changes at the farm, community, or other levels (e.g., landscape) may be required, or forced to occur. These changes may be planned or autonomous.

In most situations, a multistakeholder experiential learning process is vital for: helping improve access to information about different adaptation options; developing means of testing and comparing different options; interaction and discussion on the changes encountered, their causes, who is affected, possible adaptation options for different types of households, crops, livestock, or locations; monitoring and identification of anticipated and unanticipated impacts of the changes made; feedback into an ongoing learning cycle. The role AISs can play in meeting the continuous need for adaptation to climatic and other change is discussed in the section Strengthening AISs to respond to climate change.

Farm-Level Adaptation to Climate Change

Many agricultural communities, whose livelihoods are so closely entwined with the climate, have highly developed indigenous knowledge systems related to climate and the natural world around them. Plant developmental stages, animal behaviors, and the winds are often used by specialist individuals within agricultural communities to forecast the weather (Speranza et al., 2010). These knowledge sets and indicators are often reported to be becoming less dependable as a result of climate change. It is important to understand farmers' and

BOX 13.2 Examples of Incremental Farm-Level Adaptations

- Changing the crop varieties, types or mixtures grown;
- Staggering or changing planting dates;
- Planting crops in different locations to spread risk;
- Improved soil and water management (e.g., soil cover such as mulching, fallow or deep tillage to improve in situ rainwater harvest and reduce evapotranspiration);
- Changes to weeding, or field pest and disease management;
- Improved postharvest management to reduce losses;
- Using climate forecasts to reduce production risks;
- Purchasing crop and livestock insurance;
- Use of agroforestry trees in fields or along boundaries;
- Changing livestock types, breeds, or numbers;
- Changing livestock management practices;
- On and off-farm livelihood diversification practices, including seasonal or permanent labor migration and remittances;
- Dietary changes;
- Social networking.

other stakeholders' perceptions of climate change, as this is what influences their adaptation behavior, as opposed to scientific measurements of climate patterns (Adger et al., 2009; Mertz et al., 2009) (Fig. 13.4).

Many incremental farm-level adaptation options (Box 13.2) are seen as "no-regrets" type options, with positive sustainability outcomes across a range of situations. Many of these adaptations are already being autonomously implemented by many farmers in order to improve their livelihoods. However, there are also opportunities to improve farmers and their service providers' awareness about, and experience of, these adaptation opportunities. Combining several adaptation options can often result in substantial increases in benefits compared with single adaptations.

There is a lot of interest in not only testing different cultivars, but also developing new cultivars with improved tolerance to higher temperatures and prolonged dry spells. Such crop breeding investments can take 8–20 years, and thus today's crop breeding activities need to be targeted towards varieties suitable for climatic conditions projected in 2030 and beyond, as well as other traits such as high yield, pest and disease resistance, taste, etc. This highlights the importance of ensuring the survival of as much genetic diversity as possible, so as to be able to access genes for thermal tolerance traits, as well as tolerance to changing pest, disease, and weed threats (Wassmann et al., 2009; IAASTD, 2009).

As temperatures and rates of evapotranspiration increase, so does the need for improved crop – soil and water management. More effective water harvesting, practices such as minimum tillage, mulching, canopy management, protected crop production (e.g., in plastic tunnels), agroforestry, cultivar selection, and improved access to and storage of irrigation water, as well as planting date modifications and use of varieties and crops with a range of maturity periods, all have roles to play.

Increasingly variable crop production levels mean that other climate-affected aspects of food systems such as food reserves, storage, and distribution policies and systems may need to be enhanced (IAASTD, 2009; Stathers et al., 2013b). Farm-level "no-regrets" postharvest management options, i.e., those which provide benefits even without climate change, include: growing and/or storing varieties less susceptible to postharvest pest attack; prompt harvesting, adequate drying, good store maintenance, cleaning and hygiene, protection and monitoring of food stocks; dietary diversification as production of the main food crop becomes increasingly risky; careful handling of perishables to maintain quality and shelf-life; farmer access to market information and transport options; ensuring crop breeders evaluate postharvest as well as preharvest crop characteristics (Stathers et al., 2013b; Rufino et al., 2013).

Whilst some livestock systems are primarily farm-based, others involve grazing activities over large areas which are accompanied by increasingly complex and conflicted interactions with other individuals and communities in both rural and urban areas, and with wildlife in national parks and reserves, as pressure on natural resources increases. Adaptations can include: adjusting herd movement and size to altered seasonal and spatial patterns of forage and pasture production and water availability (although reaching agreements and organizing these routines for many individual herders is not straightforward); intervening in livestock marketing systems to incentivize increased offtake of males, and at younger ages; managing diet quality (through pasture rotation and fertility management, supplements, and silage); using different or a wider range of breeds or species of livestock; increased monitoring and management of the spread of pests, weeds, and diseases; changing the ratio and relationships of crops to livestock within a mixed system; and more diversified livelihoods (Kabubo-Mariara, 2009; Morton, 2012; Thornton and Herrero, 2014; Porter et al., 2014; Rivera-Ferre et al., 2016).

Diversification of farming and nonfarming activities can be effective adaptation options through spreading and reducing climate-related risk. In many smallholder households in risk prone areas, seasonal labor migration, typically by males, to help with land preparation, weeding, or harvesting activities elsewhere is already practiced, particularly during bad years.

When farm-level adaptation is practiced over a large enough area, its influence increases and, if the larger landscape context is considered, this can result in landscape-level adaptation. This may be characterized by adaptation practices at the field and farm scale, such as soil, water, and nutrient management, along with agroforestry, livestock husbandry, and forest and grassland management techniques (e.g., increasing soil organic matter improves adaptive capacity by increasing soil water-holding capacity and soil fertility, while also sequestering carbon); diversity of land use, including crop and variety diversity, across the landscape to provide resilience; and management of land use interactions at landscape scale to achieve social, economic, and ecological impacts (e.g., integrated agriculture and forestry strategies) (Scherr et al., 2012). See "Re-Greening the Sahel" Case Study 13.2, for example. There are diverse ways landscapes can be, and become more, multifunctional and climate smart. From an institutional perspective, identifying appropriate policies, instruments, and incentives to bring this about will be key (Minang *et al.*, 2015).

Examples of incremental farm-level adaptations tested by farmers in central Tanzania are shown in Case Study 13.1.

CASE STUDY 13.1 Agricultural Adaptation to Climate Change in Rural Central Tanzania

In 2007, farmers in Central Tanzania explained that their rainfall season had shortened and the amount of rain reduced, the winds had become stronger and pushed the rain clouds across the sky without letting them rain, temperatures had generally increased except during the cold season (June–July), when the cold had become even more intense.

Farmers viewed these climatic changes as being due to the removal of trees surrounding their village as the human population had increased, and the anger of a person practicing witchcraft. At that time, none of the farmers linked the changes to global pollution issues.

The risk of crop failure had increased as a result of poor germination, crops being blown over or wilting, grains not filling well, and increased pest and disease problems. Farmers response to climatic change and variability included: increased cultivation of drought-tolerant varieties of sorghum, maize, and groundnuts, and crops such as sunflower and sesame; seasonal labor migration by men; use of ox-plows to quicken their land preparation given the shorter rainy period; replanting; and the use of manure. They spread risk through using fields in different locations, including opening up valley-bottom fields where crops could be harvested twice per year. Crop failure also led to them reducing the number of meals they ate per day, and selling livestock to buy food.

Climate change and variability action research themes, chosen by multiple stakeholders to collectively work on were:

- Improving their soil and water management through *in situ* rainwater harvesting using different tillage implements (e.g., spring jembe, a long bladed hand hoe which allows infiltration of rainwater to a depth, power tillers, and Magoye rippers, an implement meant to be pulled by a pair of oxen in the same way as a common plow, but used in the dry season and disturbing a limited area of topsoil), soil fertility practices (e.g., use of Mapambano compost, a high quality compost constituting vegetative matter, animal urine, and ash), a locally produced and micronutrient rich Mnjingu mazao fertilizer, farmyard manure applied at different application rates, and different crop spacing and thinning options.
- Improving their access to and management of crop varieties through testing different varieties of crops (e.g., short-duration, drought-tolerant varieties of

(*Continued*)

CASE STUDY 13.1 (Continued)

sorghum, maize, sunflower, and sweet potato), and a new crop, lablab bean. They found Macia and Pato sorghum varieties could withstand the adverse climate, and an improved variety of sunflower (Record), had higher yields and oil contents than traditional varieties, despite prolonged dry spells. Some farmers became Quality Declared Seed multipliers, improving seed access for all.

- Improving access to climate and weather information and policy, through village seminars explaining climate change, extension agents helping to interpret seasonal forecasts for their local areas with farmers, and farmers operating village weather stations (rain gauges and thermometers).
- Improving their capacity to continue to adapt to future changes, through multi-stakeholder learning groups collectively planning, implementing, monitoring, reflecting, and deciding whether to adopt some of the options or test other ones. Participatory video and field days gave those involved greater voice that was influential in scaling-out the learning.

Source: *Stathers, T.E., Ngana, J.O., Katunzi, A., Swai, O.W., Kasanga, F.P.M., 2007a. Climate change adaptations in more and less favoured areas of Tanzania: local perceptions, vulnerability and current and future adaptation strategies. In: Laikala Village, Kongwa District, Dodoma Region. 80 pp. Institute of Resource Assessment, University of Dar es Salaam, Tanzania; Stathers, T.E., Ngana, J.O., Katunzi, A., Swai, O.W., Kashaga, S.B., 2007b. Climate change adaptations in more and less favoured areas of Tanzania: local perceptions, vulnerability and current and future adaptation strategies. In: Chibelela Village, Bahi District, Dodoma Region. 81 pp. Institute of Resource Assessment, University of Dar es Salaam, Tanzania (Stathers et al., 2007a,b); Majule, A. E., Liwenga, E., Nsemwa, L., Swai, E., Katunzi, A., Gwambene, B., et al., 2012. Strengthening local agricultural innovation systems in Tanzania and Malawi to adapt to the challenges and opportunities arising from climate change and variability: Final technical report. 73 pp. IRA, University of Dar es Salaam, Tanzania (Majule et al., 2012).*

FIGURE 13.4 Members of the climate change adaptation learning group compared different sunflower varieties and tillage methods in Chibelela village, Bahi district, Central Tanzania. *Photo credit: T. Stathers, NRI.*

External Interventions/Support to Farm-Level Adaptation

National safety net programs are increasingly being used to help prevent the most vulnerable households from being knocked back into poverty traps by shocks including droughts or floods. This “safety net approach” for those most vulnerable to weather shocks includes programs that provide food for work, cash transfers conditional on school attendance or child vaccination, etc., and direct relief efforts such as providing food or vouchers for redeeming food or agricultural inputs.

Another strategy being increasingly pursued is insurance schemes. These include weather-based crop or livestock index insurance products which monitor weather variables, so that rainfall levels below a certain threshold and other climatic risk conditions can trigger pay-outs, avoiding problems associated with individual loss-adjustment. These are being increasingly explored by private and public sectors, often as one of the conditions for accessing credit (Greatrex et al., 2015). Challenges include insufficient weather data, and the increasing variability in timing and amounts of rainfall, making it difficult to operate systems where rainfall indices are linked to calendar date periods which are assumed to be linked to crop growth stages, and the relatively high costs of some premiums. Numerous different agricultural insurance schemes have been piloted in Kenya in recent years, offering cover for: livestock mortality to drought; farm input (seed, fertilizer, etc.) investments against failed harvest due to extreme low or high rainfall patterns; and farm output value (e.g., maize, wheat, sorghum, cotton harvests) against adverse local rainfall. Some of the piloted products bundle access to credit, extension, and insurance.

Barriers to Adaptation

Factors that have commonly been found to act as barriers to smallholder agricultural adaptation include: inadequate information on the climate and climate impacts, and on the risks and benefits of the adaptation options; inadequate extension services; lack of technical options; incomplete adoption of adaptations; financial constraints including access to credit; lack of functioning markets and insurance systems (Dasgupta et al., 2014). A study across southern Africa suggested farmers’ use of farm-level adaptation strategies was positively influenced by their awareness of climate change, their ownership of their land, their farming experience, their access to credit, markets, and free extension services, and their access to electricity, animal power, or tractors which help in adjusting planting dates, diversifying their crop options, and using irrigation and water conservation techniques (Nhemachena and Hassan, 2008).

Transformational Adaptation

Limits to adaptation will increasingly emerge for incremental farm-level adaptations as the climate changes further, raising the need for more systemic or transformational changes. Understanding how agriculture is currently, and could be, positioned within the landscape, rural communities, and broader social, political, and cultural environment will assist in early identification of beneficial transformations, particularly those with long lead-in times and decisions (Rickards and Howden, 2012). Insular agricultural research will be inadequate in the face of growing complexity and uncertainty, and transdisciplinary action is required to incorporate off-farm, nonagricultural knowledge or processes, and to potentially facilitate cross-scale and cross-sectoral shifts (Rickards and Howden, 2012). Key considerations with transformational adaptation include: need for continuing climate change risk assessment and management, uncertainties, costs are often presumed to be high, maladaptation, adaptive capacity, institutional and behavioral barriers that tend to maintain existing resource systems and policies, locally-owned/voluntary initiatives, and the roles of government and other stakeholders.

Common adaptations can become transformational when they are used at a greater scale, or in integrated combinations with much larger effects than before (Kates et al., 2012). The current regreening of the Sahel is an example of autonomous action by individual smallholder farmers addressing problems other than climate change that accumulated into a transformative adaptation (see Case Study 13.2).

CASE STUDY 13.2 Regreening the Sahel

Farmers in the southern regions of Niger whose woodlands had been declining from drought and population growth began to adopt a technique in the 1980s that came to be known as farmer-managed natural regeneration. This method used the web of tree roots beneath a farmer's fields that regularly sprouted and were previously treated as weeds, to provide a continuing tree stock that could be selected, pruned, and allowed to grow, providing scattered trees amid the fields. The trees provided food, animal fodder, and fuel, as well as protecting the crops from wind and evaporation. So widespread has been the adoption of farmer-managed natural regeneration, that satellite images find approximately five million hectares observable as a green belt that will be highly resilient to climate change, and which produces an additional 500,000 tonnes of food per year.

Source: *Reij, C., Tappan, G., Smale, M., 2009. Re-greening the Sahel: Farmer-led innovation in Burkina Faso and Niger. In: Millions Fed: Proven Successes in Agricultural development (Chapter 7). Washington, DC: IFPRI. <http://www.ifpri.org/sites/default/files/publications/oc64ch07.pdf> (Reij et al., 2009); Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptation climate change insufficient. Proc. Natl. Acad. Sci. USA 109 (19), 7156–7161.*

CONCEPTS AND BROAD APPROACHES TO ADDRESSING CLIMATE CHANGE IN AGRICULTURAL DEVELOPMENT

The sections above have surveyed the issues of climate change mitigation and adaptation in agriculture. There is a crowded field of concepts that cut across or integrate the two, and relate them to broader concerns for sustainability. This can create confusion, especially for those trying to implement change in practice—whether policy-makers or practitioners. In this section we explore some of these concepts and frameworks. The concepts of sustainable agriculture (Pretty, 2008) and agroecology (Altieri and Nicholis, 2005) are expanded upon previously in this book, notably in Chapter 2, Agroecology: Principles and Practice; Chapter 4, Farming Systems for Sustainable Intensification; and Chapter 5, Designing for the Long-term: Sustainable Agriculture.

Promoting sustainable intensification (SI—see chapter: Farming Systems for Sustainable Intensification) has been widely discussed as a means to support farmers and farming system performance in a rapidly changing world, as stated in Foresight: The Future of Food and Farming (2011): "It follows that if (1) there is relatively little new land for agriculture, (2) more food needs to be produced, and (3) achieving sustainability is critical, then sustainable intensification is a priority. Sustainable intensification means simultaneously raising yields, increasing the efficiency with which inputs are used and reducing the negative environmental effects of food production." Although strongly supported, the concept has also attracted criticism for being too narrowly focused on production, and others suggest it may even be inherently contradictory (Garnett et al., 2013). Reed (2012) suggests that although there are shared concerns about the finite limits of the planet, demographic pressures, climate change, and the need for conservation of resources, views diverge over questions of participation, technology to be used, and the role of markets and national autonomy. The SI approach is discussed in depth in Chapter 4, Farming Systems for Sustainable Intensification.

Climate Resilience

Resilience is a concept originating in work by systems theorists seeking to understand how complex ecosystems change, with definitions such as "regenerative abilities of a system and its capacity to maintain desired functions in the face of shocks and stresses" (Pelling, 2011). Increasing recognition of the intertwined nature of social and ecological processes has resulted in the term social-ecological system (SES). Aspects of SES thinking (functional persistence, self-organization, and adaptation from social learning) have informed climate change responses (Folke, 2006). Resilience can also refer to "the capacity that ensures adverse stressors and shocks do not have long-lasting adverse development consequences" (Hoddinott, 2014), or in broader terms, the ability of households and communities to avert, cope with, and recover from shocks and stresses. Nelson et al. (2007) emphasize the need for an interpretation of resilience that explores the desired state of a system, rather than taking for granted that a system's continuance is preferable.

New concepts reflect increasing efforts to integrate mitigation and adaptation, identify cobenefits, and explore the possible trade-offs and synergies involved.

Climate Smart Agriculture

Climate smart agriculture (CSA) is one of the concepts that is gaining increasing attention, with significant promotion by key international bodies, including the FAO (FAO, 2010), as well as the World Bank, and the Climate Change, Agriculture, and Food Security (CCAFS) program.

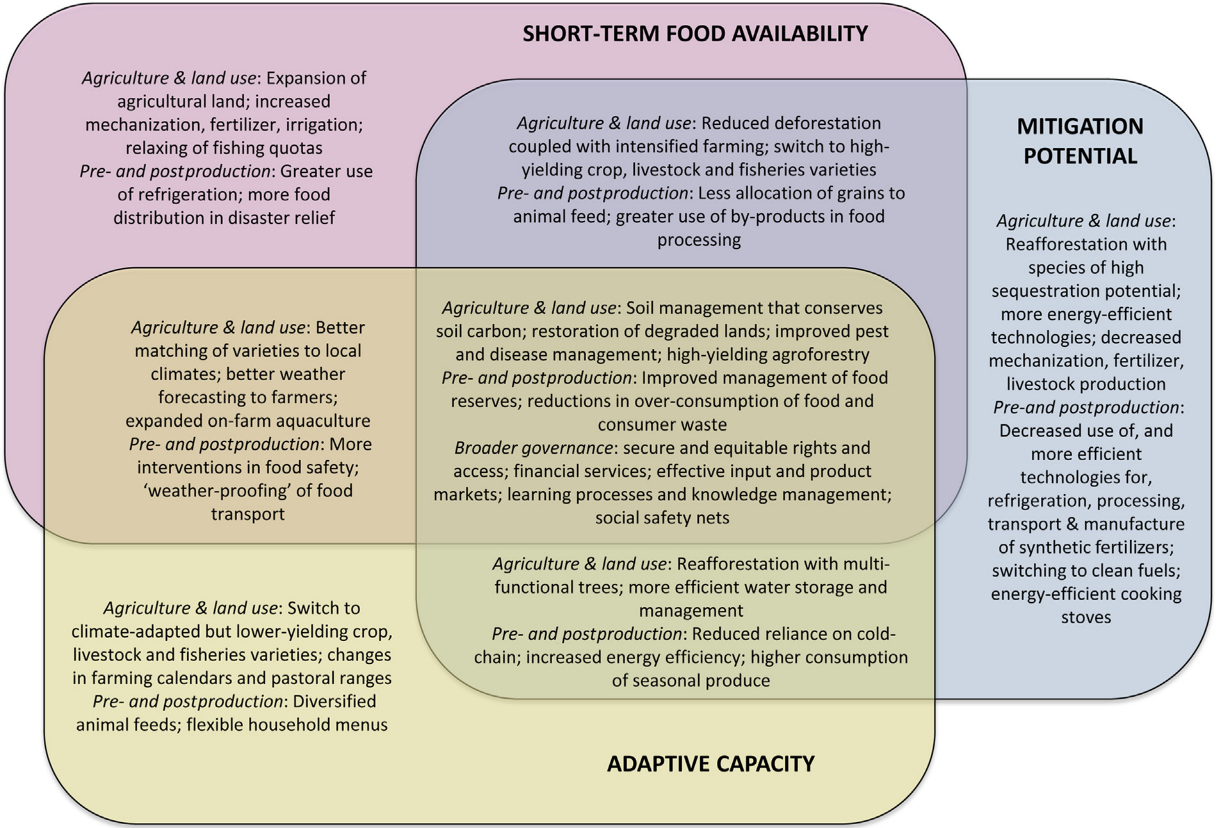
CSA aims to help guide actions to transform and redirect agricultural systems to effectively and sustainably support development and food security under a changing climate (FAO and CCAFS, 2014). CSA, as defined by the FAO (2013), integrates the three elements of sustainable development (economic, social, and environmental) by jointly addressing food security and climate challenges, and is composed of three main pillars:

1. Sustainably increasing agricultural productivity and incomes;
2. Adapting and building resilience to climate change;
3. Reducing and/or removing greenhouse gas emissions, where possible.

Important issues for the CSA approach include: (1) identifying and reducing trade-offs and enhancing synergies between the CSA objectives; (2) the scale at which CSA interventions (practices, delivery systems/institutions, and policies) are to be implemented and have influence (e.g., community, landscape, agroecological zone, regional, and national); and (3) how the baseline or reference level will be defined in order to measure progress on any of the objectives, which may be relevant in accessing climate finance.

The aim is to find integrated strategies, although it is recognized that it may not be possible to achieve all goals simultaneously in each location. Most of the literature appears to focus on examining trade-offs and synergies relating to agricultural production, with relatively little consideration of postharvest components of agricultural and food systems. Fig. 13.5 illustrates some examples of possible synergies and trade-offs in agriculture and food systems.

The concept of CSA is becoming increasingly popular as a potential unifying concept for policy, institutional arrangements, and funding channels for responding to climate change, food security, and other development goals. However, the varying interpretations of the CSA approach have



Agriculture & land use: Expansion of agricultural land; increased mechanization, fertilizer, irrigation; relaxing of fishing quotas
Pre- and postproduction: Greater use of refrigeration; more food distribution in disaster relief

Agriculture & land use: Reduced deforestation coupled with intensified farming; switch to high-yielding crop, livestock and fisheries varieties
Pre- and postproduction: Less allocation of grains to animal feed; greater use of by-products in food processing

Agriculture & land use: Reafforestation with species of high sequestration potential; more energy-efficient technologies; decreased mechanization, fertilizer, livestock production
Pre-and postproduction: Decreased use of, and more efficient technologies for, refrigeration, processing, transport & manufacture of synthetic fertilizers; switching to clean fuels; energy-efficient cooking stoves

Agriculture & land use: Better matching of varieties to local climates; better weather forecasting to farmers; expanded on-farm aquaculture
Pre- and postproduction: More interventions in food safety; 'weather-proofing' of food transport

Agriculture & land use: Soil management that conserves soil carbon; restoration of degraded lands; improved pest and disease management; high-yielding agroforestry
Pre- and postproduction: Improved management of food reserves; reductions in over-consumption of food and consumer waste
Broader governance: secure and equitable rights and access; financial services; effective input and product markets; learning processes and knowledge management; social safety nets

Agriculture & land use: Reafforestation with multi-functional trees; more efficient water storage and management
Pre- and postproduction: Reduced reliance on cold-chain; increased energy efficiency; higher consumption of seasonal produce

Agriculture & land use: Switch to climate-adapted but lower-yielding crop, livestock and fisheries varieties; changes in farming calendars and pastoral ranges
Pre- and postproduction: Diversified animal feeds; flexible household menus

FIGURE 13.5 Examples of actions in food systems that achieve different synergies and trade-offs for adaptation, mitigation, and food security (near-term food availability). *Source: Vermeulen, S., Campbell, B.M., Ingram, J.S., 2012. Climate change and food systems. Ann. Rev. Environ. Resour. 37, 195222.*

attracted a range of reactions. For example, CIDSE (2014) perceives some significant weaknesses of CSA in terms of content, particularly regarding:

- The absence of criteria to distinguish models which are sustainable, and the emphasis on productivity at the expense of the broader context and issues at stake;
- The absence of the concept of the right to food;
- The limited conception of resilience which does not challenge the structures that made people vulnerable in the first place; and
- The focus on mitigation while focusing on smallholders, and failure to recognize the contribution of specific models and historical responsibilities of developed countries regarding GHG emissions.

CSA presents potentially new funding opportunities for developing countries, but will require strong political leadership, supportive government policies, and institutional arrangements that make investments worthwhile. These are challenges which have been central to debates on agricultural development for many decades.

CSA has similarities with other concepts, such as the Green Economy (GE) as it is applied to agriculture. The GE approach is being promoted by UNEP, OECD, and FAO, and some countries such as South Korea (Benson and Greenfield, undated; UNEP, 2011a). UNEP (2011b) suggests that the greening of agriculture refers to: "the increasing use of farming practices and technologies that simultaneously: (1) maintain and increase farm productivity and profitability while ensuring the provision of food on a sustainable basis, (2) reduce negative externalities and gradually lead to positive ones, and (3) rebuild ecological resources (i.e., soil, water, air and biodiversity 'natural capital' assets) by reducing pollution and using resources more efficiently."

What GE could mean for smallholder agriculture in Africa and elsewhere, and for different social groups, remains an open question. Both Ethiopia and Rwanda have produced national strategy documents indicating a strong commitment to green growth and climate resilience (low carbon, climate resilient development), with agriculture playing a prominent role in both countries' strategies (FDR Ethiopia, 2011, 2013; Republic of Rwanda, 2011).

The broad nature of all these concepts allows for varied interpretations, enhances inclusiveness, and sparks debate. Conversely, broad definitions risk masking real differences in development visions, including questions of participation, forms of technology to be used, the role of markets and national autonomy. Thus, too open a definition could prevent recognition of the need for more radical, game changing action.

Considerations in making these concepts operational include: (1) building consensus for change at the appropriate spatial scale (e.g., farm, community, landscape, water catchment, value chain, local government area, national, global) and timescale; and (2) finding ways to measure multidimensional progress in responding to climate change adaptation in order to make progress visible and to enhance learning.

STRENGTHENING AGRICULTURAL INNOVATION SYSTEMS TO RESPOND TO CLIMATE CHANGE

In this section we discuss some approaches for strengthening the capacity of local and national agricultural innovations systems in SSA to respond to climate change.

Within the field of agricultural development, an AIS approach can be used to help identify the diversity of public, private, and third sector (nongovernmental and nonprofit-making organizations) actors that play a role in bringing new knowledge, processes, products, and forms of organization into economic and social use (see chapter: The Innovation Systems Approach to Agricultural Research and Development). It has also been promoted by many agencies in a prescriptive way, encouraging networking by multiple actors in innovation—a response to the failure of more linear/ technology transfer approaches to research and development (Spielman and Birner, 2008). In SSA, the diversity of farming, the complexity of livelihood strategies, and the uncertainties of climate change, combined with other factors, suggest a need to support localized innovation by a plurality of actors to enhance and sustain agricultural performance and resilience.

The impact of climate change presents both challenges and opportunities for AIS. In order to respond to climate change, SSA AIS may have to take on a number of roles including:

- Improving provision, access to, and use of climate science and other forms of climate knowledge;
- Analyzing the changing drivers and outcomes of farmer risk, vulnerability, and resilience;
- Strengthening adaptive capacity and resilience;
- Generating technologies that are useful in adaptation;
- Offering climate mitigation and low-carbon development options in agricultural services.

To fulfill these new or expanded roles, AIS will need to be better able to: manage uncertainty and incomplete knowledge, by understanding potential risks and by being flexible; respond to change and unpredictability by supporting farmers to manage risks and take advantage of opportunities.

Some features of a more climate responsive AIS include:

- Supporting equitable farmer access to assets (especially by the most vulnerable);
- Supporting farmer self-organization;
- Strengthening capacity for and moving towards adaptive management approaches.

An AIS has the following system functions (based on Oyelaran-Oyeyinka, 2006):

- Provision of policy and regulatory frameworks and measures;
- Knowledge generation, including R&D;
- Facilitating access to and exchange of information;
- Competence building, formal, and nonformal training;
- Stimulation of demand and creation of markets;
- Financial provision;
- Managing risks, uncertainty, and conflict.

To explore how an AIS may be strengthened in the face of climate change, we consider what is needed to strengthen each of these functions.

Public Policy and Regulatory Context

National policies, for agriculture, for climate change, for the environment (including protecting natural resources), and for growth and poverty reduction, are a crucial part of the context in which AIS operates. Policies within climate change include NAPAs (National Adaptation Programs of Action), and in some cases NAMAs. NAPAs provide a process for least developed countries (LDCs) to identify priority activities that respond to their urgent and immediate needs to adapt to climate change. Implementation of NAPAs has been constrained by a lack of funding. NAMAs encompass any actions that reduce emissions in developing countries, and are prepared under the umbrella of a national governmental initiative. They can be policies directed at transformational change within an economic sector, or actions across sectors for a broader national focus.

A review of national climate policies in Africa, focusing on Mozambique, Uganda, Benin, and Sierra Leone (Morton et al., 2014) showed that substantive agricultural issues feature in climate policies. Some NAPAs highlight the importance of strengthening farmer adaptive capacity and agricultural advisory services (AAS) in adapting to climate change, but also note their limited capacity in this regard. Despite the importance of agriculture to national economies and its vulnerability to climate change, broader linkages between climate policy and agriculture are weak. For example, prospects are poor for the continuing involvement of agriculture ministries in climate policy processes dominated by environmental ministries, with potential negative impacts on the quality and implementation of climate policies in the agriculture sector. In general, across the above four countries, there was little explicit recognition of climate change within high-level agricultural policy, and limited attention to climate change in research and extension policies. Policies and practice in the agriculture sector address important topics of natural resource management and of agricultural risk management that are relevant to climate change, but do so without putting climate change center-stage. Questions of resource scarcity and low coverage remain inescapable for both advisory services and research (Morton et al., 2014).

In contrast to the above, both Ethiopia and Rwanda have produced strategy documents indicating a commitment to green growth and climate resilience (low carbon, climate resilient development), with agriculture playing a prominent role in both countries' strategies. The GE approach decouples economic growth from high resource use—and offers potential for "leap frogging" towards more sustainable, low-environmental impact innovation (see Section Concepts and broad approaches to addressing climate change in agricultural development).

Knowledge Management

New Knowledge Generation

Farmers' existing adaptive strategies and indigenous knowledge are important resources, but adaptation will need new knowledge from diverse sources, and research at a range of scales and levels of formality. Farmers can potentially engage in activities which reduce agricultural and land use emissions, or increase carbon sequestration—but this too requires new forms of knowledge and incentives.

Improving Access to Information

Diverse AIS actors need access to climate-related information. This includes climate monitoring, seasonal forecasts, early warning systems, adaptation, and mitigation options. Media services can play an important role in some aspects of this information provision.

Facilitating Information and Knowledge Exchange

A knowledge brokering role is important, and crucially brokers need to be trusted—a potential role for AAS.

There are a range of constraints associated with knowledge management in SSA AISs, as illustrated by the situation for researchers and AAS providers in Uganda (Table 13.5).

Social Learning

Complex challenges, such as strengthening AIS to respond to climate change, need responses which take into account knowledge being incomplete, sources of uncertainty, and also diverse values and interests. Multistakeholder, social learning processes can enable different perspectives to be shared and

TABLE 13.5 Constraints in Organizing, Accessing and Using Climate Change Knowledge in Uganda

Researchers	Advisory Service Providers
• Costs involved in accessing, e.g., subscribing to journals • Authenticity of work not guaranteed • Lack of coordination among researchers • Donor restrictions on sharing information from some research • Lack of information processing equipment • Limited or lack of internet • Limited resources, e.g., funds and time • Lack of interest to share/negative attitude towards sharing information • Lack of expertise in packaging information for various audiences	• Lack of up-to-date information and technologies • Low capacity to utilize the information • Lack of initiative to search for new information • Limited resources (human and financial) for accessing and disseminating information • Lack of network/platform to share information and experiences • Political interference and preferences • Weak research – extension interface • Unhealthy competition among service providers hinders sharing • Lack of knowledge sharing strategy by districts • Limited sources of credible information • Limited facilitation to collect information • Irregular workshops/training • Lack of planned capacity building • Work overload due to low ratio of service providers to farmers

Source: Mangheni, M.N., Kisauzi, T., Miiro, R., 2013. Climate learning and knowledge management within Uganda's agricultural research and advisory services. CLAA Working Paper No. 7 (Mangheni et al., 2013); Morton, J., Kisauzi, D., Ohiomoba, I., Demby, D., Mangheni, M., Moumouni, I., et al., 2014. Climate, agriculture and knowledge in Africa: Agricultural research and advisory services in the face of climate change. Final synthesis report of the climate learning for African agriculture project.

discussed, scenarios and options to be assessed, more inclusive decision-making, strengthening of capacity, and building commitment to act. Social learning requires "change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks" (Reed et al., 2010). The learning may occur through direct interaction (e.g., dialogue) or indirectly (e.g., through ICTs).

A review of social learning processes for climate change and natural resource management identified: (1) the need to truly codesign research, rather than repackaging existing research as a "communication exercise"; (2) the importance of the facilitator as a trusted and independent broker; (3) the need to self-evolve their purpose, and for supporting processes to become more organic rather than directed social learning spaces; (4) sufficient time as key to allow new learning and change; (5) institutionalization of social learning is one of the biggest challenges; (6) the need for attention to power relations; (7) more attention needing to be given to gender, and other forms of social differentiation (Harvey et al., 2013).

Two types of learning are needed at all levels—from farmers to policymakers—both instrumental learning (task and performance oriented), and communicative learning (understanding what others mean when they communicate with us, and understanding their purposes, values, and intentions) (Diduck et al., 2012). Too often climate mitigation and adaptation research in agriculture has focused on the former, without acknowledging the need for both.

Capacity/Competence Strengthening

A wide range of varying capacities are needed in the public, private, and third sectors. These include: being able to assess shorter-term climate risks, make longer-term climate change projections and assess impacts; exploring different scenarios with farmers and other AIS actors which requires facilitation skills; tackling gender/social inequality, including new climate change-related pressures; strengthening self-organization (farmers, AIS services); developing adaptation and mitigation options in a particular socioecological context, and assessing trade-offs and synergies between shorter-term development goals, adaptation, and mitigation. Most AIS individuals have received relatively little specific training in relation to climate change in their formal education (Chakeredza et al., 2009), although this situation is now changing. Major investments are needed to strengthen AIS capacity in general.

Access to and use of information and communications technology

The meteoric growth of ownership and use of mobile phones (increasingly Smart phones) and increasing internet access via mobile net services offer vast new opportunities in AIS *vis a vis* climate change issues.

Advisory Methods

To respond to climate change and other uncertainties, methods need to enable capacity strengthening of clients (rather than delivering messages), strengthening the self-organization of farmers, and enhancing local-level innovation. There has been a major move towards more learning-based approaches and working with farmers in various forms of collectives, but success in implementation varies. Methods such as farmer field schools (FFSs) explicitly encourage experiential and shared learning, and there are climate change-related biodiversity FFSs in West Africa, and climate change FFSs in Indonesia (Lamboll et al., 2011).

The Private Sector and the Role of Markets

Climate change is starting to be addressed by the public and third sectors, but information on capacity and responses by the private sector is more difficult to access. Strengthening the climate resilience of agriculture and food value chains, and understanding the scale of GHG emissions produced through their supply chains is attracting increasing attention (Amado and Adams, 2012; Oxfam International, 2014). Hamilton et al. (2010) suggest that: "In food and agriculture over the past 5 years sustainability has shifted from the periphery to core strategy for most brand manufacturers and retail companies in Europe and the United States. Much of the rest of the world is trailing, but the growth in social responsibility is clear. The reasons are diverse: risk to supply, customer interests, public expectations and the 'license to operate.'" Specifically, in agribusiness, "Virtually every major food company is now piloting healthier value chain practices" (Hamilton et al., 2010), because agriculture as an industry has "perhaps the largest global environmental and social footprint of any human activity." The Ghana cocoa sector provides an example of a public–private sector initiative aiming to become more climate smart over the next 20 years (see Box 13.3, Asare et al., 2014). However, there has been relatively little focus on local and regional markets in Africa and the drivers for sustainability and corporate responsibility within those nations, beyond the export-led value chains.

A menu of climate smart practices and investment types which could facilitate the involvement of the private sector while also strengthening the climate resilience of smallholders includes:

- Making existing value chains more climate smart by, e.g., improving energy efficiency and substituting a relatively climate vulnerable crop with a more climate resilient crop supply. Choice of crop would be informed by other factors, such as supporting local livelihoods and economies.
- Making input markets more climate smart (e.g., range of quality seed of climate resilient and marketable crops available in appropriate sized packages; targeted soil health, organic content, and fertility management technologies; affordable climate smart equipment, such as water harvesting technology or solar powered technology).
- Identifying markets to stimulate new climate smart value chains, such as for climate resilient nontimber tree products (e.g., Fair Trade shea butter in Burkina Faso; citrus fruit drinks in Uganda), and enhancing on-farm diversity and sustainable soil and water management.
- Improving access to information, knowledge, and understanding on CSA.

BOX 13.3 Ghana's 20 Year Climate-Smart Cocoa System

Background: Ghana is facing real threats to its cocoa and forestry sectors. These include: loss of ecosystem services and forest products; declining soil quality due to farming on inappropriate soils with limited access to inputs; climate change influencing yield and cultivation area. There is recognition of a need to shift to more climate-smart production to mitigate deforestation and degradation, and adapt to climate change.

"Desired state" for Ghana's 20 year climate-smart cocoa system

- Current national production will be grown on less land;
- Yields can be increased by more than 200%—from 400 kg/ha average up to 1000 kg/ha through, e.g., improved access to extension services, planting material, inputs, and credit;
- Farmers retaining and planting shade trees among the cocoa (40% canopy cover);
- Carbon emissions per ton of cocoa produced drop by 90% (20 tons C/ton to 2 tons C/ton of cocoa produced) through, e.g., improved agroforestry systems, net tree planning encouraged by tree tenure, and benefit sharing reforms;
- Reduce threat to forest reserves, grow new forests, and expand tree cover in cocoa landscape.

Achieving this desired state requires a landscape scale, cross-sector, multiinstitutional, public – private approach.

Source: *Asare, R.A., Kwakye, Y., Tei Quartey, E., 2014. Reducing deforestation in Ghana using a climate smart cocoa production strategy: the case for a cocoa forest REDD+ program. 1st National Forestry Conference, Kumasi, Ghana. September 16, 2014. http://www.fornis.net/system/files/users/Rebecca_Asare.pdf.*

- Identifying new products for climate resilient enterprises (e.g., high quality cassava flour).
- Improving access to new drying, processing, and storage technologies or management practices which increase efficiency of enterprises using more climate resilient crops.
- Adding value to relatively equitable value chains, including regulation and private trade standards (e.g., use of new climate modules and criteria in private standards where farmer organizations are participating in certified value chains (Stathers et al., 2013a; Potts et al., 2014)).
- Improving access to alternative energy means for cooking and processing.
- Improving organizational capacity of smallholders, particularly women, to engage with climate smart value chains and sustainable finance.
- Facilitating innovative and equitable partnership and governance arrangements.
- Engaging agribusinesses to identify climate smart driven opportunities that have hitherto been overlooked, such as adding climate smart criteria to corporate social responsibility (CSR) targets.

Climate Finance and Agriculture

Access to finance is critical to an AIS's ability to respond to climate change. There are no agreed definitions for climate finance (Gupta et al., 2014), but using a broad definition, Buchner et al., (2014) estimate global climate finance flows totaling US$331 billion in 2013. These flows were split almost equally between OECD and non-OECD countries, the majority were private sector investments, and over 90% were for mitigation, primarily renewable energy and energy efficiency.

Since 1992, the UNFCCC has set out a framework for international action to prevent dangerous climate change, which recognizes that developed countries have contributed most to the global accumulation of GHG emissions. This has led to a commitment from developed countries to mobilize finance to help developing countries respond to climate change, and such "climate finance" is central to international negotiations. Developed countries pledged, in the Copenhagen Accord of 2009, to deliver approximately US$30 billion between 2010 and 2012, and to mobilize US$100 billion per year from public and private sources by 2020. The need to achieve "balanced finance" for adaptation was recognized, particularly for vulnerable, including African, states (Nakhooda and Norman, 2014). Such climate finance flows through: multilateral climate funds; bilateral funds from some developed countries; and national funds set up by many developing countries to receive finance. Types of finance include: grants, concessional loans, guarantees, and private equity (Nakhooda et al., 2014).

Climate funds contribute a small share of climate-related investment in developing countries. Developed countries' share of finance directed through their bilateral agencies is often much greater than their multilateral contributions. It was in this context that parties agreed to create the Green Climate Fund (GCF) as a new operating entity of the financial mechanism for the UNFCCC (Nakhooda and Norman, 2014). This fund may bring significant climate finance opportunities for AISs in SSA.

Funding opportunities from public and private sources for SSA AISs may be broadly split into funds to address adaptation, those for mitigation (and REDD+), and those for multiple uses (Table 13.6).

From 2010 to 2012, climate finance from public funds and carbon markets in the agricultural sector shifted markedly to increase public funds for adaptation (from US$155 to 314 million), and decrease private funds for mitigation (from US$289 to 48 million), primarily due to declining carbon prices in 2010 and 2011, and countries' commitments to fast-start finance under the UNFCCC. Emerging economies (e.g., China, South Africa, Brazil, and Mexico) were the main beneficiaries from carbon-market funds for mitigation, while SSA benefited most from the shift to adaptation (Hoogzaad et al., 2014).

Focusing on SSA, two broad funding categories for CSA, climate action and agricultural development, were identified by Shames et al. (2012).

TABLE 13.6 Broad Categories and Examples of Climate Finance Relevant to AIS

Sector	Adaptation	Mitigation and REDD+	Multiple Uses
Public	• Least Developed Countries Fund • Special Climate Change Fund • Adaptation fund • Adaptation for Smallholder Agriculture Programme	• World Bank BioCarbon Fund (public and private) • REDD+ in some countries	• International Climate Fund • International Climate Initiative • National Climate Change Funds (e.g., Rwanda National Climate and Environment Fund) • Green Climate Fund
Private	• Private company and individual investments	• Carbon market funds (voluntary and regulated)	• Private company and individual investments • CSR/corporate standards
Third sector	• International NGOs beginning to raise funds	• International NGOs beginning to raise funds	• International NGOs beginning to raise funds

Climate subcategories were carbon market dependent, purely public sources (for adaptation and mitigation), CSR/corporate standards, and philanthropy. Agricultural development subcategories were private domestic, private international, public domestic, and public international.

Nakhooda and Norman (2014) concluded that climate funds have been spent in places that need it, on activities that can reduce emissions and increase climate resilience, but funds available have been very small, complicated to access, and have not been universally successful. Climate funds need to be more flexible, and willing to take risks to foster innovation to reduce emissions and increase resilience. National stakeholders need support to strengthen policy, regulation, and institutional capacity to incentivize a wide range of actors to shift their investments in the most efficient ways possible. The right types of finance need to be used to support institutional capacity building, as well as to create incentives for investors in new areas that they perceive to be higher risk. New incentives need to be created for the institutions, investors, and businesses that are shaping infrastructure and development finance choices to do more on climate.

In order to improve coordination of finance in support of CSA, Shames et al. (2012) recommend:

1. Donors should meet current commitments and increase support for CSA;
2. Use climate funds to mainstream climate considerations into agricultural investments;

3. Develop funding mechanisms and models that support integrated CSA;
4. Private investors can take advantage of emerging certifications and standards;
5. Coordinate investments across sectors;
6. Improve monitoring systems to track the multiple benefits of CSA.

Management Under Increasing Risks, Uncertainty, and Conflict

As climate change accentuates an already risky and uncertain context, adaptive management offers an approach to guiding intervention in the face of uncertainty (Raadgever et al., 2008 and Olsson et al., 2004, cited in World Bank 2010).

Adaptive management actions are informed by explicit learning from policy experiments and the use of new scientific, and technical knowledge to improve understanding, inform future decisions, monitor the outcome of interventions, and develop new practices. Mechanisms need to be established to enable the following: evaluation of alternative scenarios; understanding and challenging assumptions and explicit consideration of uncertainties; adoption of long-term horizons for planning and capacity strengthening; alignment with ecological processes at appropriate spatial scales (e.g., decisions about agricultural water use need to take into account water catchments that cut across administrative and political boundaries); frameworks for cooperation between administrative levels, sectors, and line departments; broad stakeholder participation in problem-solving and decision-making; legislation that is adaptable to support local action and respond to new information.

CLIMATE CHANGE AND AGRICULTURAL SYSTEMS: WAYS FORWARD

Agricultural systems are both strongly affected by climate change, and one of the most important causes of global warming. The multiple demands/expectations being placed on agriculture, the diverse, dynamic and complex contexts, and the impact of climate change present challenges and opportunities for smallholder agriculture in developing countries. Climate change is exacerbating an already risky and uncertain smallholder agricultural context.

Climate change adaptation and mitigation need to be considered alongside other key priorities, such as national food security goals, poverty alleviation, addressing natural resource degradation, and adapting to the already visible effects of climate change. Various attempts to integrate climate action (adaptation and mitigation), and development into accessible new concepts (e.g., CSA and GE) are being made. We have highlighted how an AIS approach can be used in exploring how to strengthen smallholder systems in the face of climate change.

We conclude with some suggestions of what will be necessary to strengthen the ability of AIS, at local and national levels, to respond to climate change:

- *Improved policy coherence and multiobjective coordination*: much greater efforts at national level to integrate agriculture, climate, environmental, population, and other relevant policies and strategies, and to exchange information within and between countries;
- *Facilitating/ building learning networks across the innovation system and up and down the scales*: connections are needed between farmers, researchers, extensionists, NGOs, and the private sector, from local to national levels to enhance horizontal and vertical social learning, and foster innovation for agriculture in the face of climate change;
- *Informing and engaging AIS actors on climate finance*: exploration of the role of AIS actors as partners in applying climate finance to developing more sustainable agricultural systems;
- *Climate smart agrifood system development*: increased focus on wider food systems, consumer demand and education, value chains, input supply, processing and marketing alongside production; assessment of trade-offs over short, medium and long-term time frames; and the role of climate smart agribusiness in sustainable agrifood systems;
- *Scope for major ICT investment*: increased investment in and innovative use of ICTs are urgently needed, and offer significant potential for accessing information and using knowledge, at organizational and individual level at scale, equitable access is important;
- *Measurement, reporting, and verification systems*: for tracking agricultural carbon sequestration and emissions, yields and incomes (food security), and resilience;
- *Adaptive planning and management to help address climate change-related and other uncertainties:* including longer time scales in planning and capacity strengthening, challenging of assumptions, exploring different development pathways, strong co-learning, and feedback processes to inform decision-making;
- *Strong, effective, and equitable governance*: which includes issues around capacity, incentives, transparency, accountability, coordination, and participation;
- *Regional and international coordination and cooperation*: because climate change is a global issue, and many of the resources (e.g., water) and issues are shared across borders.

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Chapter 14

Tying It All Together: Global, Regional, and Local Integrations

Malcolm Blackie

THE POVERTY OF BIG IDEAS

Any discussion of poverty quickly turns to the numbers—which are frightening. The 2015 International Food Policy Research Institute (IFPRI) Global Nutrition Report claims that one in three individuals on the planet suffers from malnutrition, and improving nutrition is central to sustainable development (IFPRI, 2015). But producing sufficient food to eliminate poverty is not simply a production problem. Agriculture can have severe negative environmental impacts. Food production already takes up around half of the land suitable for growing plants; the amount of land used for agriculture has grown by more than 10 million hectares per year since the 1960s, expanding into forested and degradable areas, and threatening water resources and natural carbon cycles. Agriculture now accounts for nearly 25% of global greenhouse gas emissions, and 70% of all freshwater use (WRI, 2013).

For the poor, the struggle for food and survival dominates life. In rural communities, where poverty is typically widespread, there are no surplus resources for investment in improved, more efficient, farming systems, or to start new enterprises which create an additional income stream for the household. Those households which are unable to adopt change become locked into failing production systems. Data from across the developing world show consistently that a fundamental cause of poverty is low agricultural productivity, with consequent low incomes and poor nutrition (Pandya-Lorch et al., 2011). One-third of children in South Asia are underweight, and more than a third of childhood deaths in low-income countries are linked to undernutrition, most prominently in rural sub-Saharan Africa (Joshi and Kadiyala, 2011). This picture contrasts strongly

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with the aggregate production data. India, e.g., where almost half the children are stunted and 40% are underweight, has substantial food stocks (but too few of the poor have reliable access to these stocks at prices they can afford). The IFPRI analysis attributes this disparity to low agricultural productivity, and consequent low incomes achieved by most of the rural population. These poor households are trapped in poverty through limited access to education and food, health, and nutrition programs (Pandya-Lorch et al., 2011).

The IFPRI analysis (IFPRI, 2015) shows that addressing poverty and malnutrition requires coordinated and targeted efforts, not only in food systems, but also in education, female empowerment, health, and sanitation. The IFPRI study, drawing on information from countries as different as Bangladesh, Colombia, and Tanzania, indicates the power of such approaches. The urgent and immediate challenge facing the agricultural industries is not just to eliminate the malnutrition that exists today, but to address the issue of creating sustainable agricultural systems that enhance the lives of all, including the poor and excluded.

Differences in rural household wealth are related strongly to external factors, such as off-farm earnings and their reinvestment in farming or commercial enterprises, and to the health of working family members. The structure of farm households varies widely across the globe, but some common patterns can be discerned. For illustrative purposes, a typical Southern African farm family is detailed here (see Box 14.1). The upper stratum of farming families has more and better farmland, more improved livestock, and make greater use of improved crop varieties in both cash and food crops than the family illustrated. Irrigation is more likely to be found on medium and larger farms. They also use more fertilizer and agrochemicals, and make greater use of credit and output markets. Poorer households than the one illustrated consist of landless or marginal farmers, often with no source of draught power (essential for the time-critical tasks of planting and weeding), no regular off-farm earnings, and no high value crops. They use mainly low productivity, home-saved seed, and cannot afford to buy inputs such as fertilizer or improved seeds (Blackie and Dixon, 2016).

Increasing population density, and thus changes in the person–land ratio, has been a strong driver of change in many smallholder farming systems for over a century. Traditional farming systems often optimize the use of labor, especially as the land frontier closes. Unless industry can employ the growth of population, the trend is to reduce farm size and increase fragmentation—a time bomb which constrains agricultural development options for the next generation.

Although Africa is the most rapidly urbanizing continent, the rural population in southern and eastern Africa (which includes towns and service centers) has grown by 24% during the period from 2000 to 2010 (Blackie and

BOX 14.1 Typical Smallholder Southern African Farm Household Profile

A typical smallholder five to six person family farm would have a cropped area of 1.5–2 ha, of which 0.5–1.0 ha would be planted to maize. The equivalent of about half the maize area will be devoted to other cereals such as sorghum, millet, rice, or wheat. Maize and other cereals account for 80% of total food production, and further plantings include pulses, roots and tubers, oilseeds, and vegetables. Small areas may be allocated to cash crops such as cotton, tobacco, and coffee. The family owns two or three small ruminants or cattle, and uses its oxen to plow the land (in some areas, where cattle are scarce, cows are used, but they lack the strength, and their fertility is compromised). Typical yields are low—around 1.2 t/ha for maize, and 500 kg/ha for beans or other pulses. The household would be food self-sufficient in average-to-good years, and deficient during difficult years (due to poor rainfall, illness, or other external events). One son works in the capital and sends occasional remittances, which are used to pay for schooling, medical fees, and clothes. Home-grown maize is the main source of subsistence. Cash is obtained either from off-farm activities, local trading, or from the sale of agricultural products, such as maize, cotton, coffee, and milk. Although household income would be above the poverty line in average seasons, often sales are made at harvest when returns are lowest, and cash is a major constraint on the purchase of improved inputs.

Source: *Blackie, M., Dixon, J., 2016. Maize mixed farming systems: an engine for rural growth. In: Dixon, J., Garrity, D., Boffa, J.-M., Williams, T., Amede, T., Auricht, C., Lott, R., Mburathi, G. (Eds.), Farming Systems and Food Security in Africa: Priorities for Science and Policy Under Global Change. Routledge, London and New York.*

Dixon, 2016). Globally, the agricultural population is both "graying," and becoming feminized, with a key role for women in food production, and an increasing number of female-headed households (The number of women engaged in agriculture in sub-Saharan Africa has grown by 25% over the past decade (Dixon et al., 2016)).

Unless it is balanced by significant growth in nonagricultural areas of the economy (see, e.g., Tiffen et al., 1994), as pressure on land increases, the community becomes more impoverished, and the able-bodied migrate (typically, to rural service centers or cities, most often peri-urban slums), reducing the labor supply further (Lele, 1989). Many will remain exposed to low wages, exploitation, crime and disease, and the risk of sudden retrenchment as unskilled workers, and face the same high food costs and poverty trap that ensnared them in the countryside. Thus, the system can trend rapidly into crisis, exacerbated by the inaccessibility of modern inputs such as improved seed, fertilizer, and agrochemicals (Sachs, 2005). Value chains that make inputs expensive at the farm gate and fail to give the farmer a fair return on any crop sales entrench poverty.

Building on Hope

The moving words of Bishop Tengatenga of Malawi, who bravely and forthrightly spoke at the 2005 "Malawi after Gleneagles Conference" in Edinburgh, say it all:

> *It is difficult to believe in your own self worth if all the time you are told you are failing. The poor struggle every day to survive; recognise what they are doing, the obstacles in their way, and give them a hand of friendship and encouragement. Build – don't destroy – their confidence and they will repay a hundred-fold. That is the help they need.*

Half a century ago, much of Asia was starving. Meadows et al. (1972), amongst others (see, e.g., Paddock and Paddock, 1967), predicted an inevitable, serious, and chronic world food crisis. But this analysis underestimated the power of science. In India alone, wheat production has increased sixfold from the 1960s to today; and rice yields have more than doubled (Mukherjee, 1987). The celebrated Asian "Green Revolution" focused on improving the productivity of cereals through the development of crop varieties that could exploit intensive cropping systems, combined with building agricultural markets, and transforming deeply conservative peasant societies (Schultz, 1964).

But, while there have been many and obvious gains from the Green Revolution, it has not been a universal solution. In Africa, e.g., where farmers have reasonable access to markets, they follow the Asian example, put part of their land down to cash crops, and use the income to buy the inputs they need to improve their food security. But in much of landlocked Africa, poor infrastructure and consequent high transport costs make producing for the market unattractive. Neglected road and rail maintenance, lengthy delays at corrupt border crossings, and inefficient handling of goods at ports and airports compromise efforts at rural transformation (Eicher, 1990; Blackie, 1994). (Well over half the cost of fertilizer imported into Tanzania is caused by delays in handling at the port of Dar es Salaam (Blackie and Dixon, 2016)).

At the same time, diseases such as malaria, diarrhoea, and the AIDS pandemic cause suffering and death in almost every family. Civil wars, insurgencies, and power struggles throughout the developing world have caused millions of deaths, and have constrained or reversed development. Often, illness of the farmer or her children, or local civil disruption, will result in her planting her crop late. With a poor rainy season her crop may fail. Too often she will be unable to produce enough food for her family's needs, and will seek work for food elsewhere, often planting, weeding, or fertilizing a neighbor's crop, which means that her own is left unplanted, unweeded, and unfertilized until late in the season. Late planting and poor weeding mean a poor harvest, and once again she finds herself without food before the next crop comes in. This is the downward spiral that creates much of the developing world's poverty (Kumwenda et al., 1996; Dixon et al., 2016).

Poor farmers know about improved technologies and are desperate for access to them. However, they typically face a dreadful series of choices based on information that is incomplete, lacks economic rigor, and does not provide a reliable and effective road out of poverty. The options offered to them as a route out of poverty are too frequently flawed and, unsurprisingly, the poor (who may be illiterate, but are not stupid) reject them firmly. Those most in need of new livelihood options are the least able to pay for them. Furthermore, the advice they receive on the choices open to them is disgraceful—what the farmer needs is reliability and consistency of performance. Farmer recommendations are too seldom based on economically viable production assumptions (see Snapp et al., 2003). While group savings and credit schemes (such as Savings and Credit Cooperative Societies, Household Income Security Associations, and Self-Help Groups) can help poor families to access inputs to get out of the poverty spiral, the effectiveness of such interventions is badly blunted when the inputs themselves are poorly tailored to the needs of the poor.

Much of the debate on poverty revolves around the low prices that farmers get for their produce. A high priority for the poor is to grow their own food; but many fail to feed themselves all year round. They eat their own harvest first, and then turn to the market—just as supplies are short and prices high (This can be countered by warehouse receipt systems and grain banks which aim to reduce the need for farmers to sell their crops immediately after harvest when prices are low, and the need to buy in food on the open market when prices are high—but the reach of these schemes is limited). Poor people do not need expensive food. Thus, an evident priority in the struggle against poverty is to bring food prices down. The costs of many of the improved technologies (seeds, fertilizer, improved livestock breeds) needed by smallholders, despite the on-going efforts at market development, will remain high. Low cash cost technologies (home produced seed, household composts) often have a substantial cost in terms of labor—which is also a scarce resource in many poor households.

The missing element is a focus on input use efficiency. The advice given to many poor farmers for the use of essential inputs (both those purchased from outside and those which the farmer may generate from homestead resources, such as manure and home-saved seed), does not incorporate fundamental economic parameters into farmer recommendations (Blackie, 2005). In addition, recommendations too frequently ignore farmer needs, see, e.g., Easterly (2013) and Andersson and Giller (2012). An expensive input (whether in cash or labor terms) can be profitable if it is used efficiently. The knowledge the poor seek is how to make the best use of the limited amounts that they are able to purchase. Poverty alleviation and food security have to be arranged around low food prices and efficient production methods. With low food prices, the poor can use their limited cash to invest in better housing, education, and health care. With high food prices, they are further trapped in poverty, and the opportunities for livelihood diversification are few. The Green Revolution fails to take off.

High food costs brought about through the inefficient use of inputs and markets benefit, at best, some traders. The farmer needs good reliable profits, not high prices and low profits. Breaking out of the poverty trap requires the efficient use of available resources of land, labor, and inputs, thus allowing food to be sold profitably, even when prices are low. A profitable, efficient, agriculture sector allows both the food-consuming and food-producing poor to use their limited cash to invest in better housing, education, and health care. The following sections will illustrate that, even in the face of government indifference and poor policy, real change in the welfare of the poor, both rural and urban, can be achieved through building thoughtful, farmer demand-led initiatives, backed by high quality science.

A GREEN EVOLUTION STRATEGY

A new vision is needed. Easterly (2006) has succinctly reviewed the development "fads" of the last half century—and notes quietly that "if you want to win the Kentucky Derby, don't enter a donkey." The big money, big push initiatives that have dominated development policy for so long have proved blunt and ineffective. A different approach, building a cadre of highly skilled, adaptable, and innovative young professionals who know their own "turf" is what developing agriculture needs today. Victoria Okot (Box 14.2) needed a small loan to build a big, but locally adapted, business. Conventional finance was denied her, and she was fortunate that the

BOX 14.2 Small Seed Money; Large Returns

In 1994, Victoria Okot, a Ugandan agriculturalist, sought to establish her own seed company. Although the funds she sought were modest, no lending institution would consider her for a loan. She was an unknown small business woman. If she had been working for one of the international or regional seed companies, a loan would not have been a problem, as the business case for a quality local seed company was sound. She was fortunate in that the Ugandan Government set up a loan guarantee scheme for small businesses that she successfully applied for. Today, her company has three processing centers across Uganda, employs directly some 1000 people, and has several thousand more (many of them women) growing and supplying high value seed, and participating actively in the value chain.

Ugandan government was able to step in (albeit in a limited fashion). The agricultural industries of the developing world require new thinkers with a fresh vision of development, what I will term here "the Green Evolution approach." This derives from my own personal field experience, as well as that of others, in working to create change with severely limited resources of cash, time, and skills. The strategy relies on building a powerful partnership of scientists, farming communities, and development agencies (both private and public). It encourages the efficient and swift transformation of agricultural production through harnessing the best skills in a collaborative, "learning by doing" manner in which all feel ownership and pride. Existing structures are improved and enhanced to build change through an evolutionary rather than a revolutionary approach. This is cost-effective, brings the best of developing country and international expertise together in a problem solving format, and can (as will be shown later in the chapter) be rapidly scaled-up to reach the poor quickly and effectively.

Through emphasizing the highly efficient use of the right inputs, used in the right way, broad-based and accessible opportunities are created for the poor to benefit directly from effective access to improved seed, fertilizers, and other critical inputs that are the foundations of essential growth in productivity. Efficiency and consistency are the guiding principles to developing a productive, commercialized, and profitable agricultural sector, with wide and diverse participation, specifically involving the poor and vulnerable in creating realistic and profitable options for change.

The approach is efficient in selecting the best, and encourages partnership and collaboration; through the use of multiple channels and players, choices emerge and can be tested—and the best adopted. It fits comfortably into the increasingly practiced participatory framework for development which facilitates the empowerment of the poor and disadvantaged. Such a strategy, with a strong foundation of high quality science, directed by farmers' needs and informed by the commercial, social, and ecological environments of developing countries, can provide gains, not only for the better-off producers, but also for the poor and excluded. No change is without costs and risks. But, as the Victoria Seed example (Box 14.2) illustrates, with even modest policy support, significant change is possible.

The focus in the Green Evolution is on quality and impact along the value chain—from production to market. This is facilitated through enhanced networking and coordination among the various sector stakeholders and international organizations (see, e.g., African university networking (www.ruforum.org) where graduate students form the working elements of a coordinated university-focused initiative to address rural poverty, with their professors providing the long-term and overall vision). The best options are pulled together, and then promoted through large-scale initiatives. The poor influence the choice of recommendations, while the private sector contributes toward sector needs, such as seeds and market systems. The promotion of proven and well-validated research, using proven and novel (but justified) communication pathways, can have a rapid impact on poverty. The objective is to create multiagency, multidisciplinary buy-in, to build teams that work systematically and with strong national leadership, to develop solutions to pressing national problems.

There are examples of this happening (see Blackie, 2005, and subsequent sections of this chapter). These studies suggest that innovative partnerships can make real impacts on poverty in the developing world. These partnerships encourage a coordinated, cost-effective, and efficient technology transfer process (through learning by doing at all levels), using the best of national and international expertise in a focused, problem-solving effort. Local knowledge and expertise (at farmer, market/private sector, and researcher/policy maker level) can be tapped to link research, extension, markets, and national policy to improve living standards for rural people reliant on agriculture. The Green Evolution embodies the farmers' need for consistency and reliability, with the requirement for substantially enhanced efficiency over key areas of the farming system.

IMPLEMENTING THE DREAM

The alleviation of poverty and the development of sustainable livelihoods for the poor and excluded require close and effective collaboration between "public good" research, and the market. Pro-poor agricultural development will involve low-income farmers and consumers as active participants in setting priorities for, and the implementation of, development initiatives, including private sector expansion (Rukuni, 2014). Led in southern and eastern Africa by Collinson (see Collinson, 2002) in the 1970s and 1980s (building on work by a number of others, particularly in Asia and Latin America), farming systems research (FSR) was introduced to help guide technology development to address the priorities of the poor. FSR was based around a farm management-orientated informal survey process, supplemented by secondary data from key sources and informants (Collinson, 2002). Variations on this theme—with a broader, less directly agricultural focus—such as rapid rural appraisal and participatory rural appraisal—have been developed. Implicit in this is the central role of technology as a route out of poverty. The scientist facilitates the development of ideas and helps define options, rather than entering with already identified solutions. The overall theme is that of encouraging participants to take real control of the process of change (see Box 14.3), thus empowering them to become more active partners in development.

While increasing the demand-led component of the research agenda is important, this will not, on its own, act sufficiently fast to lift the technologically disconnected rural poor out of poverty. Typically, to get research from field experimentation to widespread adoption requires between 6 and 10

BOX 14.3 Establishing Demand

Linking research priorities to farmer demand is more complex than many "demand led" activities admit. In Bolivia, a number of research partners worked on problems of potato-based farming systems on hillsides in the mid-Andean valleys, under the umbrella of a new framework for agricultural research and extension (El Sistema Boliviano de Tecnologia Agropecuaria, or SIBTA). Within SIBTA, four foundations (FDTAs) have been established, one for each of the principal agroecological zones (Chacos, Altiplano, Valleys, and Humid Tropics). The FDTAs are responsible for resource capture, research prioritization, and the management of competitive grant schemes (using national and donor funds) for agricultural research and extension.

Research teams have been highly active in promoting a collaborative effort on the promotion of improved potato technologies, using the new SIBTA framework and engaging potential and existing partners. The outcome has been an innovative, imaginative, and impressive exercise which links demand with supply for agricultural research, while at the same time taking into account evolving market factors. The potato food chain is complex, and the outreach requires technical support to identify products and associated chains with commercial potential, and to identify the demand for technical innovation along those chains. A variety of mechanisms for exchange between researchers and end-users have been developed to prioritize research and transfer, based on real evidence of demand, and developing effective mechanisms for uptake. The poor will gain access to improved markets and sources of technical innovation that is relevant, timely, and affordable.

professionals in nonresearch areas (market development, finance, credit delivery) (Blackie, 2016; Purchase, 2014). The fruitful interaction between academia, government, and industry, which has led to the technological explosion in wealthy parts of the globe, is needed to produce a strong and effective partnership between national and international science, and between science and the user of science; who is typically the resource-poor smallholder. (This already exists for cash crops such as tobacco in Africa (and in non-African countries for a wide range of cash-earning commodities). The need now is to create the conditions that make it happen for staple crops also—see Janssen (2002)).

Implementing the Dream: Building Confidence, Trust, and Ownership

The key element in creating farmer involvement is building the trust and respect of the farmers. This requires a continuing exercise of discussing and coming to a consensus on options, together with obtaining routine and informed feedback on results. Some of the tools are already in use. Researchers, in particular, have been highly innovative in developing the necessary tools to meet the challenge of conducting participatory activities with many clients over an extended geographical area in a cost- and time-effective manner. Snapp, e.g., developed the "mother and baby" trial design (The terminology is, in fact, the farmers', who were delighted to have responsibility for their own trials) (see Snapp et al., 2003). The design comprises "mother" trials which test a number of different technologies, and "baby" trials which test a subset of three (or fewer) technologies, plus one control. The design makes it possible to collect quantitative data from mother trials managed by researchers, and to systematically cross-check them with baby trials that are managed by farmers. By facilitating hands-on experience for farmers, the clustered mother and baby trials provide a relatively rapid approach to developing "best bet" options. The linked trial approach provides researchers with tools for quantifying feedback from farmers, and helps generate new insights and priorities (Snapp et al., 2003).

Another element necessary for enhancing the impact and sustainability of change, is building ownership of the process by the poor. Making farmers proud of their involvement in creating and contributing to change, and making their participation in the process an enjoyable and interesting experience is typically, often unintentionally, downplayed in many development programs. The benefits from correcting this neglect are considerable. A radio soap opera in Kenya, "Tembea na majira," incorporating development issues, has an audience of nine million, with impressive percentages of people taking on board the development messages embedded in the storylines.

An impressive program led by CIAT in Tanzania to involve farmers in learning to work as research teams to solve their own problems provides another example of technology-led innovation. Over large areas of eastern and southern Africa, beans are widely grown by the poor. This fact was used as an access point for involving the poor in creating change within the community (Ward et al., 2007). The team involved in design and implementation focused not only on improving bean production; they emphasized making individuals proud of their farming, and encouraged the community to increase the value they place on farming. Scaling-up was achieved through showing community groups how their knowledge could bring others benefit, who then spread the ideas further. The emphasis in the implementation was to build pride and interest in the new technologies, and help encourage the poor to engage with the program. Through humor, drama, and music the implementation team made the interaction between farmers and outside actors enjoyable. Early adopting farmers, extension personnel, community development staff, and local leaders sensitized the rest of their community farmers to organize themselves into research groups for effective access to information and technologies. These farmer groups also served to boost farmer confidence as a forum of like-minded people. Farmers volunteered pieces of land for experimentation to inform others about what they were doing. This was especially appreciated by women, who had little time for experimenting or participatory learning, but were very keen to see how the crop responded.

Farmers started actively to seek further improved services (such as quality seed, markets, credit, improved livestock, fertilizers, tree nurseries, irrigation facilities, and soil and water conservation methods) (Blackie and Ward, 2005), and raised these issues openly with local officials and visitors. By 2006, there were almost 80,000 farmers in almost 400 farmer groups, and 11 constraints addressed with 13 different partners. Over 60% of the group members were women farmers who also played key roles in group leadership. Group members continue to be very keen to learn by doing and sharing knowledge, exchanging experiences, training other farmers, and reporting their own research results. Participating farmers and partners organized and implemented cross-visits to other locations for different lessons independently from the project (There is a serious issue of sustainability with this kind of initiative. Long-term support, both financial and technical, is essential and, too frequently, lacking).

Implementing the Dream: Building Partnerships With the Wider Community

The five dominant pathways using change in farming systems to reduce farm household poverty are exit from farming, diversification, intensification (Diversification implies a change in the farm production pattern, typically through the introduction of new production or value-addition enterprises. Intensification refers to the increased productivity through increased yield or reduced inputs of the existing pattern of crops, livestock, and trees), expanding off-farm income sources, and increasing farm size. Exiting agriculture, in the absence of an encouraging nonfarm economy, simply transfers poverty from rural to urban areas. Africa has achieved an average annual growth rate in agricultural GDP of 3.8% per year from 2000 to 2011, largely from increased crop areas (Blackie and Dixon, 2016). But this increase in farming area has failed to address the needed reduction in poverty levels for Africa's population. The new land under agriculture is too often of poor quality, and remote from services. Often intensification precedes significant diversification, as farmers gain experience in managing production, risks, and markets.

In the extensive mixed systems there are opportunities for sustainable transitions toward higher and more sustained levels of intensification and outputs by making more efficient use of the crop–livestock interactions (Baltenweck et al., 2003; Tarawali et al., 2011). Crop residues are becoming more important as livestock feed due to the expansion of croplands into rangelands, where biomass production is limited (Alkemade et al., 2012). However, greater crop–livestock integration also creates resource competition over the uses of crop residues for soil amendment or livestock feed (Valbuena et al., 2012). Farmers largely rely on crop residues to feed livestock during the winter or dry season, which implies substantial opportunity costs to their use as mulch (Giller et al., 2011). The form and pressure of such trade-offs depends on the local biophysical and socioeconomic farming characteristics and context. Diversification may lead to a major shift in both the farming system, and the enterprise being adopted. The emergence and adoption of small-scale dairy farms in Kenya is a success story of diversification where labor-intensive smallholder dairy farms have evolved from previous maize mixed systems (see chapter: Research on Livestock, Livelihoods, and Innovation). These are expanding in number, relative to the medium and large-scale dairies, due to their high returns and efficiency in the current pricing structure (Gibbon, personal communication).

There is growing recognition of the role of environmental services in rural development (see chapter: Climate Change and Agricultural Systems). In this connection, improved vegetative cover and pastoral management offers prospects of substantial carbon sequestration. Fermont et al. (2008) note the impact of cassava in farmers' attempts to address soil fertility decline. Their analysis shows that increasing land pressure during the past three to four decades has transformed farming systems in the mid-altitude zone of East Africa. Traditional millet-, cotton-, sugarcane-, and/or banana-based farming systems with an important fallow and/or grazing component have evolved into continuously cultivated cassava or cassava/maize-based systems. Declining soil fertility, and not labor or food shortage, was apparently the primary trigger for this transformation.

Sustainable resource management must address widespread land degradation, declining soil fertility, and low crop yields resulting from inadequate rainfall; it should result in soil recapitalization and improved productivity. Components include farmer-centered agricultural knowledge, and information systems to document and share successes. In many cases, investments are required in resource enhancements such as small-scale irrigation, water harvesting, and improved seed systems, along with participatory applied research focused on integrated technologies blending indigenous and scientific knowledge. Technologies have not been effective when promoted as packages without flexibility, as shown by the limited adoption of conservation agriculture, despite its promising biophysical properties (Giller et al., 2011). It is essential that research for development pays attention to flexible, judicious, input use, along with supporting farmer innovation to adapt technologies to local priorities (Giller et al., 2011; Snapp et al., 2003).

Implementing the Dream: Building in the Market

Moving from subsistence (or below subsistence) to agriculture which provides a healthy and sustainable life means providing opportunities for the poor to engage effectively in markets—both for needed inputs and for sales of the surpluses they generate. One typical problem the poor face is getting access to inputs—conventional markets struggle to serve communities of dispersed households living in poverty. Building ownership amongst the poor again provides the route out. For example, local, reliable seed systems for "orphan" crops (which are important to the poor), such as sweet potatoes, groundnuts, and pigeon pea, can be developed amongst the poor themselves. In Uganda, the Kapchorwa Seed Potato Production Association (KASPPA), a self-help group of farmers, reduced the devastating disease of bacterial wilt in potatoes to below 1%. Improved sweet potatoes, with enhanced vitamin A, were disseminated in Central Uganda and quickly adopted by farmer groups. In just 2 years (2001–03), 36,000 farmers tripled sweet potato production, producing 34,000 tonnes with a value of over £1.2 million (Blackie and Ward, 2005).

Farm Input Promotions (FIPS)-Africa, a "not-for-profit" company in Kenya, works with the private sector in that country (with Athi River Mining (ARM), Monsanto, Western Seed Company, Lachlan Agriculture, and the Kenya Seed Company), and with public sector agencies such as the Kenya Agriculture Research Institute (KARI). Farm Input Promotions-Africa use a participatory methodology to build demand for improved inputs at the farm level, by helping farmers make informed choices as to what is best for them, and then ensuring these choices are available for sale in convenient locations. It builds market links by working through local stockists to ensure that needed inputs are available for sale in quantities the farmer can afford (not just those which are convenient for the supplier to deliver). The promotion of new options for farmers includes collaboration with church and school groups, providing information at market days, and the provision of samples for farmers to experiment with on their own.

Evaluation of data on FIPS show the approach to be remarkably successful in improving food security amongst participating farmers. Spillover to neighboring farmers shows that farmer-to-farmer advice carries the best of the new messages quickly amongst the poor. In an analysis of FIPS impact, food security amongst poor farmers with whom FIPS was working nearly doubled within 3 years, from around 30% to 60%. But, in the same time period, food security amongst the clearly less well-off who were not working with FIPS also doubled, from nearly 15% to almost 30% (Blackie et al., 2006).

Improving input and output market efficiency is a major priority. Gabre-Madhin (2007) has emphasized the need for "getting markets right" instead of "getting prices right." Getting markets right depends on underlying institutions and supporting infrastructure, requiring guidance from a “visible hand,” and a concerted effort for the public sector to facilitate the role and performance of the private sector. With poor infrastructure, the transportation costs in many areas of the developing world will continue to be expensive. Therefore, addressing the longer-term infrastructural issues that hamper trade should be prioritized. Other critical areas include developing profitable irrigation systems, commodity exchanges, market information systems based on rural radio and short messaging systems, warehouse receipts, and market-based risk management tools (Gabre-Madhin, 2007).

Snapp et al. (2010) note that Malawi has addressed the problem of chronic national food insecurity largely through a subsidy program for nitrogen fertilizer and improved maize seed provided to over a million farmers annually since 2006. Consequent increases in production have been heralded as a triumph for input intensification of rain-fed cereals. But the costs are high; the program has consistently exceeded its approved budgetary allocation (13–17% of the national budget), resulting in reductions in expenditure in other key areas, such as education and health. But an analysis of data from on-farm trials showed that improving biodiversity through the incorporation of legumes into the system could increase fertilizer use efficiency significantly, thus improving the sustainability of the fertilizer subsidy initiative. A further series of on-farm trials enabled the development of improved cereal – legume rotations that produced equivalent quantities of grain with half the amount of fertilizer, and on a more stable basis (yield variability reduced from 22% to 13%), compared to monoculture maize with fertilizer. The improved rotation system was more profitable for the farmers, and also produced more reliable yields. The nutritional benefits of legume diversification were particularly valued by female farmers, and labor constraints were frequently noted by poorer households.

Reviewing the demand for improved maize seed in East Africa, Langyintuo et al. (2010) show that the dominating factors were the price of the seed, and lack of awareness of the potential from growing improved seeds. Innovative private – public cooperation can provide a solution to this demand constraint. For example, in October 2004, FIPS-Africa introduced Katumani beans (KB9) as part of their “food security package” for drought prone areas. The KB9 is a drought- and heat-tolerant bean developed by the public sector research agency, Kenya Agricultural Research Institute (KARI), and is suitable for areas with a short growing season. But farmers neither knew of the bean, nor could they get access to the seed. Through local stockists, FIPS set up a promotion whereby if farmers bought one of their maize mini-packs, that farmer would also get a free 250 g packet of KB9 seed to try (together with the necessary agronomic information). Farmers quickly saw that the KB9 bean was well suited to their area, and returned the next year to buy more seed. Farm Input Promotions-Africa initially contracted a local farmer to multiply the seed to meet the immediate anticipated future demand. Today, this open-pollinated variety is produced commercially by the privately owned Western Seed Company, and is marketed throughout the country (Blackie et al., 2006).

The availability of information to small farmers will be a critical factor in both intensification and diversification. The adoption of knowledge intensive methods, such as conservation farming and integrated pest management (IPM), will require educational rather than prescriptive approaches to extension. Each farmer must be given the means to judge which avenues for livelihood improvement best match his or her resource endowment. Thus, investment in farmer training, including the revitalization of farmer training institutes, and complementary village and field level education, is indicated.

The rapid development of modern ICT offers the prospect of a quantum leap in the availability of technical and market information to farmers. Farm production could benefit from the rapid dissemination of information on disease outbreaks, as well as market information on prices, and categories of stock demanded in the market place.

Implementing the Dream: Scaling-Out

A Green Evolution is, in principle, a process of linking farmers, researchers, and policy makers to bring the power of new technology positively and effectively into the process of poverty alleviation. The examples which follow, drawn from African experience, provide reason for such optimism. They highlight, across a range of very different commodities from food crops to high quality export production, the power of linking farmer knowledge and interest with the best of modern science. Each example has influenced the lives of tens of thousands of poor families in Africa—so it can be done. The need to learn from, and build on, these successes is urgent. Millions of Africans are food insecure, and too many of the young die from nutrition-related illnesses every year (Conroy et al., 2006).

The Malawi Starter Pack

In response to Malawi's serious food crisis of the late 1980s, in remarkably few years, CIMMYT (Centro Internacional de Mejoramiento de Maiz Y Trigo) and Malawian scientists produced new varieties of flinty, high-yielding, hybrid maize well-suited to Malawi's needs. Companion agronomic research promised to reduce the need for commercial fertilizer, and improve soil fertility. It identified crop rotations and complementary agroforestry cultures that both economized on purchased inputs, and improved diets. Five years of extensive farmer trials—nearly 2000 a year—identified, for each of Malawi's major agroclimatic zones, the most economically efficient package of practices—the "best bet" for that region.

However, few Malawians had the necessary cash to purchase even minimal amounts of the new seeds and fertilizer that could help them break the cycle of poverty. The Universal Starter Pack was designed to use the promise of the best bet technology to jump-start maize production for all smallholders. All smallholders in Malawi were given a small package containing enough hybrid seed, and the economically viable recommended quantity and type of fertilizer, sufficient to plant 0.1 hectare of land. Each household would gain sufficient extra maize to feed itself for a month in the food shortage season. All of the inputs in the Starter Pack generated incremental production. They did not displace commercial purchases, since the poor could not afford even these small amounts. There were evident rewards to good husbandry, especially to timeliness of planting, fertilizing, and weeding, which provided a strong incentive and reward for using the inputs well. It provided a nationally implemented, but individually operated, technology testing and demonstration program for a small part of each farm, facilitating experimentation by farmers of promising, but not yet widely adopted, technologies. The program was intended to be developed, refined, and adapted in future years to "fast track" further technology choices into the smallholder sector, and thus diversify farming systems and increase smallholder incomes.

The Starter Packs were distributed to 2.8 million smallholder farmers in 1998 and 1999, together with a carefully developed extension message to assist farmers in the use of the pack (Blackie and Mann, 2005). Evaluation data showed that the starter packs raised maize production on average by about 125–150 kg per household (significantly more than was estimated). Production in each of those 2 years was approximately 2.5 million tonnes, 500,000 tonnes higher than ever before or since; 67% higher than the 20-year average. In terms of cost-effectiveness, the starter pack program performed extremely well compared to alternative food crisis prevention measures, such as general fertilizer price subsidies, and relief interventions, such as subsidized commercial food imports and food aid (Levy, 2005). Several of Malawi's development partners took the ideological view that this modest financial support to the poor (who had little access to the market) interfered with the evolution of free markets in that country. Despite widespread evidence globally of the inefficiency and costs of agricultural subsidies, under external pressure the program was changed to one of providing subsidies for seed and fertilizer. This, unsurprisingly, proved unsustainable (consistently exceeding its approved budgetary allocation of between 13% and 17% of the national budget, and competing heavily with other priorities such as education and health).

Rescuing Africa's Cassava Farmers

Cassava crop protection successes are an interesting mixture of farmer-led enterprise, and focused scientific endeavor. Cassava was introduced to

Africa by Portuguese traders using trading stations in the Congo in the mid-1500s. The crop was attractive to farmers due to its drought tolerance, known resistance to locusts, low labor requirements, and the capacity to survive in low-fertility soils (Jones, 1957; Gabre-Madhin and Haggeblade, 2001). It supplanted yams in some locations and cereals in others, spreading across Central Africa (Jones, 1957). Introduced into East Africa after 1800, cassava spread west into the interior from Zanzibar and Mozambique. It is now a major African staple food and, in particular, is an important source of household food security for many of the continent's poor (Gabre-Madhin and Haggeblade, 2001).

In the 1920s and 1930s, cassava mosaic virus, spread by a white fly, threatened this increasingly important food security crop in Ghana, Nigeria, Cameroon, the Central African Republic, Tanganyika, and Madagascar (Jones, 1957). Farmers responded immediately by replacing affected plants with cuttings from unaffected varieties. This theme was taken up by colonial agricultural research stations in Tanzania, Kenya, Madagascar, and Ghana, which introduced cassava breeding into their programs for the first time (Cours et al., 1997). The result, after a decade of intensive research, was a series of new resistant varieties which spread rapidly and largely replaced the affected "local" varieties (Gabre-Madhin and Haggeblade, 2001).

In the early 1970s, two imported pests—the cassava mealy bug in the Democratic Republic of Congo (then Zaire) in 1973, and the cassava green mite in Uganda—threatened the crop. Lacking natural predators, both spread rapidly across the continent. The mealy bug, the more voracious of the two, caused crop losses of 80% as it ate its way across the continent at over 300 km/year. By the early 1980s, the mealy bug had infested the entire African cassava belt, where it threatened the principal food source of over 200 million Africans (Herren and Neuenschwander, 1991). A decade of collaborative work by international and national research institutes lead to the identification of a natural predator wasp of the mealy bug. The International Institute for Tropical Agriculture (IITA) mounted a mass rearing and distribution program in collaboration with African NARSs. First released in 1981, the predator wasp had, by 1988, largely controlled the mealy bug threat throughout Africa (Gabre-Madhin and Haggeblade, 2001). A rather more challenging program to identify a suitable predator for the cassava green mite has also proved successful.

Disease Prevention in Uganda's Staple: Bananas

Bananas in the Central Highlands of Africa owe their importance as a food crop to skillful farmer plant selection over about the last 800 years. The crop, like cassava an introduction (but by Arab traders), was well suited to the climate in what are now Uganda, Rwanda, Burundi, and eastern Congo.

Farmers liked the crop because of the high calorie yields per hectare, and its ability to protect the soil from erosion (Gabre-Madhin and Haggeblade, 2001). Uganda farmers grow some 60 different cultivars, the largest pool of genetic diversity anywhere in the world—and this despite the difficulties of undertaking crop improvement with a vegetatively propagated crop (De Langhe et al., 1996; Reader, 1997).

In recent times, while the banana remains an established staple, it is increasingly threatened by pests and fungal disease, and farmers have not been able to develop varieties sufficiently quickly to meet these new challenges. Tissue culture methods have been introduced to promote rapid and sterile multiplication of pathogen-free planting material. The KARI, in conjunction with a local private biotechnology company, has begun to produce in vitro banana plants commercially. These have been shown roughly to double both yield and income under farm conditions (Qaim, 1999). This farmer–scientist collaboration has supported the development of a highly suitable food security crop that currently accounts for over one-fourth of calorific consumption in countries such as Rwanda and Uganda. A commercial tissue culture laboratory is now established in Uganda, and tissue culture plants produced by a South African company have been used in national trials in Uganda.

Diversifying Into Export Horticulture

Kenya, with a high value tourist industry, developed local, quality vegetable production capacity in the 1950s. The rehabilitation of previously ecologically declining areas such as Machakos bear testimony to the positive effects of this industry on smallholders with access to markets associated with the expanding tourist industry in Kenya (Tiffen et al., 1994). In 1957, private traders in Kenya began expanding this trade into the export of off-season vegetables, and tropical and temperate fruits. After 1970, this trade expanded steadily as a result of growing demand in Europe, improved technologies and marketing systems for fresh vegetable distribution there, and substantial increases in air-freight space from Nairobi to Europe, a by-product of Kenya's booming tourist industry (Gabre-Madhin and Haggeblade, 2001).

The steadily increasing production quality standards, particularly in Europe, have led to a marked expansion in the considered use of pest control methods amongst the 500,000 smallholder vegetable farmers who today supply about 75% of all vegetables, and 60% of all fruits, under contract to exporters (Noor, 1996). Today, horticultural exports in Kenya generate over US$300 million in foreign exchange earnings, making Kenya a major world producer and exporter of horticultural products (HCDA, 2013). Uganda, Zimbabwe, and Zambia have all entered this market in recent years.

Smallholder Cotton Successes in Zimbabwe

In Zimbabwe, before the 1960s, virtually no cotton was grown by smallholders (Blackie, 1986). By 1980, some 42,000 Zimbabwean smallholders produced nearly a third of the national cotton crop. A few years later, the number of registered smallholder cotton growers had doubled, and they were producing consistently more than half the national cotton crop. By 2000 (a record year), over 80% of national cotton production was produced by smallholders. Not only were smallholders growing more cotton than their large-scale counterparts, typically they were producing higher quality lint through careful picking and sorting before delivery. Cotton had become the biggest smallholder cash crop in Zimbabwe. This rapid uptake of a new cash crop came about through the work of Melville Reid, one of the most innovative extension workers involved with Zimbabwean smallholders. Reid, through careful discussion with both farmers and research colleagues, made cotton an attractive crop by removing the obstacles facing smallholders. He devised a low-cost cotton production system suited to the family labor and cash availability of the typical smallholder household. He arranged training courses for farmers and for farm advisors, and ran regular field days to promote the crop. He also worked with the marketing agency to create a "smallholder friendly" marketing system.

LOOKING BEYOND THE FARM GATE

The story we have developed so far is founded on building from the bottom up—the poor are actively engaged in finding avenues through which they can change their own lives. But they cannot work alone—there are forces beyond their control that can outweigh what they can do for themselves. For a comprehensive analysis of the factors which trap the poor in poverty see, e.g., Conroy et al. (2006).

The fertilizer market offers challenges and opportunities. The inefficient supply chain, combined with highly variable international energy prices, make fertilizer exceptionally expensive to many farmers in remoter areas. Demand problems include the low profitability of high-cost inputs, significant output price and weather risks, problems of affordability (given high fertilizer prices relative to the incomes of poor farmers), ineffective fertilizer use, and hence low physical grain-to-nutrient responses. "Smart" subsidies can be provided to poor and vulnerable households in the form of vouchers, which can be used to develop, rather than undermine, rural agricultural input markets that serve the poor. Public resources then promote input use in a way that is more likely to foster the emergence of a sustainable, private sector-led input marketing system (Morris et al., 2007).

Morris et al. (2007) and Ariga and Jayne (2009), also point to the need for support to imaginative public−private partnerships. The government has a critical strategic role in the early stage of development, especially in remote areas, because it is unlikely that private traders will deliver research, extension, and credit services to smallholders (see Eicher, 2004, on Zimbabwe). The public sector role is to create an enabling environment for business development which includes providing macroeconomic stability, investment-friendly policies, and infrastructure development.

The potential is enormous. One of the major obstacles faced by the poor in the developing world is lack of access to information and to financial services. The widespread growth of mobile phone use, spurred on by low-cost handsets and competitive service provision, has opened new options to the rural poor. They can explore commodity and input prices easily. New services, such as Kenya's M-PESA money transfer system, allows simple, reliable, and cheap payments to be made by those previously excluded from the banking system. The system has grown to serve some 17 million customers in Kenya, and it now operates in six other African countries, as well as in Asia and Eastern Europe.

Trade and Subsidies

Suffice to say that, as commonly implemented, most subsidies to agriculture in the developing world are a spectacularly inefficient way of helping poor people. But this is only half the story—developed countries cheerfully subsidize their own agriculture by huge amounts. This matters, since the outcome is not only to support rich country farmers but, much more importantly, it directly takes income from the poor in poor countries.

The most effective way we could help the poor in poor countries would be to allow them to trade freely with the developed world (Pingali et al., 2006). Brazil and India, amongst others, have shown how effectively they can compete in the production (and processing) of cotton, sugar, soya beans, maize, and many other products—only to find their goods are shut out of the markets where consumers have the cash to purchase them. These market distortions mean that farm commodity prices in the developed world no longer reflect supply and demand. This leads, in the first instance, inevitably to a growth in production (beyond that which the national market can absorb). So the surplus is dumped on the international market—depressing prices in markets open to poor farmers. Space does not permit discussion of the full complexities of farm subsidies—either in the developed or the developing world. Hypothetically there are three effects that agricultural support measures in advanced countries may have on agricultural production in developing countries (Herrmann, 2006):

- *None*: because advanced countries produce and support different things from developing countries—temperate agricultural products as opposed to tropical ones.

- *Negative*: the elimination of agricultural support in advanced countries means the cost of food imports in developing countries rises as international food prices increase.
- *Positive*: the elimination of agricultural support in advanced countries increases international prices to which developing country farmers respond.

Herrmann (2006) shows clearly that the negative effects dominate. Trade is a key driver of economic growth. Developing countries, particularly in Asia, have used trade to break into new markets and transform their economies. However, in Africa, the last three decades have seen a collapse in the continent's share of world trade, from around 6% in 1980 to 2% in 2002 (Commission for Africa, 2005). The trade barriers imposed by the rich nations are "politically antiquated, economically illiterate, environmentally destructive, and ethically indefensible" (Commission for Africa (2005), p. 49)—but little effective is being implemented to do away with them (see, e.g., the case of cotton (Oxfam, 2004)).

The costs are substantial, as Oxfam (2004) illustrate, using the case of sugar subsidies: a product that developing countries are especially good at producing. The European Union (EU) is the world's second-biggest sugar exporter; yet the cost of producing a kilogram of sugar in the EU is more than six times higher than in Brazil. In addition, Oxfam (2004) claim that the EU subsidy is not just the US$1.5 billion of subsidies to farmers, it also includes a further US$0.63 m of "hidden subsidies" which go to large EU sugar refiners. On the Oxfam analysis, Brazil loses around US$500 m a year, and Thailand about US$151 m, even though these two countries are the most efficient sugar producers in the world. Less efficient, and poorer, African countries lose out as well: Mozambique lost some US$38 m in 2004 (as much as it spends on agriculture and rural development), while sugar subsidies cost Ethiopia what it spends on HIV/AIDS programs.

Developing an efficient value chain can bring enormous benefits to the poor and disadvantaged. Purchase (2014) estimates that agricultural exports from sub-Saharan Africa could triple by 2030 if quite achievable improvements in providing enhanced services for marketing, insurance, logistics, and finance were in place. Rukuni (2014) emphasizes that these services will largely come from the local informal sector, as households diversify into new activities. The future growth path of agriculture, particularly in sub-Saharan Africa, will not be the displacement of households from agriculture into industry, but directly into building the services needed for sustainable agricultural systems.

Disease

Any discussion of poverty is incomplete with consideration of disease. Take the effects of HIV/AIDS—a pandemic of increasing severity across the developing world. Governance, macroeconomic management, economic policy, health, HIV/AIDS, agricultural collapse, and hunger are all linked. Poor governance and macroeconomic stability deter investment and undermine growth, while the AIDS pandemic undermines the capacity to implement programs in poverty alleviation. Food crises exacerbate malnutrition and fuel the AIDS pandemic, as people are forced into high risk sexual behavior as a survival strategy. The threat of food shortages creates macroeconomic difficulties, as scarce foreign exchange is diverted to purchase and import food reserves, diverting resources from investment in development programs. External and internal debt rises inexorably. Recall Easterly's (2006) analysis which opened this chapter. World poverty need not persist, and could be halved within the coming decade. Billions more people could enjoy the fruits of the global economy. Tens of millions of lives can be saved. Practical solutions exist, the framework is established, and the cost is affordable.

An international development assistance regime which does what it claims to do would provide space for the many talented and concerned individuals in poor countries, who are too often sidelined at present, to begin to influence development policy (as they so ably did during the 2002 famine in Malawi) (A remarkable collaboration of individuals across the public, private, and voluntary sectors mobilized, at very short notice, a feeding and rehabilitation program in Malawi to provide emergency aid to nearly 3.5 million Malawians in an efficient and timely manner) for the benefit of all (Conroy et al., 2006). Rich countries could then know that their aid investments were, indeed, creating change for the better. Poor countries would no longer stagger from crisis to crisis, but would be able to put in place thoughtful, long-term strategies for development. The only losers would be the tyrants, people smugglers, and war mongers of rich and poor countries alike.

Aid built on a genuine sense of solidarity and mutual trust will put the economics of the poor world on durable developmental paths that go beyond ending hunger (Mkandawire, 2005). As Anne Conroy so passionately writes in the closing chapter of Conroy et al. (2006), 20 years ago President Julius Nyerere asked the governments of the West "Should we really starve our children to pay our debts?" It appears the (silent) answer was "Yes." "The heaviest burden of a decade of reckless borrowing is falling not on the military or on those who conceived the years of waste, but on the poor who have to do without necessities" (Peter Adamson quoted in Stephen Lewis (2005)). Return to Malawi. Malawi owes some US$3.1 billion, of which 82% is owed to multilateral creditors (the World Bank, the International Monetary Fund, and the African Development Bank), 17.5% to bilateral creditors, and 0.5% to commercial creditors. Debt service totaled US$112 million in 2004. Yet five million Malawians are in need of humanitarian assistance today—and there is a major gap between the resources pledged by the international community and requirements for both food aid (to keep people alive) and any substantial agricultural recovery program (to help Malawians pull themselves out of poverty). The cost of servicing Malawi's external debt will be malnutrition and famine unless someone mobilizes the resources to provide smallholder households with sufficient seed and fertilizer to increase productivity.

Stephen Lewis wrote angrily in June 2007:

> *Everyone is aware of the solemn promises that were made at Gleneagles in July of 2005. They followed in the wake of Tony Blair's Commission on Africa, with all of the attendant triumphalism, and it seemed to promise a new dawn for the African continent....Fast forward, then, to 2007 and the G8 Summit just completed in Germany. In the weeks prior to the Summit itself, quite predictably a number of groups and institutions took stock of the extent to which the promises at Gleneagles had been honoured. Every single assessment found a staggering shortfall...What actually happened in Germany is deeply, deeply troubling, and it's worthy of every piece of scorn that can be heaped upon it. The G8 communiqué is deficient in so many ways: fundamentally, it's intellectually dishonest and riddled with arithmetic sleight-of-hand.*

Lewis concludes—"It's a terrible thing we do to the uprooted and disinherited of the earth. Together, we must bring it to an end." He says it all (Lewis, 2007).

Concluding Comments

Ending poverty will require honest delivery of the commitments made at the multiple high levels meetings—Rio, Monterey, and Gleneagles—of new money provided to meet the needs of the poor in the developing world. Thandike Mkandwire is forthright:

> *....by the mid-1990s, "institutional reforms" − or "good governance", as this was popularly known in donor circles − became the new mantra in the policy world. A wave of institutional reforms swept across the African continent. Already by the beginning of the millennium, there were increasing doubts about the "institutional fix" and the institutionalists began to lose ground. While many countries had, under the aegis of the international financial institutions, introduced major institutional reforms, the economic recovery remained elusive. This prompted the new question, "Why is it that even when countries adopt the recommended polices and the right institutions, economic growth does not take place?" One response to this new question is that "institutions do rule", but the institutions peddled by the international financial institutions were the wrong ones, partly because of "mono-cropping" through the one-size-fits-all institutional design, and "monotasking" that insisted that all institutions should be harnessed to the protection of property rights.*
>
> *These institutions differed radically from not only those behind the East Asia miracle and China, but also from those of any successful case of development in modern times. Indeed, in the successful "late industrializers" many of*

> *the institutions being pushed as prerequisites for development never served the functions attributed to them and they were assiduously avoided in all strategies of "catching up" (Mkandawire, 2005).*

Mkandawire is right. National ownership and leadership are fundamental to coherent progress on development and poverty reduction. Enlightened political leadership at the national and international level is needed now more than ever before. The process has to be led by the nationals of the country—the "green evolution" concept can be developed to include faith communities, and civil society, and the technocrats have shown a remarkable ability to represent the needs and priorities of the poor. National governments will need explicitly to recognize the impact of their policies on the successful development of the concept at national and regional levels. Producers need high returns from investment in new technologies in order to provide them with incentives to invest in productivity increasing technologies; and poor consumers need low prices for food security, for welfare, and to raise real incomes to drive and support growth. Far sighted, long-term, and carefully implemented policies to support the transformation of the agricultural sector are needed to complement programs to alleviate the immediate impacts of food insecurity.

With imagination, effort, and hard work, change can come about. What is needed is for those in the developing world to be given the opportunity to express themselves as equals and not as supplicants. This will only happen when we transform values to genuinely respect the dignity and equality of all human beings.

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https://www.imperial.ac.uk/a-z-research/agriculture-for-impact/ An independent advocacy initiative led by Professor Sir Gordon Conway, author of the book "One Billion Hungry: Can We Feed the World?" It aims to enable better European government support for productive, sustainable, equitable, and resilient agricultural development in sub-Saharan Africa, focusing in particular on the needs of smallholder farmers. It also convenes the Montpellier Panel, a group of European and African experts in the fields of agriculture, trade, ecology, and global development.

http://www.odi.org.uk. The London-based Overseas Development Institute. A very useful source of well-documented case studies and research reports on development issues.

http://www.eldis.org. An excellent broad-based source of summaries of information from a wide range of development agencies.

http://www.africanhunger.org/. The Partnership to Cut Poverty and Hunger in Africa. A very high-powered group and some excellent publications. You have to join to access the website fully, and the costs are quite high unless your institution is paying. Lower costs apply to individuals and institutions in Africa.

http://www.scidev.net/. An international science and development network that publishes a wide range of challenging materials. There is a regular newsletter which always has information of interest, and a very accessible database.

http://www.irinnews.org/. This is a UN-based website that provides news updates in areas and fields that you can specify for yourself. It is a useful tool for keeping up-to-date on information from the field.

http://www.globalpolicy.org/. Another UN website—the Global Policy Forum. A very good source of information on a wide range of topics.

http://www.economist.com/. You need to be a subscriber and the journal is not cheap, but provides a wealth of accessible and well written materials. An excellent database and a very good source for teaching information, and for closely argued oversights on topics of importance in development. In particular, the following link takes you to an article on "The Green Evolution in sub-Saharan Africa."

http://www.economist.com/news/briefing/21694521-farms-africa-are-prospering-last-thanks-persistence-technology-and-decent.

http://www.n2africa.org/ This is an outstanding network. It reports on Africa focused work, but is an invaluable source of information on latest developments in soil fertility initiatives.

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