Chapter 26

Cultivated Systems

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Main Messages

Approximately 24% of Earth's terrestrial surface is occupied by cultivated systems. Cultivated areas continue to expand in some areas but are shrinking in others. As the demand for food, feed, and fiber has increased, farmers have responded by expanding the cultivated area, intensifying production (for example, higher yields per unit land-time), or both. Globally, over the past 40 years intensification of cultivated systems has been the primary source (almost 80%) of increased output. In countries with high levels of productivity and low population growth rates, the extent and distribution of land under cultivation is stabilizing or even contracting (for example, Australia, Japan, the United States, and Italy). The area in agricultural production has also stabilized and begun to contract in China. But some countries, predominantly found in sub-Saharan Africa, have had persistently low levels of productivity and continue to rely mainly on the expansion of cultivated area.

Globally, opportunities for further expansion of cultivation are reducing. Since nearly all well-suited land is currently cultivated, continued expansion draws more economically marginal land (steeper slopes, poorer soils, harsher climates, or reduced market access) into production—often with unwelcome social and environmental consequences.

Cultivated systems specialize in the provision of food, feed, and fiber, often at the expense of other ecosystem services. Cultivation has affected the provision of other services in three ways: by conversion of biologically diverse natural grasslands, wetlands, and native forests into less diverse agroecosystems; by the choice of crop species grown and the pattern of cropping in time and space; and by the manner in which crops, soil, and water resources are managed at both plot and landscape levels. For many ecosystem services, significant losses arise as a direct consequence of conversion to agriculture. Subsequent impacts are conditioned primarily by the intensity of cultivation in time and space, by the type and amount of applied inputs, including water, nitrogen, and pesticides, and by the effectiveness with which production inputs and residues are managed.

Two key "win-win" strategies have emerged to increase economic benefits to farmers while reducing negative ecosystem aspects of cultivation: first, increasing the productivity of existing cropland through intensive management of specialized cropping systems and use of improved crop, soil, and water management practices and, second, designing more diverse crop and agroforestry systems that provide improved livelihood options as well as supporting greater levels of biological diversity and other environmental services at a local level.

Because food security requires that increasing demand for food be met, difficult choices about ecosystem service trade-offs are faced when evaluating alternative cultivation strategies. For example, intensification of production to gain more output per unit land area and time runs the risk of unintended negative impacts associated with greater use of external inputs such as fuel, irrigation, fertilizer, and pesticides. Likewise, area expansion of production reduces natural habitat and biodiversity through land use conversion and decreases the other environmental services that natural ecosystems provide. Which strategy has the least overall impact on ecosystem services depends on the specific context.

This assessment strongly suggests that pursuing the necessary increases in global food output by emphasizing the development of more environmentally and ecologically sound intensification is likely to be the preferred, and in many cases the only, long-term strategy.

Improved cultivation practices can conserve biodiversity in several ways: sustaining adequate yield increases on existing cropland in order to limit expansion of cultivation, enlightened management of cultivation mosaics at the landscape scale, and increasing diversity within cropping systems. At the global level, conversion of natural habitat to agricultural uses is perhaps the single greatest threat to biodiversity. Hence, sustaining yield increases on existing farmland to meet growing human food needs will be essential for the conservation of existing biodiversity. At the local level, advances in ecological science coupled with field-based experimentation have yielded improved insights as to how farmers might configure and manage cultivated systems so as to enhance opportunities for wild biodiversity through, for example, habitat creation, wildlife corridors, refugia, and buffers around sensitive areas. More has also been learned about maintaining viable collections of wild relatives of commercially cultivated products, particularly in farming communities (in-situ conservation). But such approaches are most likely to be used where there are demonstrable benefits to farmers.

The economic benefits of pollinators, biological control of pests, soil bacteria, insects, birds, and other animals are better understood and are increasingly being articulated to farmers and the agricultural community. Successes include the rapid and extensive spread of integrated pest management in Southeast Asia and the growing acceptance of the role of sustainability-focused platforms such as eco-agriculture, agroecology, and integrated natural resource management by both subsistence and commercial farmers.

Cultivated systems have become the major global consumer of water. While rain-fed croplands might consume more or less water than the natural plant communities they replaced, irrigated areas consume significantly more. About 18% of the area of cultivated systems is irrigated, but the crop output generated by such irrigation represents about 40% of global food production. While irrigation systems divert 20–30% of the world's available water resources, chronic inefficiencies in distribution and application result in only 40–50% of that water being used in crop growth.

Growing water demand for uses other than agriculture is increasingly competing with water demand for food production in many areas, and more transparent and equitable approaches to water allocation are needed. There is significant scope to achieve substantial increases in irrigation efficiency from improvements in water delivery systems (irrigation system maintenance and design; drip irrigation) and from improvements in water application methods (improved irrigation scheduling). Water harvesting practices, including small tanks, runoff farming, and zai (dug pits that concentrate water at the plant), have also proved effective, as have structural landscape features such as shelterbelts that reduce evapotranspiration.

In addition to water quantity trade-offs, intensification of food production involving increased use of applied nutrients and agricultural chemicals can lead to water pollution that degrades downstream freshwater, estuarine, and marine ecosystems and that limits downstream water use or raises its costs. Technologies or practices that increase nutrient use efficiency and minimize the need for pesticide application can greatly reduce water pollution from intensive agriculture. Inappropriate farming practices on sloping land prone to erosion and expansion of rain-fed cropping onto sloping lands with marginal soils can result in severe erosion that also contributes to pollution of rivers, water bodies, and estuary or marine ecosystems.

Cultivation has accelerated and modified the spatial patterns of nutrient cycling. Most pressing is the disruption of the nitrogen cycle, caused primarily by the application of inorganic fertilizers, which included around 85 million tons of nitrogen in 2000. Nitrogen is the most commonly limiting plant nutrient and a major constituent of dietary protein. While some form of augmentation of naturally "fixed" N is an essential component of more productive cultivation, application of inorganic N increases emission of nitrous oxide, a potent greenhouse gas, and contributes to acid rain, soil acidification, and eutrophication and, through these changes, to biodiversity loss.

The best opportunity for limiting these negative effects is to increase the efficiency in the handling and application of fertilizers, as well as increased or rationalized use of organic sources of nitrogen (such as mulching, animal manure, and legume crops) to substitute for inorganic fertilizers and increase nitrogen use efficiency. Some landscape elements (ponds and buffer strips, for example) can also provide cost-effective means for mitigating water contamination. In some countries, notably the United States, Japan, and the Netherlands, there has been significant progress in improving N use efficiency and even in decreasing N application rates on several major cereal crops.

A clear distinction must be made, however, between the overuse or inefficient use of nitrogen in some parts of the world and the desperate need for substantial increases in the amount of nitrogen (and other nutrients) applied to crops in regions like sub-Saharan Africa where yields are low and often declining—precisely because of the cumulative depletion of soil nutrients. Phosphorus is another nutrient that must be applied to maintain crop yields on most agricultural soils, and lack of adequate phosphorus significantly limits agricultural productivity in regions where phosphorus fertilizers are not available or affordable.

The impact of cultivation on climate regulation can, as with biodiversity, best be viewed in two distinct stages. When natural ecosystems have been converted for cultivation, carbon-based greenhouse gases are generally released and carbon sequestration potential is reduced to an extent dependent upon the original land cover and the means of conversion. Thereafter, the impact of cultivation on climate regulation is intimately linked to production system choices and management practices. Frequent cultivation, irrigated rice production, livestock production, and the burning of cleared areas and crop residues now contribute about 166 million tons of carbon a year in methane and 1,600 ± 800 million tons in CO_2. About 70% of anthropogenic nitrous oxide gas emissions are attributable to agriculture, mostly from land conversion and nitrogen fertilizer use.

But while agriculture contributes to greenhouse gas emissions, it also represents an opportunity for mitigation. Minimum tillage and tree-based production systems are two of a growing number of practices being adopted by farmers for their direct productivity and income benefits, which also represent successful strategies for mitigating GHG emissions from cultivated systems. The cultivation of biofuels (such as corn, sorghum, and sugarcane used for ethanol production) is seen as having great potential, although these are of relatively minor significance at present. However, a growth in demand for biofuels would result in expansion of cultivated areas or displacement of traditional crops or both unless there is a concomitant acceleration in the rate of gain in crop yields to offset the grain and biomass used for biofuels and bio-based industrial products.

While better practices and new technologies have been and must continue to be developed to reduce the negative environmental impact of cultivation, such measures will only be adopted if they generate benefits for the farmer in a time frame of relevance to the socioeconomic context in which cultivation takes place. For example, adoption of improved soil and water conservation practices has been low in many developing countries where farmers are often poor and have few assets, limited access to credit, and uncertain access or rights to land and water resources. From an economic perspective, many negative ecosystem service impacts are production "externalities"—impacts whose costs, while real from a broader social perspective, are not factored into production decisions.

In richer countries, public funds are increasingly being used to provide incentives for producers to take greater account of the external negative impacts of production. These have included investments in payments to producers to help offset the additional costs of environmentally friendly practices, research and development of new technologies and practices that reduce the trade-offs between food provision and other ecosystem services, and environment-related regulation and enforcement systems for the agriculture sector. But the principle of engaging the potential beneficiaries of improved cultivation practices in some form of dialogue with producers continues to define new institutional arrangements to better manage production externalities. Examples are watershed user groups, commodity boards, organic certification systems, and trading of carbon credits.

National policies, international agreements, and market forces play a significant role in determining farmers' choices about the scale of cultivation, the selection of the cultivation system, and the level and mix of production inputs—all of which influence trade-offs among ecosystem services and external impacts on other ecosystems from cultivated systems. For example, where governments have invested in agricultural research and extension, productivity growth rates have been higher and area expansion rates often lower. Likewise, although investments in irrigation schemes and subsidized seeds, fertilizers, and pesticides have almost certainly resulted in depletion of river flows and increased salinization, eutrophication, and biodiversity loss, they have also led to greater productivity per unit of arable land, which reduces pressure for the expansion of cultivated systems into marginal areas and natural ecosystems. Agricultural subsidies in many industrial countries have encouraged overproduction while at the same time reducing the economic viability of cropping systems in poorer countries by driving down the prices of traded commodities such that unsubsidized (and sometimes domestically taxed) producers in those countries find it hard to compete.

Some, mainly richer, countries have introduced "conservation" or "set-aside" programs to encourage farmers to take environmentally sensitive land out of production. Others, such as Costa Rica, have gone further through programs that explicitly compensate farmers for delivering ecosystem services. Governments are playing an increasing role in ensuring that farmers will profit from cultivation choices that deliver the broad array of ecosystem services valued by society, including but not limited to food production.

Significant challenges will be faced at both global and regional levels to meet increasing food, feed, and fiber demand and to do so in ways that support key environmental services. At the global level, the rate of increase in cereal yields is falling below the rate of projected demand, which will likely lead to a large of expansion of cultivated area unless yields can be increased. Many more low-input systems in marginal lands may soon reach irreversibly low levels of soil quality and face increasingly erratic climatic patterns and new crop and livestock pests and diseases, such as coffee and banana wilt and avian flu. Such trends could lead to the collapse of important cash and food producing systems on a regional basis. There is also growing concern that market liberalization, coupled with the inability of farmers and governments in poorer countries to make the investments necessary to raise the productivity of their predominantly subsistence and smallholder agricultural sectors, may lead to further impoverishment of rural populations. A warmer global temperature associated with climate change is an emerging challenge to sustaining yield increases in currently favorable crop production areas and may decrease yield stability in dryland cropping systems dependent on rainfall.

26.1 Introduction

Human transformation of natural ecosystems for production of food, fiber, and fuel has occurred on a massive scale—cultivated systems now occupy 24% of Earth's terrestrial surface and are the single greatest land use by humans.[1] Although there are a wide variety of cultivated systems, this chapter focuses on those that constitute major providers of food, feed, or fiber or that have significant impacts on the provision of other ecosystem services, at regional or global scales. In this chapter, ecosystem services are divided into those that provide food, feed, fiber, and other cultivated outputs and ''other services'' that include, for example, biodiversity, fresh water, nutrient cycling, and cultural services.

Despite a tripling of the human population in the twentieth century, global food production capacity more than kept pace with demand. In fact, per capita food supply increased while food prices decreased in real terms. (See Chapter 8.) At the turn of the millennium, cultivated systems provided around 94% of the protein and 99% of the calories in human diets (FAOSTAT 2003). At the same time, they represented a major source of income for the estimated 2.6 billion people who depend on agriculture for their livelihoods (FAOSTAT 2004).

Despite these successes there are still many parts of the world, often the poorest, where the productive capacity of cultivated systems has stagnated or even declined in the face of increased food demand from growing populations. Local disruption of cultivation by drought, flood, pests, disease epidemics (crop, animal, or human), armed conflict, and social unrest can be catastrophic in human, economic, and environmental terms. The prospect of providing sufficient food to sustain another 2 billion people by 2020 has rightly focused attention on the very real threats to food security and income generation if the productivity of cultivated systems cannot keep pace with this demand.

But food security and concern for the more than 852 million who currently go hungry each day (FAO 2004) are only part of the challenge faced by cultivated systems. Human well-being depends not only on a sufficient and safe supply of food, feed, and fiber but also on access to clean water and air, timber, recreational opportunities, cultural and aesthetic pleasure, and so on. Cultivation often has a negative impact on provision of these services.

For example, cultivated systems tend to use more water, increase water pollution and soil erosion, store less carbon, emit more greenhouse gases, and support significantly less habitat and biodiversity than the ecosystems they replace. Hence, as the share of the world's natural ecosystems converted for cultivation has increased, the overall supply of ecosystem services other than food, feed, and fiber has fallen (Wood et al. 2000), despite growing demand for these additional services. Cultivated systems are under increasing pressure, therefore, to meet the growing need for cultivated products as well as to supply an amount and quality of other ecosystem services. Appropriately responding to this ''double burden'' represents a critical, long-term challenge to modern agriculture (Conway 1999; Runge et al. 2003).

This chapter assesses the global extent, distribution, and condition of cultivated systems with regard to their continued capacity to both deliver food, feed, and fiber and contribute to the broader range of ecosystems services on which human well-being depends.

26.1.1 The Emergence of Cultivation

Agriculture first emerged almost 10,000 years ago in several different regions, including Mesopotamia, eastern China, meso-America, the Andes, and New Guinea (Smith 1998). The extent of agriculture and its impact on ecosystem services tracks population pressures at local, regional, and global scales. While human population and agricultural extent maintained a relatively steady rate of increase for much of human history, both increased dramatically with the rapid rates of scientific discovery, economic development, and global trade that accompanied the Industrial Revolution and as a consequence of European economic and political control (Richards 1990). The direct impact of European settlement and accompanying agricultural technologies was seen in North and South America, Southern and Eastern Africa, and Australia/New Zealand. Other parts of the world also experienced significant cropland expansion as they connected to European markets.

In 1700, most of the world's cropland was confined to the Old World. (See Figure 26.1 in Appendix A.) While indigenous peoples elsewhere modified the landscape, their impact was not as large as that of the Europeans, who used more advanced cultivation technologies that supported higher population densities. Since 1700 cropland has increased by 1,200 million hectares (466%), including major expansion in North America and the former Soviet Union, with the greatest expansion occurring in the past 150 years. Indeed, more land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850.

The rate of cropland expansion in China has been steady throughout the last three centuries. Cropland in Latin America, Africa, Australia, and South and Southeast Asia expanded very gradually between 1700 and 1850, but subsequently expanded rapidly. Since 1950, cropland area in North America has stabilized, while it has decreased in Europe and China. Cropland area increased significantly in the former Soviet Union between 1950 and 1960 but has decreased since then. In the two decades before 2000, the major areas of cropland expansion were located in Southeast Asia, parts of Asia (Bangladesh, Indus Valley, Middle East, Central Asia), in the Great Lakes region of eastern Africa, and in the Amazon Basin. The major decreases of cropland occurred in the southeastern United States, eastern China, and parts of Brazil.

Since the middle of the twentieth century there has been a major shift in emphasis away from area expansion toward intensification of agriculture, which produces greater yields per unit time and area (Ramankutty et al. 2002). This shift was made possible by widespread investment in irrigation systems, mechanization, cost-effective means of producing inorganic fertilizers (especially nitrogen), and new crop varieties that could better exploit water and nutrients. Declining availability of suitable agricultural land and growing competition for land from human settlements, industry, recreation, and conservation have also increased pressure on existing farmland.

Hence, most of the increase in food demand of the past 50 years has been met by intensification of crop, livestock, and aquaculture systems rather than expansion of production area. For example, Bruinsma (2003) states that for all developing countries over the period 1961–99, expansion of harvested land contributed only 29% to growth in crop production versus the contribution of increases in yields, which amounted to 71%. Expansion of harvested land accounts for both expansion in arable land (23%) and increases in cropping intensity (6%). Furthermore, the share of growth in crop production attributed to yield increases varies by region; sub-Saharan Africa has the smallest portion (34%) and South Asia has the largest (80%). Inclusion of industrial countries lowers the global contribution of harvested area expansion to crop production growth, as a consequence of their greater reliance on increased yields.

Today, nearly all of the world's suitable land is already under cultivation. Although Africa and Latin America contain the majority of the world's remaining stock of potentially cultivatable lands, most of this currently supports rain forest and grassland savannas that provide many other ecosystem services and are crucial habitat for fauna and flora in natural ecosystems (Bruinsma 2003). In many parts of North America, Europe, Japan, and China, where productivity has grown faster than demand, land is increasingly being withdrawn from cultivation. The decline would likely be even more rapid in the United States, the European Union, and Japan in the absence of production-related subsidies (Watkins 2003). On a global basis, there has been a steady decrease in area devoted to the major cereal crops—maize, rice, and wheat, which account for the majority of calories in human diets—amounting to 2.4 million hectares per year since 1980 (FAOSTAT 2004).

26.1.2 Typology of Cultivated Systems

While there are several global frameworks for classifying the biophysical potential of agriculture (e.g., Koeppen 1931; Papadakis 1966; FAO 1982), none fully capture the enormous diversity of cultivated systems and practices on a global basis. The most comprehensive approach to date covers the farming systems of the developing world (Dixon et al. 2001), which identifies and characterizes a total of 44 crop, livestock, mixed, forest-based, and fishery-based systems, using agroecological, management, and commodity-related criteria. However, the omission of cultivated systems of North America, Western Europe, and Oceania limits its application to a global assessment.

In the absence of a widely accepted and truly global cultivated system framework, the MA assessment makes use of a schema built on easily accessible, more highly aggregated system characteristics, based on two key dimensions of cultivated systems—the agroecological context and the enterprise/management context. (See Table 26.1.) The agroecological context is defined by (sub-)tropical and temperate conditions, reflecting broad day length, radiation, and thermal differences, and by (sub-)humid and (semi-)arid conditions, reflecting differences in rainfall and evapotranspiration regimes. The importance and distinctiveness of highland and mountain cultivated systems in the (sub-)tropics is further recognized. Cultivation enterprises and practices themselves are divided into six broad categories: four crop-based categories (irrigated, high external-input rain-fed, low external-input rain-fed, and shifting cultivation) as well as confined ("landless") livestock production and freshwater aquaculture. Combining the agroecological and enterprise/management dimensions generates a matrix into which most of the world's important cultivated systems can readily be categorized. (Extensive grazing systems are not treated here as cultivated systems but are dealt with in Chapter 22.)

26.1.2.1 Irrigated Systems

The roughly 18% (250 million hectares) of total cultivated area that is irrigated accounts for about 40% of crop production (Gleick 2002). Irrigated systems are served by water from impoundment or diversion structures, boreholes, and wells or other means of delivering water. From an investment perspective, irrigation systems range from large civil engineering works delivering water to hundreds of thousands of hectares in Pakistan and India (Barker and Molle 2004) through farm-based wells that use small pumps to tap groundwater aquifers all the way to small-scale community-based systems powered by draught animals and manual labor, such as those found in West Asia, North Africa, and the Sahel (Oweis et al. 1999). In addition to increasing and stabilizing the yields of individual crops, irrigation can extend the growing period and allow two or even three crops to be grown each year on the same piece of land, where water availability and temperature permit such intensification.

26.1.2.2 Rain-fed Systems

Rain-fed agricultural systems account for the largest share (about 82%) of the total agricultural land area and exist in all regions of the world. In Asia and the Pacific, for example, rain-fed agriculture represents about 223 million hectares, or 67% of the total arable land (Asian Development Bank 1989), and rain-fed production accounts for 16–61% of agricultural GDP in this region (excluding Pakistan as part of West Asia).

Rain-fed systems are prevalent in both high and low yield potential areas, as largely determined by the amount and distribution of precipitation in relation to crop water requirements. Lower potential lands, also referred to as marginal or less-favored lands, are discussed in Chapter 22 (and also occur in higher-altitude mountain systems, see Chapter 24). The discussion here focuses on more-favorable rain-fed areas where both high and low levels of external inputs are used to produce crops. Pressure on these systems is increasing as arable land becomes scarcer; as the productivity of existing irrigated lands declines due to a reduction in water availability or to land degradation, especially salinization; and as food demand increases.

Rain-fed systems may involve both annual and perennial crops as well as livestock. In Asia, the rain-fed humid/sub-tropical systems and arid/semiarid areas include a range of mixed crop-livestock systems, which can be categorized into lowland and upland systems. The former is more associated with crop cultivation due to higher levels of soil moisture. Rain-fed lowland rice, for example, is defined as nonirrigated, but the topography is generally flat and the soil surface is inundated for at least part of the crop cycle with sustained flooding. Rain-fed upland rice, on the other hand, is grown on well-drained fields that are never flooded. Major rice cropping systems in the rain-fed lowlands are rice-wheat, rice-pulses (including chickpea, lentil, peanut, and pigeon pea), and rice-mustard. Maize, sugarcane, and cotton are also important crops in humid lowland areas of tropical/subtropical Asia. Cropping systems that use more drought-tolerant cereal crops such as sorghum and millet are found in semiarid rain-fed lowland areas.

The uplands, by comparison, have sloping to hilly topography, and typically have less fertile soil that is easily degraded by erosion and nutrient depletion without the use of appropriate husbandry practices. (See also Chapter 24.) Although both annual crops (such as cereals, legumes, roots, and vegetables) and perennial ones (such as coconuts, oil palm, rubber, and fruit trees) are grown, agroforestry systems involving the latter are especially important. Rain-fed areas have relatively large populations of livestock, and their contribution via animal manure to crop cultivation, food security, and the livelihoods of poor people is significant (Devendra 2000). Overstocking and uncontrolled grazing of ruminants are major problems in semiarid rain-fed regions where land tenure rights are not well defined, such as in the Sahel region of sub-Saharan Africa.

26.1.2.3 Shifting Cultivation

Shifting cultivation, also called "swidden" agriculture or "slash-and-burn" agriculture, is one of the oldest forms of farming and consists of cropping on cleared plots of land, alternated with lengthy fallow periods. These systems are the dominant form of agriculture in tropical humid and subhumid upland regions and are typically associated with tropical rain forests.

Table 26.1. Global Typology of Cultivated Systems with Examples

Farming System[a]		Tropical and Sub-tropical (62%)			Temperate (38%)	
		Warm Humid/Subhumid	Warm Semiarid/ Arid	Cool/Cold (Highland/ Montane)	Humid/Subhumid	Semiarid/Arid
		(26%)	*(12%)*	*(24%)*	*(22%)*	*(16%)*
Irrigated	(18%)	rice (e.g., East, Southeast Asia) rice-wheat (e.g., Pakistan, India, Nepal)	rice (e.g., Egypt, Peru)			cotton
Rain-fed—high external input (crops, livestock, tree crops	(82%)	rice-wheat (e.g., Pakistan, India, Nepal)		tea, coffee plantations (e.g., East Africa, Sri Lanka)	maize and soybean–Argentinean pampas, U.S. corn belt small grains (wheat, barley, rapeseed, sunflower, oats) and mixed crop-livestock systems (e.g., West and North Central Europe)	
Rain-fed—low external input (crops, livestock, tree crops)		staple tropical crops in humid tropics (e.g., yam, cassava, banana in SSA)	mixed crop, livestock (e.g., Sahel, Australia)	cereals/tubers (e.g., High Andes)	mixed crop–livestock systems (e.g., Europe)	wheat–fallow systems (e.g., Central Asia, Canada, United States, Australia)
Shifting cultivation	NA	e.g., Amazon Basin, Southeast Asia				
Industrial confined livestock	NA	"landless" livestock systems, e.g., cut and carry systems, mixed low-intensity livestock/crop systems, beef feeding lots, broiler and pig houses				
Freshwater aquaculture	NA	e.g., artisanal ponds, industrial cages				

[a] High-level aggregations of the global farming systems typology developed by Dixon et al. 2001.

Notes: Agroecological characterization according to FAO Global Agroecological Zones (FAO/IIASA 2001). Total area shares shown in parentheses are for settled agriculture (e.g., excluding shifting cultivation areas). Derived from FAOSTAT 2004. Breakdown of cropland by agroecological zones from Wood et al. 2000. The MA cultivated systems do not encompass marine and coastal aquaculture (Chapter 19) and extensive grazing systems (Chapter 22).

Shifting cultivation is practiced on about 22% of all agricultural land in the tropics and is the primary source of food and income for some 40 million people (Giller and Palm 2004). While the contribution to global food security is negligible, given the low yields and general lack of infrastructure in areas where shifting cultivation predominates, this method of cultivation has a potentially large impact on regional and global ecosystem services through its effects on biodiversity, greenhouse gas emissions, and soil nutrients. (For a more comprehensive analysis of such effects in the humid tropics, see the MA Sub-Global Assessment of the Alternatives to Slash and Burn program.)

Although these systems are generally associated with soils of low fertility, they are highly sustainable and resource-conserving in areas with low population density. High population density increases the pressure on available land and resources, reducing the time available for a regenerative fallow between cropping cycles. One method used to raise productivity and reduce land degradation in areas of shifting cultivation is ''alley cropping,'' growing tree crops in conjunction with annual crops. In the Philippines, for example, alley cropping in sloping upland rice areas with *Flemingia macrophylla* showed that over two years, average soil loss was cut down to 42 cubic meters per hectare, compared with 140 cubic meters under traditional practices, together with concurrent increases in rice yields (Labios et al. 1995).

26.1.2.4 Mixed Crop and Livestock Systems

Mixed crop-livestock farming systems, where crops and animals are integrated on the same farm, represent the backbone of smallholder agriculture throughout the developing world, supporting an estimated 678 million rural poor. In Asia, more than 95% of the total population of large and small ruminants and a sizable number of pigs and poultry are reared on small farms with mixed crop-livestock systems, which are dominant in both irrigated and rain-fed areas in humid and subhumid environments.

Mixed farming systems enable farmers to diversify agriculture, to use labor more efficiently, to have a source of cash for purchasing farm inputs, and to add value to crops or their by-products. Mixed farming systems provide the best opportunities to exploit the multipurpose role of livestock in many rural societies (Devendra 1995). A number of crop-animal interactions are important and dictate the development of mixed systems. These include animal traction for field operations, animal manure, and animal feeds from crops, as evident in sub-Saharan Africa (McIntire et al. 1992) and Asia (Devendra and Thomas 2002). These interactions have demonstrated the important contribution that animals make to increased production, income generation, and the improved sustainability of annual and perennial cropping systems.

Crop-livestock systems can be separated into those that mix animals with annual and perennial crops; of the two, the use of the latter has been more limited. Examples of integrated annual crop-animal systems include rice, maize, cattle, and sheep in West Africa; rice, wheat, cattle, sheep, and goats in India; rice, goats, duck, and fish in Indonesia; rice, buffalo, pigs, chicken, duck, and fish in the Philippines; rice, vegetables, pigs, ducks, and fish in Thailand; and vegetables, goats, pigs, ducks, and fish in Viet Nam. Examples of integrated perennial tree crop-animal systems include rubber and sheep in Indonesia; oil palm and cattle in Malaysia and Colombia; coconut, sheep, and goats in the Philippines; and coconut, fruit, cattle, and goats in Sri Lanka. In West Asia and North Africa, integration of sheep with wheat, barley, peas, and lentils is common, together with olives and tree crops.

With annual cropping systems, ruminants graze native grasses and weeds on roadside verges, on common property resources, or in stubble after the grain crop harvest. Crop residues and by-products are also fed to livestock throughout the year or seasonally, depending on availability. In the perennial tree crop systems, ruminants graze the understory of native vegetation or leguminous cover crops. Non-ruminants in these systems mainly scavenge in the villages, on crop by-products, and on kitchen waste. However, village livestock systems can evolve into more-intensive production systems depending on the availability of feeds, markets, and the development of co-operative movements. This is evident in many parts of Central America, West Africa (Nigeria), Southeast Asia (Indonesia), and South Asia (Bangladesh).

Because of the synergies between crop and livestock components, mixed crop-livestock systems have shown themselves to be both economically and environmentally robust from a smallholder perspective. It is likely that smallholder mixed farms will remain the predominant form of agricultural land use in rain-fed cropping regions in developing countries where labor is abundant.

26.1.2.5 Confined Livestock Systems

Confined livestock production systems in industrial countries are the source of most of the world's poultry and pig meat production and hence of global meat supplies. Such large-scale livestock systems are also being established in Asia to meet increasing demand for meat and dairy products. In addition, beef and mutton are produced from intensive confined feeding operations, the former mostly in North America and the transition states of Eastern Europe. The majority of sheep and goat fattening under ''landless'' (non-grazing) conditions occurs in the Near East and in much of Africa. Cut-and-carry, zero-grazing dairy production systems are similar to confined systems in industrial countries in that hand feeding and disposal of manure are involved. These systems involve cutting feed, crop residues, or litter and transporting them to livestock that are confined in pens on the farm.

The use of purchased cereals and oilseeds for feed in confined livestock systems allows separation of crop production and utilization of feed in livestock rations. These concentrated feeds are less perishable and easier to transport than the livestock products. Even if several kilograms of concentrates are needed to produce one kilogram of meat, it is still cheaper to establish the production system near the consumer market and to transport the feeds to the animals. A significant share of the increase in cereal imports to developing countries over recent decades has occurred to provide feed for the expanding poultry or pig industries (Delgado et al. 1999).

Animal confinement facilitates the management of nutrition, breeding, and health but increases the labor and infrastructure requirements for feeding, watering, and husbandry of the livestock. Apart from the capital embodied in the animals, additional investment is needed in providing fencing, housing, and specialized equipment for feeding and other activities. Special equipment is also needed for animal slaughter and meat processing or for milk cooling and processing. There are economies of scale in the provision of such processing services and the associated product marketing, and possibly in the supply of inputs (feed and feed supplements) and genetic material (such as day-old chicks or semen). This has often led to either co-operative group activity or vertical integration of smallholder producers with large-scale processing and marketing organizations.

While there are good economic arguments for the concentration of large numbers of animals associated with many confined systems, there can be significant impacts on surrounding ecosystems. Problems often arise in the disposal of large amounts of manure and slaughtering by-products. While some types of manure can be recycled onto local farmland, soils can quickly become saturated with both nitrogen and phosphorus because it is too costly to transport manure, which has relatively low nutrient concentration, for long distances. Manure treatment or digestion to produce methane can help minimize pollution, but even in countries with strong regulation and enforcement systems, nutrient and bacterial leakage to water courses can occur, with consequential impacts on freshwater and aquatic systems (de Haan et al. 1997; Burton et al. 1997).

Confined systems tend to be located near markets in peri-urban areas. Distance from these centers, or from their main transport routes, has an important influence on the net prices received for farm products. Similarly, location in relation to urban centers affects access to markets for purchased inputs and the costs of such inputs (Upton 1997). Transport costs vary from one commodity to another, depending on the perishability and bulk-to-value ratio. Milk and eggs are relatively perishable and therefore are most often produced intensively in peri-urban zones. Furthermore, agricultural enterprises dependent on purchased inputs, such as concentrate feeds, are likely to be established in peri-urban zones with easy access to input markets. In contrast, ruminant meat can be produced in more-distant rural areas and transported as live animals to urban markets for slaughter.

26.1.2.6 Freshwater Aquaculture Systems

Aquaculture involves the propagation, cultivation, and marketing of aquatic plants and animals from a controlled environment and usually involves tenure and ownership, as opposed to the open-access or common property systems that occur in land agriculture. Aquaculture can be applied in coastal (mariculture), brackish, or fresh water (inland), but this chapter focuses on freshwater aquaculture. (Coastal and brackish aquaculture systems are discussed in Chapter 19.) There are four types of production systems: ponds, cages, raceways, and recirculating systems:

- Earthen ponds are most common for both small-farm and commercial production systems, and they may be specifically designed and built for aquaculture. Ponds for aquaculture (called dike or levee ponds) require an adequate amount of water of sufficient quality and clay soils that retain water. The size of a levee pond depend on its planned usage, whether as a holding, spawning, rearing, or grow-out pond.
- Cage culture uses existing water resources (lakes, ponds) but encloses the fish in a cage or basket that allows water to pass freely. Its main advantage is ease of harvesting. Small lakes, mining pits, and farm ponds may be used for cage culture. The potential for expanding cage farming is more limited in areas where freshwater bodies are already actively used.

- Rectangular raceways are mostly used in industrial countries (whereas ponds and cages are common in developing countries). Rectangular raceways are almost exclusively used for trout production and require large quantities of cheap, high-quality water. Using gravity, water passes from a spring or stream through raceways arranged in a series on slightly sloping terrain.
- Water recirculating systems are also common in industrial countries. Water is recirculated rather than passing through once; hence, less water is needed than for a pond or open raceway. Most recirculating systems are indoors, allowing growers to maintain more control on water characteristics like temperature. Clearly, this type of production requires high initial capital investment.

In addition, production systems can be distinguished by the level of production intensity or amount of inputs (labor, feed, materials, or equipment) used. Such production intensity can be extensive, where low levels of external inputs result in lower production levels, or intensive, where higher levels of inputs of technology and greater degree of management generally increase yield (FAO 2003).

Aquaculture can also be land-based or water-based. Land-based aquaculture consists mainly of ponds, rice fields, and other facilities built on dry lands. Carp and tilapia are the most commonly grown species in freshwater ponds, while shrimp and finfish are cultivated in brackish-water ponds. Water-based systems include enclosures, pens, cages, and rafts and are usually situated in sheltered coastal or inland waters. Pens and cages are made up of poles, mesh, and netting. Cages are suspended from poles or rafts that float, while pens rest on the bottom of the water body (FAO 2003).

Unlike livestock, where only a limited number of species are farmed, aquaculture production involves many species of aquatic organisms, although some predominate. In freshwater aquaculture alone, some 115 freshwater species of finfish, crustaceans, and mollusks were cultured in 2000, with finfish contributing the bulk of production. Over the period 1991–2000, carp (and other cyprinids) and tilapia (with other cichlids) ranked first and second respectively in global freshwater fish production, accounting for 76–82% and 5–6% respectively of the total (FAO 2002).

Though a number of freshwater species were cultivated, only a few freshwater species, like carp, milkfish, and tilapia, have been domesticated—that is, breeding agencies (government and private) produce fry as a source of fingerlings for aquaculture. This contrasts with the livestock and crop sectors, where selective breeding has been able to develop superior animal breeds and crop varieties suitable for intensive production. As a result, many forms of freshwater aquaculture are still very dependent on wild sources of fish spawn, seed, or young fish.

Aquaculture operations can have both positive and negative impacts on the environment. On the positive side, if aquaculture is integrated with agriculture, environmental benefits include recycling, lower net pollution, and reduced use of pesticides and fertilizers. On the other hand, some aquaculture operations can have damaging effects on water quality and quantity and aquatic biodiversity—similar to the externalities associated with confined livestock feeding operations or intensive, high-input cropping systems.

26.1.2.7 Major Cropping Systems

Among the tremendous diversity of crops and cropping systems, both in terms of agroecologies and management practices, five major cropping systems stand out in importance. These systems supply a substantial portion of the world's food, occupy a large portion of the world's cultivated lands, or both. The major systems are shifting cultivation in the forest margins of tropical Africa, Asia, and Latin America; irrigated lowland rice systems in Asia; irrigated rice-wheat systems in the Indo-Gangetic Plains of India, Pakistan, Nepal, Bangladesh, and south-central China; rain-fed wheat in north, west, and central Europe; and rain-fed maize-soybean systems in the United States, southeast Canada, Argentina, and south-central Brazil. Estimates of the scale of these systems are provided in Table 26.2.

The highly productive irrigated rice-based cropping systems are practiced in regions with fertile soils and access to supplementary ground or surface water. The wheat and maize-soybean rotations are located on deep, fertile soils in regions that typically have adequate and consistent rainfall during the growing season. Because of these natural endowments, these systems provide food to about half the human population and do so on a relatively small area. In addition to meeting local food needs, these systems account for more than 80% of all grains that enter international markets.

To sustain high yields in these systems, modern farming practices are employed, including high-yielding varieties and hybrids, substantial fertilizer inputs, and integrated pest control methods that include use of herbicides, insecticides, and fungicides when other management practices are inadequate. For example, three cereals—rice, wheat, and maize—receive 56% of all nitrogen fertilizer applied in agriculture (Cassman et al. 2003). Yield increases in these systems during the past 50 years are estimated to have avoided the need to expand cultivation by hundreds of millions of hectares globally, thus helping to maintain the ecosystem services derived from tropical and temperate forests, grasslands, and wetlands (Waggoner 1994; Evans 1998; Cassman 1999). Given the 670 million hectares of global cereal production in 2000, each 1% increase in productivity is equivalent to saving 6.7 million hectares of additional land that would be required for cereal production, keeping cropping intensity constant. (For a discussion of cropping intensity, see Bruinsma 2003:127–37.)

However, the relatively high levels of nutrients, pesticides, and water applied to these systems can deplete water resources, reduce water quality, increase greenhouse gas emissions, and accelerate the loss of terrestrial and aquatic biodiversity (Hooper et al. 2003; Mineau 2003). While nutrient losses from applied nitrogen fertilizer via denitrification release N_2O, a powerful greenhouse gas, to the atmosphere, recent studies have also demonstrated that these intensive cropping systems can sequester carbon in soil organic matter, thus reducing global emissions of CO_2 (Bronson et al. 1998; Lal et al. 2003; Paustian et al. 1997). Achieving global food security for an increasing and rapidly urbanizing population will depend on sustaining continued yield increases in these major high-potential cereal production systems.

The key challenge to sustaining cereal yield increases to meet anticipated demand while also protecting ecosystem services is to use crop and soil management practices to greatly increase the efficiency with which fertilizers, water, and other external inputs are used. For example, greater efficiency of nitrogen fertilizer use allows more grain to be produced per unit of applied nitrogen, reducing nitrogen losses and diminishing associated negative impacts on ecosystem services (Dobermann and Cassman 2002). Likewise, substantial increases in water use efficiency can be achieved by investment in improved irrigation infrastructure, better irrigation scheduling, and application equipment, such as a shift from furrow irrigation to subsurface drip irrigation (Howell 2001). Ensuring continued progress toward ecological intensification of these major cereal cropping systems requires long-term and sufficient investments in research and extension.

Table 26.2. Extent of the World's Major Cropping Systems and Population Dependent on Them as the Major Source of Cereal Supply. The population given is of the countries or regions where these cropping systems represent the predominant form of agriculture. Food production from the high potential systems, which include the two irrigated rice-based systems, rain-fed wheat, and rain-fed maize-soybean, not only accounts for a major food source for the countries and regions in which they occur but also accounts for a large majority of all traded grain that crosses international borders. (Compiled from Giller and Palm 2004; Dixon et al. 2001; Huke and Huke 1997)

Cropping System	Area *(mill. hectares)*	Population *(million)*	Region/Countries
Shifting cultivation	1,035	40	Forest margins in tropical Africa, Asia, Latin America
Irrigated continuous lowland rice	24[a]	1,800	Tropical/sub-tropical lowlands of Asia
Irrigated rice-wheat annual double crop	17[a]	248	Indo-Gangetic Plains of India, Pakistan, Nepal, Bangladesh, and south-central China
Rain-fed wheat	40	500	North, west, central Europe
Rain-fed maize-soybean	85	420	United States, southeast Canada, Argentina, southcentral Brazil
Total	1,227	2,968	

[a] Continuous irrigated lowland rice systems in the tropics and sub-tropical lowlands of Asia produce two and sometimes three rice crops per year. A total of 49 million hectares of harvested rice is obtained from these systems (McLean et al. 2002; Huke and Huke 1997). Similarly, the rice-wheat systems produce 17 million hectares of each crop on an annual basis, for a total harvested grain area of 34 million hectares (Huke and Huke 1997), which supports an agricultural population of 248 million (Dixon et al. 2001).

26.1.2.8 Assessing the Global Distribution and Intensity of Cultivated Systems

While the global typology is helpful in broad stratification of the major cultivated systems, the spatial extent, distribution, and condition of cultivated systems requires further analysis. For mapping purposes in this assessment, the global extent of cultivation has been defined on the basis of rain-fed and irrigated croplands only. There is no comprehensive information, even at a national scale, on the number and location of industrial livestock and freshwater aquaculture enterprises.

The global cropland map is a composite of an updated version of the 5-kilometer resolution PAGE Agroecosystems Map (Wood et al. 2000) that incorporates revisions of the underlying 1992–93 1-kilometer resolution AVHRR datasets, combined with the 10-kilometer resolution global irrigation map produced by University of Kassel and FAO (Döll and Siebert 1999).[2] (See Figure 26.2 in Appendix A.) The revisions aim to identify all occurrences of agriculture, even those that are minor cover components under the classification scheme. (This was limited by the seasonal land cover naming convention, which did not identify an agricultural component if it occupied less than 30% of the land cover class area.)

Intrinsic weaknesses in the dataset include regional variations in the reliability of the satellite data interpretation, reflecting differences in the structure of land cover and in the availability of reliable ground truthing data (Brown and Loveland 1998) (See Box 26.1.) Specific agricultural land cover types for which interpretation is considered problematic include irrigated areas, permanently cropped areas (especially tree crops in forest margins), mixed smallholder agriculture, and extensive pasture land.

For mapping purposes, the extent of cropland is defined as areas where at least 30% of a 1x1-kilometer grid cell is classified as cropland through the interpretation and ground truthing of satellite imagery. By this definition, it is likely that a significant share of the 1,035 million hectares of shifting cultivation as practiced in the humid tropics is not detected and classified as cropland because fallow periods are typically greater than five years, implying that no more than 20% of the land area is actually planted to crops at any given point in time.

Within the physical extent of cultivated systems (rain-fed and irrigated cropland), an existing agroecologically based characterization schema has been used to delimit cultivation system subtypes (Wood et al. 2000). This is a 16-class schema that provides a spatial visualization of the location and extent of most elements of the cropland typology presented in Table 26.1. (See Figure 26.3 in Appendix A.) The classification of climatic variables into tropical, sub-tropical and temperate, humid, subhumid, semiarid, and arid are made in accordance with FAO's agroecological zones approach implemented in a global spatial database (FAO/IIASA 2001). The agroecological classification also relies on slope and the presence or absence of irrigation technologies. Slope is an important attribute in terms of potential for mechanization as well as for increased surface runoff and soil erosion due to cultivation. The slope data used in this characterization are also derived from the FAO/IIASA digital agroecological database, and the irrigation data are from Döll and Siebert (1999).

Cultivated systems are extensive. Globally, they cover 36.6 million square kilometers, or approximately 27% of land area (24% if inland waters, Greenland, and Antarctica are included in the definition of land area). (See Table 26.3.) By intersecting the extent of agriculture with maps of global population, it is estimated that 74% of the world's population lives within the boundaries of cultivated systems and that cultivated systems overlap in significant ways with other systems, such as forests, mountains, and drylands. Close to half of all cultivated systems are located in dryland regions, where cultivation is strongly linked to livelihoods and resource issues—particularly poverty, land degradation, and water scarcity.

The characterization presented in Figure 26.3 identifies domains within which biophysical and environmental constraints and opportunities are broadly similar from a cultivation perspective and where common ecosystem service impacts might be faced. However, as this chapter illustrates, it is the specific type of cultivation practiced in any location and the precise ways in which cultivation is managed that ultimately determine the type and scale of impacts on ecosystem services and human well-being. Integrating additional information about the ways in which cultivated systems are managed can only be accomplished at smaller geographic scales (see, e.g., Dixon et al. (2001) for a regional ap-

BOX 26.1

Reliability of Satellite-based Global Assessments of Cultivated Systems

Obtaining global-scale information about the location and extent of cultivated systems is fraught with difficulties. Satellite-based remote sensing offers a visualization of land cover for the entire globe in a more or less uniform way, and several publicly available, coarse-resolution (1km pixel size) datasets offer opportunities for locating cropland. These include Global Land Cover 2000 (GLC2000), MODerate resolution Imaging Spectrometer (MODIS) land cover, GLCCDv2, and the cultivated systems extent used by the MA, which is a cropland-focused reinterpretation of GLCCDv2. (More information on these datasets is available at edcdaac.usgs.gov/glcc/background.asp (GLCCDv2), www-gvm.jrc.it/glc2000 (GLC2000), and edcdaac.usgs.gov/modis/mod12q1.asp (MODIS). The MA reinterpretation of GLCCDv2 is based on methods described in Wood et al. 2000.)

However, a comparison of these data sources reveals large differences in the extent and distribution of areas classified as cropland. The GLCCDv2 imagery and the MA extent represent land cover in 1992–93, while the GLC2000 and MODIS imagery are for the year 2000. Clearly, land cover change took place between these years, but the significant differences between the 1992–93 and 2000 cropland areas, as well as those between the two 2000-based assessments of cropland, cannot be explained by changes over time alone. Many of the differences result from the use of different data sources, methodologies, and classification systems. These findings raise concerns about our present ability to detect cropland reliably using globally applicable analysis of coarse-resolution data sources, and they cast extreme doubt on the possibility of assessing cropland change by comparing global data sets from different sources.

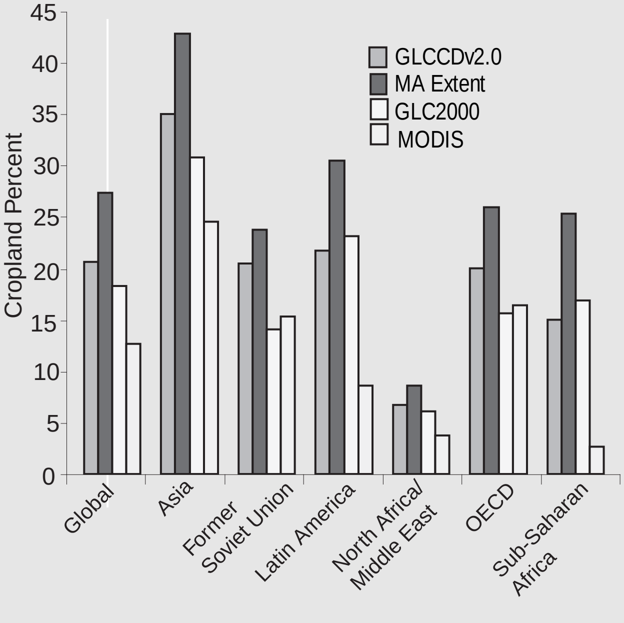


Figure A. Comparison of Cropland Estimates by Region and Data Source

Figure A compares the share of land area that falls within the extent of cultivated area, by region, for these four different land cover data sets. The extent of cultivation is defined as any cell classified as cropland or a cropland mosaic. Cropland mosaics are areas that appear in the imagery as composites of multiple landscape types (cropland and forest, for example, or cropland and grassland). The variations across the globe are large: in sub-Saharan Africa, MODIS land cover classifies less than 3% of the total land area as cropland, while according to the classification adopted by the MA, just over 25% of land in sub-Saharan Africa falls within the extent of cultivated area.

Part of this discrepancy is definitional. For mapping purposes, the MA classifies areas as "cultivated systems" if at least 30% of the land cover grid cell appears to be cropland. MODIS land cover and GLC2000, on the other hand, use higher cutoffs of about 50% cropland. The MA considers that ecosystem services are already likely to be significantly affected by cultivation at the lower cutoff.

Most of the differences among datasets involve the "mosaic" land-cover classes. Mosaic landscapes are some of the most important ones from an ecosystem service perspective, as they are likely to be transitional areas where change is taking place or where agricultural systems exist in close proximity to natural biodiversity. They are also some of the hardest to classify. In contrast to large, intensively farmed agricultural systems found in much of the industrial world, smaller plots of agricultural land, mixed in with forest or grassland, are more difficult to distinguish. Isolated or even clusters of small cultivated plots and fields, even if they can be identified as agriculture, are easily lost due to the coarse resolution of the data.

Figure B (see Appendix A) compares the geographic location of cropland and cropland mosaic classes used by the MA to the MODIS and GLC2000 land cover classifications for Africa. Africa is among the most challenging continents for mapping cropland because of generally small field sizes and mixed cropping systems. Areas of agreement are shown in orange, and areas of near-agreement (classified as cropland in one dataset and cropland mosaic in the other) are shown in yellow. Blue areas are those classified as either cropland or cropland mosaic by the MA, but not classified as cultivated in the other data sets. Much of the additional area within the MA cultivated systems compared with other datasets can be attributed to its lower threshold for defining cultivated landscapes—that is, a grid cell is considered to be a cultivated system if at least 30% of it is cropland.

Given the difficulties in classifying cultivated areas using coarse resolution satellite data, cultivated area maps and statistics derived from such data should be interpreted with caution. Mapping changes over time presents an additional set of challenges, as it requires comparing data sets that may be mismatched in multiple ways. Much more needs to be done to improve the reliability of publicly available regional- and global-scale spatial cropland data, including improved use of higher-resolution data such as LANDSAT and SPOT imagery, the use of consistent methodologies and classification systems over time, and field validation.

proach and Wortmann and Eledu (1999) for a national application in Uganda).

26.2 Cultivated Systems and Ecosystem Services

To achieve increased production of food, feed, and fiber, cultivated systems use biodiversity and numerous supporting, regulating, and provisioning services such as pollination, nutrient cycling, soil formation, and fresh water for irrigation. While cultivated systems depend on such services, they in turn also influence the supply of a host of other services, including food, feed, and fiber; clean water; climate regulation; pollution control; flood control; viable populations of wildlife; clean air; and scenic qualities (Allen and Vandever 2003). Some types of production systems, such as

Table 26.3. Area and Population of Cultivated Systems and the Extent of Cultivation in Other MA Systems.

	Cultivated Total		Drylands		Mountains		Coastal		Forest	
System	**Area**	**Population**	**Area**	**Population**	**Area**	**Population**	**Area**	**Population**	**Area**	**Population**
	(thousand km²)	*(million)*	*(thousand km²)*	*(million)*	*(thousand km²)*	*(million)*	*(thousand km²)*	*(million)*	*(thousand km²)*	*(million)*
Temperate										
10 Irrigated and mixed irrigated	1,684	554.2	999	249.8	245	39.7	179	110.7	166	43.5
11 Rain-fed, humid and subhumid, flat	3,954	463.9	935	93.5	274	45.6	284	69.9	965	75.7
12 Rain-fed, humid and subhumid, sloping	2,380	254.5	238	21.6	680	61.2	17	4.4	1,191	83.5
13 Rain-fed, arid/dry and moist semiarid	6,041	172.4	4,832	116.6	1,104	47.3	47	3.1	1,407	27.0
Moderate cool/cool/cold tropics										
20 Irrigated and mixed irrigated	1,501	20.5	71	5.1	72	8.1	7	0.8	34	8.5
21 Rain-fed, humid and subhumid	1,098	110.8	370	16.2	743	65.4	19	2.6	417	26.6
Moderate cool/cool/cold sub-tropics										
30 Irrigated and mixed irrigated	1,428	262.7	1,042	148.1	342	31.1	73	35.5	173	39.6
31 Rain-fed, humid and subhumid	4,028	496.7	642	63.9	1,482	201.5	299	33.8	1,320	162.6
32 Rain-fed, dry and semiarid	1,684	73.9	1,407	51.9	596	27.7	48	1.5	150	6.6
Warm tropics and sub-tropics										
40 Tropics, irrigated and mixed irrigated	989	328.4	395	105.7	88	23.8	202	127.3	162	40.5
41 Sub-tropics, irrigated and mixed irrigated	1,245	509.0	714	335.3	124	36.7	133	85.3	178	43.6
42 Rain-fed, humid, flat	1,721	197.0	214	30.7	73	14.7	325	40.5	659	52.2
43 Rain-fed, subhumid, flat	2,709	168.3	646	32.5	94	66.3	100	16.8	1,237	62.5
44 Rain-fed, humid/ subhumid, sloped	2,783	192.9	293	19.3	980	66.3	100	16.8	1,237	62.5
45 Semiarid/arid, flat	4,028	262.7	3,042	199.0	460	29.3	102	12.0	983	50.2
46 Semiarid/arid, sloped	476	41.0	417	37.1	83	7.3	17	2.3	77	4.1
Total	**36,614**	**4,104.9**	**16,256**	**1,526.4**	**7,439**	**710.6**	**2,051**	**617.8**	**9,863**	**747.4**

Note: By definition, these MA systems may overlap spatially, so area totals cannot be added across columns without risk of counting areas and populations twice. Note also that the global cultivated total includes areas and populations contained in ecosystems other than those shown in the breakouts.

multitiered, tree and crop-based farming systems, can be very effective in building up soil nutrients, reducing soil erosion, enhancing water-related, climate, and flood regulation services, and even promoting biodiversity. But they often possess other features less attractive to farmers, such as high labor needs, longer establishment and payoff times, or lower food productivity.

Because cultivated systems are so extensive, pressure is growing for them to make a greater contribution to meeting human needs for services other than food, feed, and fiber. They may do this by being managed to have less impact on supporting and regulating services, by consuming fewer provisioning services, or by supplying more of all three types of services. Moreover, effects on specific services at a local level may differ from the aggregated effects of a given cultivated system at a regional or ecosystem level.

26.2.1 Biodiversity

There are several dimensions to biodiversity in cultivated systems. These systems contain cultivated or "planned" biodiversity—that is, the diversity of plants sown as crops and animals used for livestock or aquaculture. This is largely domesticated biodiversity and is supplemented by wild food sources. Together with crop wild relatives, this diversity comprises the genetic resources directly needed for food production. (See Table 26.4.)

Agricultural biodiversity is a broader term, also encompassing the "associated" biodiversity that supports agricultural production through nutrient cycling, pest control, and pollination (Wood and Lenne 1999). Sometimes biodiversity that provides broader ecosystem services such as watershed protection, as well as biodiversity in the wider agricultural landscape, is also included in this term (FAO/SCBD 1999; Cromwell et al. 2001; Convention on

Table 26.4. Biodiversity and Cultivated Systems

	Inside Cultivated Systems	Outside Cultivated Systems
Components of production	*crops, livestock, aquacultured fish*	*wild food sources*
Sources of genetic improvement	*crops and crop wild relatives*	*crop wild relatives (also ex situ collections in gene banks and breeders collections*
Biodiversity providing ecosystem services to agricultural production	"associated biodiversity" including soil biota, natural enemies of pests and pollinators, as well as alternative forage plants for pollinators; alternative prey for natural enemies	alternative forage plants for pollinators etc. in the wide landscape
	biodiversity that protects water supplies, prevents soil erosion, etc.	biodiversity that protects water supplies, prevents soil erosion, etc.
Other biodiversity	other biodiversity, including species of conservation/aesthetic interest (e.g., farmland birds)	other wild biodiversity

Key:
italics Definition of genetic resources for food and agriculture
▢▨ Different definitions of "agricultural biodiversity"

Biological Diversity 2000). In addition, cultivated systems contain biodiversity beyond that used in or directly supporting production systems. Since agriculture is now so widespread, strategies for biodiversity conservation should address the maintenance of biodiversity within these largely anthropogenic systems as well as the aggregate impact of various cropping systems and management practices on biodiversity at regional levels.

The multiple dimensions of biodiversity in cultivated systems make it difficult to categorize production systems into "high" or "low" biodiversity systems, especially when spatial and temporal scales are also included. Figure 26.4 attempts to illustrate how different types of production systems relate to three biodiversity-related variables (building upon the approach of Swift and Anderson (1999)). The Figure also focuses on a single production system—tropical lowland rice—to illustrate how the levels of various dimensions of biodiversity can vary with management practice.

Thus the relationship between cultivated systems and biodiversity is manifold: biodiversity is cultivated in such systems (genetic resources for food and agriculture); biodiversity supports the functioning of cultivated systems (associated agricultural biodiversity); and cultivated systems harbor biodiversity beyond agricultural biodiversity of functional significance. In addition, cultivated systems have an impact on biodiversity outside the cultivated field in surrounding areas and through both expansion and intensification of agriculture. The following sections focus on these four issues.

26.2.1.1 Maintenance of Cultivated Species and Genetic Diversity

Diversity at species and genetic levels comprises the total variation present in a population or species in any given location. The cultivated species diversity of some production systems such as shifting cultivation and home gardens is high. Most major staple crops, however, are grown in monoculture. Even such systems may contain other dimensions of agricultural biodiversity: intensive rice "monocultures," for example, can support small areas of vegetable cultivation (on the dikes between paddies) as well as fish cultivation. In fact, in some rice-growing areas in South and Southeast Asia, fish may provide most of the local dietary protein. Genetic diversity can be manifest in different phenotypes and their different uses. It can be characterized by three different facets: numbers of different entities (such as the number of varieties used per crop or the number of alleles at a given locus); evenness of the distribution of these entities; and the extent of the difference between the entities (as in the case of pedigree date, for example) (UNEP/CBD 2004). Crop genetic diversity can be measured at varying scales (from countries or large agroecosystems to local communities, farms, and plots), and indicators of genetic diversity are scale-dependent.

The conservation and use of plant genetic resources for food and agriculture has been comprehensively reviewed by FAO (FAO 1998). Since 1960, there has been a fundamental shift in the pattern of intra-species diversity in farmers' fields in some regions and farming systems as a result of the Green Revolution. For major cereal crops, the germplasm planted by farmers has shifted from locally adapted and developed populations (landraces) to more widely adapted varieties produced through formal breeding systems (modern varieties) (Smale 2001, 2005; Heisey et al. 2002; Morris and López-Pereira 1999; Morris and Heisey 1998; Cabanilla et al. 1999). While there is no absolute dichotomy, traditional, landrace-based farming systems tend to contain higher levels of crop genetic diversity in situ than modernized systems. Depending upon the species (and its breeding system), traditional landrace-based farming systems also tend to include a higher number of varieties and more genetic variation within varieties.

Adoption of modern varieties among the three major cereal crops—wheat, rice, and maize—has been most rapid where land is scarce and where there is a high degree of market integration. In general, modern varieties of these crops have been adopted in "high potential" production areas, which have favorable climatic conditions, good soils, and either adequate rainfall or irrigation. They have been less successful in marginal areas, where landraces are still widely cultivated and are often the main source of crop germplasm.

Roughly 80% of the wheat area in the developing world is sown to modern semi-dwarf varieties. However, landrace varieties are grown extensively in Turkey, Iran, Afghanistan, and Ethiopia, with smaller pockets in countries of the Near Eastern and Mediterranean region (Morocco, Tunisia, Syria, Egypt, Cyprus, Spain, and Italy) (Heisey et al. 2002). Over three quarters of all rice planted in Asia is planted to improved semi-dwarf varieties, although farmers continue to grow landrace varieties in upland rain-fed areas, as well as in deep-water environments. Landrace varieties are grown in upland areas of Southeast Asia (Thailand, Laos, Viet Nam, and Cambodia), as well as in parts of West Africa (such as Mali and Sierra Leone) (Smale 2001; Cabanilla et al. 1999).

Relative to wheat and rice, maize has a much higher proportion of area planted to landraces. In Latin America, most of the maize area is planted to landraces, as is a higher proportion of the maize grown in sub-Saharan Africa (Morris and López-Pereira 1999). However, it can be expected that there has been genetic exchange between modern maize varieties or hybrids and maize landraces in some of these areas (Morris and Heisey 1998).

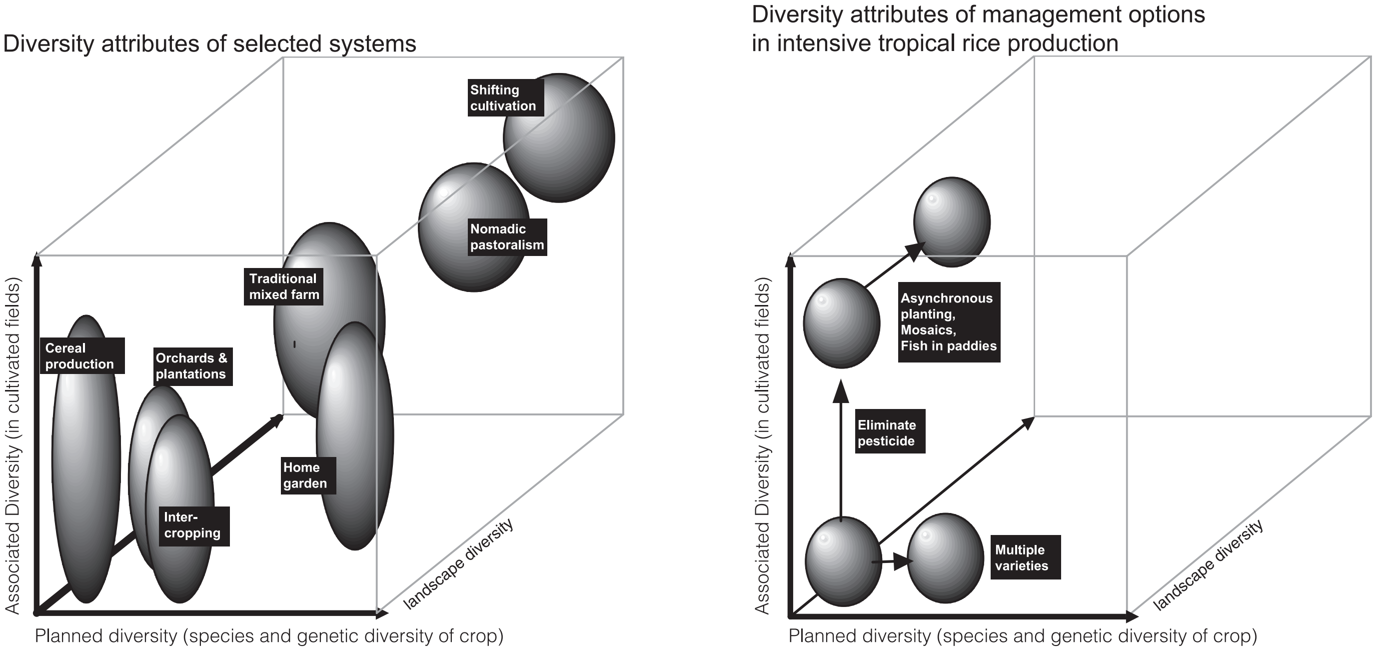


Figure 26.4. Dimensions of Diversity in Selected Production Systems

For some other major crops, such as sorghum and millet, the picture is quite different. While sorghum- and millet-growing regions of North America and parts of India have modernized systems, in the African Sahel, where these crops provide the main food source, there has been very little adoption of modern varieties and traditional practices prevail.

Farmers continue to use landraces rather than modern varieties for a range of different reasons which can be categorized into different groups (FAO 1998; Brush et al. 1992; Gauchan 2004; Meng 1997; Smale et al. 2001; Van Dusen 2000). First, landraces provide a wider range of end uses and have distinct culinary purposes, which may also contribute to maintaining a balanced diet. For example, in the Sahel and other dryland areas of Africa, certain varieties of sorghum produce better porridge, while others are better for boiling, and entirely different varieties are used for brewing beer. Some crop varieties have long stalks for animal feed or fencing, while others have sweet stalks that provide a refreshing snack in the field. Markets may have specific requirements, distinct from preferences at home, and some varieties have distinct cultural uses.

Second, production factors and risk management provide additional motives for continued use of landraces. Farmers frequently explain that they select different landraces to match differences in soil water regimes, even within the same field. Varieties with different maturities may be used to spread labor requirements through the season. Where weather patterns are uncertain or diseases are prevalent, planting several varieties can spread risk. Poor farmers are more likely to be faced with failures in insurance markets and thus use natural resource allocation as a means of insuring. Maintaining a diverse set of crop varieties to insure against production or market risks may be the most accessible means of insurance available to low-income households, whereas higher-income households with greater access to formal financial markets or other means of risk management may be more likely to risk a narrower portfolio of crop varieties. In addition, some traditional varieties (of millet, for instance, in West Africa) are photoperiodic: the time of maturity is set by day-length changes, allowing planting time to be varied according the start of the rains while still ensuring that the crop is ready for harvest on time (Niangado 2001).

Finally, in some unfavorable and heterogeneous environments, appropriate modern varieties have simply not been developed or are not available. Breeding for such environments requires a decentralized approach to exploit ''genotype x environment interaction'' (Simmonds 1991; Ceccarelli 1994; de Vries and Toenniessen 2001). Participatory approaches to plant breeding are, however, having some success in developing suitable varieties for such areas (Ceccarelli et al. 2001; Weltzein et al. 1999; Cleveland and Soleri 2002).

Though empirical evidence is limited, both theory and observation suggest that genetic heterogeneity provides greater disease suppression when used over large areas. Some studies, including those of wheat mosaic virus (Hariri et al. 2001), fungal pathogens of sorghum (Ngugi et al. 2001), and rice blast (Zhu et al. 2000), have shown that mixed planting of resistant varieties with other varieties can reduce the disease incidence across the whole crop, while possibly extending the functional ''lifespan'' of the resistant genotypes. However, evolutionary interactions among crops and their pathogens mean that improvement in crop resistance to a pathogen is, in most cases, likely to be transitory. Thus, maintaining stocks of genetic diversity for plant breeding is critically important.

Cultivated systems also support a high diversity of livestock. Globally, there are 6,500 breeds of domesticated animals, including cattle, goats, sheep, buffalo, yaks, pigs, horses, chicken, turkeys, ducks, geese, pigeons, and ostriches. A third of these are under near-future threat of extinction due to their very small population size. Over the past century, it is believed that 5,000 domesticated animal and bird breeds have been lost. The situation is most serious in industrialized farming systems, with half of current breeds at risk in Europe and a third at risk in North America. While only 10–20% of current livestock breeds are at risk in Asia, Africa, and Latin America, it is likely that the risk of breed loss will increase as these countries pursue the path of economic development followed in industrial countries (FAO/UNEP 2000; Blench 2001).

26.2.1.2 Management of Associated Agricultural Biodiversity That Supports Production

The biodiversity of fauna and flora found in agroecosystems often plays an essential role in supporting crop production (Swift et al. 1996; Pimbert 1999; Cromwell et al. 2001). Earthworms and other soil fauna and microorganisms, together with plant root systems, maintain soil structure and facilitate nutrient cycling. Pests and diseases are kept in check by parasites, predators, and disease control organisms, as well as by genetic resistances in crop plants themselves. Insect pollinators also contribute to cross-fertilization of crop species that outcross.

As the examples in this section illustrate, it is not only the organisms that directly provide such services that are important, but also the associated food webs, such as alternative forage plants for pollinators (including those in small patches of wild lands within agricultural landscapes) and alternative prey for natural enemies of agricultural pests. Agroecosystems vary in the extent to which this biological support to production is replaced by external inputs. In industrial-type agricultural systems, they have been replaced to quite a significant extent by inorganic fertilizers and chemical pesticides; but in the many areas, particularly in the tropics, agricultural biodiversity provides the primary forces governing nutrient availability and pest pressure.

26.2.1.2.1 Soil biodiversity

Soil organisms contribute a wide range of essential services to the function of terrestrial ecosystems by acting as the primary driving agents of nutrient cycling and regulating the dynamics of soil organic matter formation and decomposition, soil carbon sequestration, and greenhouse gas emission. They modify soil physical structure and hydraulic properties that influence root growth and function and nutrient acquisition. In addition, many pollinators as well as natural enemies of agricultural pests spend part of their life cycle in the soil.

Soil biodiversity is responsive to the management of cultivated systems (Giller et al. 1997). Cultivation drastically affects the soil environment and hence the number and kinds of organisms present (Karg and Ryszkowski 1996; Ryszkowski et al. 2002). In general, tillage, monoculture, pesticide use, erosion, and soil contamination or pollution have negative affects on soil biodiversity. In contrast, no-till or minimal tillage, the application of organic materials such as livestock manures and compost, balanced fertilizer applications, and crop rotations generally have positive impacts on soil organism densities, diversity, and activity. Soil condition can thus be improved by farm practices and, indeed, some soils are in effect created by farmers (Brookfield 2001).

26.2.1.2.2 Pollination

Over three quarters of the major world crops rely on animal pollinators. While bees are the principal agents of pollination, flies, moths, butterflies, wasps, beetles, hummingbirds, bats, and others serve also as pollinators. Approximately 73% of the world's cultivated crops, including cashews, squash, mangos, cocoa, cranberries, and blueberries, are pollinated by bee species, 19% by flies, 6.5% by bats, 5% by wasps, 5% by beetles, 4% by birds, and 4% by butterflies and moths (Roubik 1995). Of the hundred or so crops that make up most of the world's food supply, only 15% are pollinated by domestic bees, while at least 80% are pollinated by wild bees and other wildlife. The services of wild pollinators are estimated to be worth $4.1 billion a year to U.S. agriculture alone. Wild plants and weeds provide alternative forage and nesting sites for pollinators, whose diversity is directly dependant on plant diversity, and vice versa (Kevan 1999). Forest-based pollinators in Costa Rica have been shown to increase the value of coffee production from a single farm by approximately $60,000 per year by increasing yields and improving crop quality (Ricketts et al. 2004).

Many pollinating species are at risk of extinction, and pollination is now regarded as an ecosystem service in jeopardy, which requires attention in all terrestrial environments—from intensive agriculture to wilderness (Buchmann and Nabhan 1996). Pollinators are declining because of habitat fragmentation, agricultural and industrial chemicals and associated pollution, parasites and diseases, the introduction of exotic species, and declines in non-crop nectar and larval food supplies. Due to declining pollinator populations, an increasing number of farmers around the world are now paying for pollination services, importing and raising pollinators to ensure that crop seed yields are not limited by lack of pollination. Despite their tremendous importance, little is known about wild pollinator populations or the consequences of their decline (Kevan 1999; Kevan and Phillips 2001). (See Chapter 11 for further information on pollinators.)

26.2.1.2.3 Pest management

Insects, spiders, and other arthropods often act as natural enemies of crop pests. Research in the rice fields of Java has documented that other components of arthropod diversity are important in this respect (Settle et al. 1996). Without alternative food sources, populations of natural enemies would be directly dependent on the plant pest, which in turn is directly dependent on the rice plant for food. Such a linear system would be expected to give rise to seasonal oscillations in populations at the various trophic levels. In the Javanese rice fields, however, ''neutral'' arthropods, mostly detritivores and plankton feeders, such as midges and mosquitoes, provide an alternative source of food for the natural enemies of rice plant pests, thus stabilizing the populations of the natural enemies and providing better pest control. Furthermore, the detritivores depend on high levels of organic matter in the paddy soils, which provide the food source for an array of microorganisms (bacteria and phtytoplankton) and zooplantkton.

Further stability is provided by spatial and temporal heterogeneity at the landscape level. In Central Java, for example, the landscape is made up of a patchwork of small to intermediate sized plots of paddy rice (patches of between 10 and 100 hectares), planted continuously to rice at differing times throughout the year, with only a short fallow period and interspersed with patches or lines of trees and shrubs. There is some evidence of greater abundance of natural predators in such landscapes (as compared with more-uniform rice environments found in West Java, for instance) and that asynchronous planting of rice and the patches of uncultivated land mean that there are always alternative food supplies for natural enemies (Settle et al. 1996).

26.2.1.3 Conservation of Wild Biodiversity in Agricultural Landscapes

Besides the services required to sustain agriculture, biodiversity in agricultural ecosystems has a wider significance. Agricultural ecosystems represent substantial portions of watersheds, which are often landscapes that support recreation and tourism. They also harbor important biodiversity in their own right. Moreover, biodiversity in agricultural landscapes has powerful cultural significance, partly because of the interplay with historic landscapes associated with agriculture and partly because many people come into contact with wild biodiversity in and around farmland. In fact, in some regions elements of biodiversity now only exist in areas dominated by agriculture. Management of biodiversity in such areas is therefore an essential component of an overall approach to its conservation.

Indeed, in some parts of the world, notably Europe, biodiversity conservation has in recent years been acknowledged as one of the aims of agricultural policy. In spite of this, the negative trend of biodiversity in agricultural ecosystems, which was initiated with the intensification of agriculture in the latter part of the twentieth century, still prevails in Europe. Indicators such as the populations of farmland birds tend to show a negative trend (Birdlife International 2004). (See Figure 26.5.) Other indicators also show a loss in wildlife distribution and habitat as a consequence of intensification in agricultural production (Mankin and Warner 1999; Gall and Orians 1992). In developing countries, however, the expansion of agriculture is considered to be the greatest threat to extinction of threatened bird species, and a recent study suggests that intensification of agriculture in these areas to avoid further expansion of cropland would reduce this threat to biodiversity of bird species (Green et al. 2004).

One positive landscape-wide impact noted in sub-Saharan Africa, South Asia, and Southeast Asia is the trend of growing more trees for a wide variety of purposes. Trees can stabilize and enhance soils, can contribute to plant biodiversity in the landscape, and may provide habitat for a variety of birds, reptiles, small mammals, and insects. Some birds and small mammals can be important sources of revenue in farmlands, such as when farmers make agreements with outfitters and hunters and plan their management in an integrated way. Wildlife in cultivated systems can contribute to food security by providing an important source of animal proteins for the most marginal rural settlers. It should be noted, however, that the introduction of trees and other woody vegetation into some ecosystems, particularly remnant tracts of grassland or where area-sensitive grassland species are present, can have negative consequences to those species and become invasive woody perennials in these ecosystems (Allen 1994; Samson et al. 2004). (See Chapters 4 and 11 for more on alien invasive species.)

26.2.1.4 Impacts of Agricultural Practices on Biodiversity

Cultivated systems have large impacts on other ecosystems and on the services they supply. The most obvious impact is through expansion of cultivated systems. Globally, agricultural land has expanded by around 130,000 square kilometers a year over the past 25 years, predominantly at the expense of natural forests and grasslands. In addition, a rapid increase in coastal aquaculture has led to the loss of many mangrove ecosystems. Though future rates of conversion are expected to be much lower in absolute terms, assuming no shortage of staple food crops, the locations of major agricultural expansion frequently coincide with remnants of those natural habitats with high biodiversity value (Myers et al. 2000).

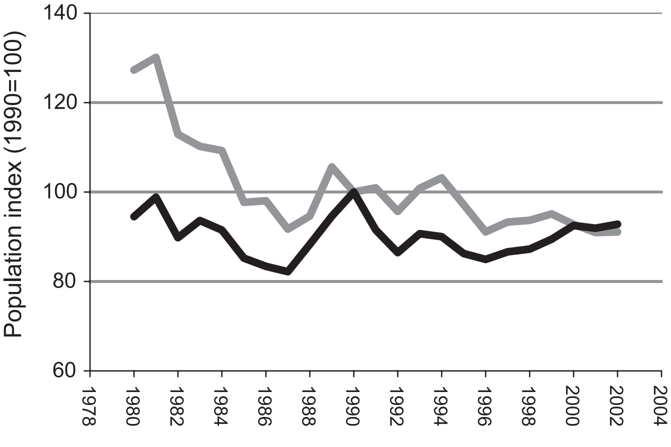


Figure 26.5. Supranational Multi-species Indicator of European Bird Populations, 1980–2002. Farmland birds (grey line: 18 countries, 23 species, ± 1.96 SE) and woodland, park, and garden birds (black line: 19 countries, 24 species, ± 1.96 SE). The index for the base year, 1990, is set to 100. Data come from the Pan-European Common Bird Monitoring Scheme, an initiative of the Royal Society for the Protection of Birds, the European Bird Census Council, and BirdLife International.

Other externalities associated with cultivated systems include the use of water and nutrients and the pollution of ecosystems resulting from excess use of pesticides and nutrients. Irrigated agriculture is a major user of fresh water. Both the direct loss of wetland habitats from conversion and the pollution of inland waters by excess nutrients have major negative impacts on inland water biodiversity. (See Chapter 20.) Despite increases in water use efficiency, total water demand for agriculture is increasing and in many regions is projected to outstrip supply over the coming decades. (See Chapter 7.)

Agriculture is the major user of industrially fixed nitrogen, and only a fraction of this fertilizer is used and retained in food products. The excess nitrogen leads to biodiversity loss in inland water, coastal, and marine systems through eutrophication and to loss of terrestrial plant diversity through aerial deposition. (See Chapters 18, 19, and 20.) Conversely, the soils of several cultivated systems, especially in Africa South of the Sahara, are nutrient-depleted. This is especially problematic where fruits, vegetables, and other crops are exported or transferred on a large scale from rural areas to large urban centers. Significantly greater use of fertilizers will be necessary in some regions to maintain soil nutrient stocks and support increased production by these systems.

Pesticides and herbicides have direct impacts on biodiversity through the degradation of ecosystems. Birds are particularly vulnerable to losses in invertebrate populations due to the use of pesticides and herbicides (Hooper et al. 2003). Especially important are those pesticides and herbicides that are persistent organic pollutants, since they have effects on large spatial and temporal scales. Many of the more persistent chemicals are being phased out and replaced by others with much lower toxicity that are less persistent. However, the overall use of pesticides is still increasing (FAOSTAT 2004).

26.2.1.5 Concluding Comments on the Relationship between Biodiversity and Cultivated Systems

Although cultivated systems often have a negative impact on it, biodiversity remains essential for the productivity and sustainability of cultivated systems. In modern industrial agricultural systems, many components of biodiversity relevant to agriculture can be separated from the production system (such as ex situ germplasm collections and plant breeding programs). Biodiversity is still required for production, however, even if partially maintained ex situ.

In addition, some of the services provided by biodiversity can, to a certain degree, be provided by externally provided services. For example, market integration and insurance services can substitute for risk management provided by crop genetic diversity, and other forms of pest management, including the use of pesticides, can substitute for pest and disease control. But it is important to note two points. First, poor farmers often do not have the option of introducing modern methods for services provided by biodiversity because of the lack of market integration or heterogeneity of the environment or because they cannot afford the alternatives. Second, substitution of some services may not be sustainable and may have negative environmental and human health effects (for example, the reliance on toxic and persistent pesticides to control certain pests can have negative effects on the provision of services by the cultivated system and other ecosystems connected to the cultivated system).

The relative cost-effectiveness of biodiversity-based over substitute services is sensitive to many factors and may be amenable to the application of incentive measures. The levels of biodiversity in cultivated systems and the ecosystems services they provide can be manipulated directly or indirectly by management practices. For instance, practices such as integrated pest management and minimal tillage agriculture, as well as multicropping, the use of genetic diversity, and mosaic landscaping can increase biodiversity in cultivated systems. However, if such measures reduce crop yields per unit land area-time, the aggregate effects of such practices could result in the expansion of crop area at the expense of natural ecosystems, thus trading increased biodiversity within cultivated systems for a decrease in the extent of natural ecosystems and the biodiversity they contain.

26.2.2 Fresh Water

Agriculture is by far the most consumptive human use of fresh water. Water requirements for cultivation are large; it takes 500 liters, 900 liters, 1,400 liters, and 2,000 liters of transpired water to produce 1 kilogram of potatoes, wheat, maize, and rice respectively (Klohn and Appelgren 1998). Other crops, such as sugarcane and bananas, are even more water-demanding.

Cultivation both relies on and influences the provision of fresh water. Both the quantity and quality of water resources can be affected, as well as the timing and distribution of water flows in local catchments and large river basins. The impact of cultivation on freshwater quantity is much larger in irrigated than in rain-fed systems. Deforestation associated with rain-fed cultivation tends to increase the amount of water available for agriculture because of reduced transpiration losses. Impoundments for irrigation can regulate downstream flows, while seasonally bare soil and field drainage systems can accelerate runoff and reduce infiltration, resulting in more severe local flooding and decreased dry weather flows (Bruijnzeel 2001). Water quality effects have been reported for all forms of cultivation, including confined livestock systems and aquaculture, but the nature and magnitude of impact can vary substantially. Poorly managed cultivation, particularly on sloping lands, is often associated with soil erosion, high silt loading, and downstream sedimentation. Intensive, high-input production systems can result in water pollution from leaching or runoff that carries nutrients, pesticides, or animal wastes to waterways (National Research Council 2000; de Haan et al. 1997).

The negative impact of cultivation on water resources can limit options for, and increase the cost of downstream water use (for example, through reduced domestic water supply or recreational opportunities). It can also have additional negative effects on the supply of other ecosystem services (such as reducing aquatic biodiversity and increasing nutrient flows) and on the condition of other ecosystems (the integrity and productivity of inland waters and coastal systems, for instance). (See Chapters 19 and 20.)

This section briefly reviews the sources and means by which fresh water is provided to and utilized by cultivated systems, identifies some of the issues surrounding water use efficiency, and considers some of the most important environmental consequences of cultivation on water resources.

26.2.2.1 Irrigation

Irrigation involves the withdrawal of groundwater and the diversion of surface water resources to help meet the transpiration requirements of crops and to lengthen the growing period when rainfall alone is insufficient to support crop growth. By mitigating moisture deficits, irrigation can significantly increase yields and total crop biomass, stabilize production and prices (by dampening the effects of rainfall variability within and across seasons), and encourage production diversity. But irrigation requires increased freshwater use and promotes more-intensive land use with regard to labor and other inputs, such as improved seeds, fertilizers, and pesticides (because such inputs are usually needed to achieve the yield increases that are possible when water limitations to crop growth are removed).

Of the 9,000–12,500 cubic kilometers of surface water estimated to be available globally for use each year (UN 1997), between 3,500 and 3,700 cubic kilometers were withdrawn in 1995 (Shiklomanov 1996). Of that total, about 70% was withdrawn for irrigation (Postel 1993). According to the World Bank (2000), the share of extracted water used for agriculture ranges from 87% in low-income countries to 74% in middle-income countries and 30% in high-income countries. By 2002, there were 276 million hectares of irrigated cropland globally—five times more than at the beginning of the twentieth century. While this irrigated area represents only 18% of all croplands, irrigated agriculture provides about 40% of the global food supply (FAOSTAT 2004; Bruinsma 2003; Wood et al. 2000).

The wide variability in freshwater endowments between regions and countries has a large influence on the potential for the development and long-term viability of irrigated agriculture. While the 206 cubic meters per capita withdrawn annually for agriculture in Africa represents 85% of total water withdrawals on that continent, the 1,029 cubic meters per capita withdrawn for agriculture in North America represents just 47% of that continent's withdrawals (World Resources Institute 2000). Compared with high-income countries, mostly located in subhumid/humid temperate and sub-tropical climates, many poor countries tend to have scarcer water supplies and relatively large agricultural demands due to the higher share of agriculture in their economies.

The simplest measure of irrigation intensity is the amount of irrigation water withdrawn (or applied) per year. This is most commonly expressed as an equivalent water depth per unit area (cubic meters of water per year divided by hectares irrigated). Using data from WRI (1998) and FAOSTAT (1999) across 118 countries, Seckler et al. (1998) calculated the mean depth of irrigation globally to be about 1 meter per year on the 276 million hectares of irrigated cropland.

Although irrigation is by far the largest global water user, the net rate of increase in irrigated area has decreased steadily in each of the past four decades and now stands at just under 1% annually (FAOSTAT 2004). Expansion in irrigated area has slowed as unexploited freshwater resources have become more limited and more expensive to develop. In addition, cereal prices have trended downwards in real terms, and environmental and social objections to the construction of large-scale impoundments have grown. There is also increasing competition for water from domestic and industrial users. Such pressures have resulted in increasing regulation of the allocation of water resources in many countries and of effluent and water quality standards (including the establishment of "minimum environmental flows" in some cases). These trends have increased public awareness of water use by agriculture and have fostered greater concern by farmers and researchers about improvements in water use efficiency in cultivated systems (Tharme 2003; Benetti et al. 2004).

Irrigation can have positive in addition to negative externalities. In some rural areas, it is the only reliable source of water for cooking and cleaning. Infiltration from rice paddy systems also contributes to groundwater reservoirs that are important sources of water in urban areas, as well as contributing to flood control and prevention of saltwater intrusion (Renault and Montginoul 2003).

Water loss also occurs with aquaculture through evaporation and pond seepage. Pond seepage may be as much as 2.5 centimeters per day, while as much as 1–3% of the fish pond volume may be lost daily (Beveridge and Phillips 1993).

26.2.2.2 Water Use Efficiency

Irrigation systems, particularly those involving surface water impoundment and conveyance, are often inefficient in terms of water loss through evaporation and leakage. Water efficiency is defined as the ratio of water used by crops to the gross quantity of water extracted for irrigation use. Global estimates of irrigation efficiency vary, but the average is around 43% (Postel 1993; Seckler et al. 1998). Seckler et al. (1998) estimate that arid agroecosystems have more efficient irrigation—for example, 54% and 58% efficiency for the two driest groups of countries, compared with 30% for the least water-constrained countries. China and India show irrigation efficiencies of around 40%, and they strongly influence the global average because of their large irrigated area. Irrigation efficiencies typically range from 25% to 45% in Asia, but up to 50–60% in Taiwan, Israel, and Japan (Seckler et al. 1998:25).

Recognizing the large potential for water efficiency improvements in agriculture, and spurred by increasing competition for water, many technologies have been developed to enhance the effectiveness of water use in both irrigated and rain-fed cultivation. Postel (1999) describes how microirrigation systems, such as drip and micro-sprinklers, often achieve efficiencies in excess of 95% compared with standard flood irrigation efficiencies of 60% or less. She cites significant water productivity gains for a wide range of crops, resulting from the shift from conventional to drip irrigation in India. For example, water use declined as much as 65% in the case of sugarcane cultivation, and water productivity increased by 255% in cotton. The reason for these increases in irrigation efficiency is that a precise water application can both reduce total water use and increase yields. Sugarcane and cotton yields increased 20% and 27% respectively, along with substantial reductions in water use. Postel (1997) indicated that as of 1991, only 0.7% of irrigated farmland worldwide was being microirrigated. While this fraction is expected to have increased since 1991, no recent, comprehensive global data are available (Gleick 2002).

Other techniques for improving water use efficiency in both irrigated and rain-fed systems have included furrow diking, land leveling, direct seeding, moisture monitoring, low-energy precision application sprinklers, low pressure sprinklers, water accounting, and stomatal control by chemical signaling (Gleick 2002; Davies et al. 2003). Complementary strategies have included the development of more drought-tolerant crop germplasm (Edmeades et al. 1999; Pantuwan et al. 2002), experimentation with policies that foster water markets or other economic or regulatory arrangements, and institutional reforms that engage farming communities more directly in improving water resource management (Postel 1997; Subramanian et al. 1997).

Water conservation methods, such as mulching, deep tillage, contour farming, and ridging, also help increase water use efficiency by ensuring that the rainwater is retained long enough to ensure infiltration into the soil root zone (Habitu and Mahoo 1999; Reij et al. 1988). These approaches can be complemented by ''water harvesting'' techniques involving the small-scale concentration, collection, storage, and use of rainwater runoff for both domestic and agricultural use.

Increasing effective rainfall use through improved water harvesting technologies and water conservation methods has largely been pioneered in arid and semiarid regions, and water harvesting techniques have been classified in various ways (Reij et al. 1988). Pacey and Cullis (1986) described three broad categories: external catchment systems, microcatchments, and rooftop runoff collection, the latter used almost exclusively for nonagricultural purposes. External catchment rainwater harvesting involves the collection of water from areas distant from where crops are grown (Oweis et al. 1999). Microcatchment techniques are those in which the catchment area and the cropped area are distinct but adjacent (Habitu and Mahoo 1999). Microcatchments generate higher yields per unit area than larger catchments (Bruins et al. 1986) and they are simple, inexpensive, and easily reproduced where land is available (Boers and Ben-Asher 1982). Microcatchments have been used in Asia, Africa, America, and Australia, where they are often used for medium water-demanding crops such as maize, sorghum, millet, and groundnuts (Habitu and Mahoo 1999), but evidence of large-scale adoption and impact is so far limited.

Water use efficiency can also be improved by carefully designed landscapes. Studies of processes induced by shelterbelts and woods in agricultural landscapes indicate that the structure of plant cover has an important bearing on agricultural water resources (as well as on habitat and natural biodiversity). The protective effects of trees decrease wind speeds close to Earth's surface and lower saturation vapor deficits, thus decreasing evapotranspiration from sheltered fields. Fields between shelterbelts conserve moisture (Brandle et al. 2004; Cleugh et al. 2002; Kedziora and Olejnik 2002). Shelter effects are greater under dry and warm meteorological conditions compared with wet and cool weather (Ryszkowski and Kedziora 1995).

In addition, shelterbelts have been shown to decrease surface runoff rates, protect soil against water erosion, and increase soil infiltration rates, thus improving dry-season flows (Kedziora and Olejnik 2002; Werner et al. 1997). Some studies suggest that heterogeneity of plant cover structure, including trees in agricultural landscapes, also generates meso-scale atmospheric circulation, which can increase regional or local precipitation (Pielke et al. 1991, 1998) and recycling of water in the landscape (Lawton et al. 2001; Stohlgren et al. 1998). Counterbalancing these positive effects, tree shelterbelts also compete for land, nutrients, and water with crops and also shade them, which can reduce crop yields or total crop output.

With rapid urbanization and growing competition for water resources (particularly in arid and semiarid regions), as well as budget constraints for effective treatment of growing wastewater volumes, the reuse of urban wastewater for agriculture is receiving increasing attention. Wastewater is being used as a low-cost alternative to conventional irrigation water to support vegetable production in urban and peri-urban agriculture, despite the health and environmental risks that might be associated with this practice. It is suggested that raw wastewater use in agriculture is increasing at close to the rate of urban growth in developing countries, where urban and peri-urban land is available (Scott et al. 2004).

Just how prevalent wastewater irrigation is today is a matter of conjecture, as no reliable global data exist. However, as an important step toward a global figure, Rachid-Sally et al. (2004), Cornish and Kielen (2004), and Ensik et al. (2004) present assessments of the area irrigated with wastewater at the country level, with estimates of 9,000 hectares for Viet Nam, 11,900 hectares for

Ghana, and 32,500 hectares in Pakistan. As the recycling of wastewater for irrigation grows, there are increasing concerns about the long-term human health consequences (Scott et al. 2004).

26.2.2.3 Impacts on Water Quality

Besides their effect on water quantity, cultivated systems can have negative impacts on freshwater quality through pollutants contained in the drainage water, runoff, and effluents. Where irrigation depletes rivers and aquifers that receive increased agricultural pollution, quality impacts are exacerbated because of reduced dilution capacity. Physical loading of water resources with inorganic (soil particles) and organic sediments or particulate matter, as well as chemical loading of plant nutrients, especially nitrogen, phosphorus, and pesticides, can often occur as a result of cultivation or intensive livestock and aquaculture operations (Sharpley and Halverson 1994; Owens 1994;).

Agricultural impact on water quality is also mediated through erosion brought about by poor crop cover, field drainage, and cultivation operations, particularly on sloping lands. Gleick (1993) estimates that about 22% of the annual storage capacity lost through siltation of U.S. reservoirs is due to soil erosion from cropland. Water-borne transportation of nitrates and phosphates is quite common where external nutrients are applied in excess or inefficiently and can cause eutrophication of surface waters. In some countries, such as Belgium and the Netherlands, the nitrogen input to some crops has in the past exceeded 500 kilograms per hectare (Wood et al. 2000).

Phosphorus transportation into aquatic ecosystems is the principal cause of blue-green algae blooms in reservoirs, and the anoxia in the Gulf of Mexico is one example of eutrophication attributable to nutrient enrichment (Snyder 2001). The off-site economic impact of water quality changes attributable to cultivation include damage to water-based recreational facilities, fisheries, navigation, water storage facilities, municipal and industrial water users, and water conveyance systems as well as increased flooding or inundation of low-lying urban areas and civil structures.

Salinization and waterlogging are two significant consequences of poor irrigation management and inadequate drainage (Ghassemi et al. 1995). Salinization occurs through the accumulation of salts deposited when water is evaporated from the upper layers of soils and is especially important in irrigated arid areas where evaporation rates are high. Since most crops are not tolerant of high salt levels, salinization decreases yields. This problem is particularly severe in arid and semiarid areas, such as Pakistan and Australia. Waterlogging is more common in humid environments and in irrigated areas where excessive amounts of water are applied to the land.

Ghassemi et al. (1995) estimated that around 45 million hectares, representing 20% of the world's total irrigated land, suffers from salinization or waterlogging. Losses amount to approximately 1.5 million hectares of irrigated land per year (Ghassemi 1995 quoting Dregne et al. 1991) and about $11 billion annually from reduced productivity (Postel 1999), representing about 1% of the global totals of both irrigated area and annual value of production respectively (Wood et al. 2000). Once salinization has occurred, rehabilitation for further cultivation is difficult and costly, but successes via specific vegetation strategies, using tree species, have been documented (Cacho et al. 2001; Barrett-Lenard 2002).

Freshwater aquaculture operations are strongly linked to water quality in terms of both the necessary quality of incoming water as well as the impacts of aquaculture effluents. Wells and springs are the best sources of water, but other sources are used if a number of water quality characteristics, including temperature, dissolved oxygen, ammonia, nitrites, nitrates, pH, alkalinity, and hardness, are within viable ranges. Water pollution risks arise in aquaculture when large amounts of harmful materials are added to the water body, adversely affecting its local and effluent water quality.

Fish culture operations, especially in intensive aquaculture, require fishmeal or fish feed. Feed contains nutrients such as nitrates and phosphates, and excess of these nutrients can lead to eutrophication and triggering of intense growth of aquatic plants (micro and macro). While in some aquaculture systems phytoplankton are themselves used as a food, overproduction of aquatic plants, particularly algae, causes algal blooms and can consequently lead to clogging of waterways, depletion of dissolved oxygen, and hindrance of light penetration to deeper water depths affecting photosynthetic and other metabolic functions of aquatic organisms. Thus unused feed, algal blooms, and detritus from the fish themselves impose additional pollutant loads when they discharge into external freshwater sources.

Pond and recirculation systems, as well as integrated agriculture-aquaculture systems, pose fewer risks of external pollution than the more open cage and raceway forms of aquaculture (Boyd 1985; Beveridge and Phillips 1993). In some cases, freshwater aquaculture ponds can improve water quality by acting as sinks for sediments (Stickney 1994).

To reduce the direct discharge of effluents and increase water use efficiency, wastewater from integrated agriculture-aquaculture systems has been used for irrigation. Where fresh water is available, aquaculture is a good way of using marginal land that is less suited to crop and livestock agriculture. Freshwater aquaculture ponds can be designed to contribute positively to soil and water conservation by dissipating the energy of overland flow and reducing erosion and downstream flooding.

26.2.3 Food

Trends in food provision, predominantly derived from cultivated systems, are assessed in detail in Chapter 8. This short section simply summarizes relevant key findings of that chapter.

The production of food and other products is, by design, the primary goal of cultivated systems. The global demand for food continues to be driven by population growth (albeit at a slowing rate), by the increasing real incomes of many households worldwide, and by evolving consumer preferences for more convenient, safer, and nutritious foods. Furthermore, wealthier consumers in industrial countries are increasingly willing to pay more for foods produced and marketed in ways that are perceived to be more environmentally sustainable and socially equitable.

From a food supply perspective, the scale of conversion of natural ecosystems for cultivation purposes, and the nature and extent of the trade-off between provision of food and of other ecosystem services within cultivated systems, has been shaped by the cultivation practices and technologies accessible to farmers. The decisions of most farmers about which crops to produce and how to produce them has also been influenced by a wide range of economic signals and, particularly in richer countries, by regulatory standards.

Farmers and, increasingly, scientists have accelerated the processes of domestication and adaptation of plant species and available germplasm through breeding and biotechnology to enhance food output from crops and animals across a very broad range of environmental and agronomic conditions. Use of transgenic crop varieties developed with recombinant DNA technology is increasing rapidly worldwide in both industrial and developing countries. Although this technology holds tremendous promise to increase productivity significantly and to improve end-use properties of crops for both rich and poor producers, the widespread use of transgenic crops, often referred to as genetically modified organisms, continues to generate controversy with regard to ethical, environmental, equity, and intellectual property issues.

Over the past half-century, and at a global scale, food provision has more than kept pace with growth in demand, leading to a significant, long-term decline in the real price of food and allowing an ever-growing share of a rapidly increasing world population to be fed adequately at reasonable cost. Nevertheless, there remain significant causes for concern about food provision on several fronts. First, there remains a persistent and, recently, growing population of undernourished people, estimated at 852 million for 2000/02 (FAO 2004). Second, in many of the same countries where hunger and poverty persist, population growth rates tend to be high, and expansion of food production is failing to keep pace with demand. In the face of population pressure, often compounded by limited access to resources and technologies, poor intensification practices have all too frequently degraded the productive capacity of existing cultivated areas. Depletion of soil nutrient stocks in subsistence systems has, for example, reduced the productive capacity of large areas in sub-Saharan Africa.

Third, the linear rate of increase in the yields of the three major cereals (maize, rice, and wheat) is falling below the rate of increase in demand in many of the world's major production areas (Cassman et al. 2003). Moreover, global warming from human-induced climate change may reduce crop yield potential and thus decrease the rate of yield gain (Peng et al. 2004; Lobell and Asner 2003; Rosenzeig and Parry 1996; Brown and Rosenberg 1997). Fourth, there are concerns of growing divergence, rather than convergence, between the economic, science, and technology capacities of richer and poorer nations with regard to food production. This divergence is hindering efforts to promote the emergence of profitable and sustainable smallholder agriculture in poorer countries. Finally, there is growing recognition that virtually all forms of cultivation have involved trade-offs between provision of food and provision of other ecosystem services. See Chapter 8 for further details on food provision.

26.2.4 Non-food Products

Besides producing food, cultivated systems provide other products such as fiber (cotton, flax, and jute, for instance), biofuels, medicines, pharmaceutical products, dyes, chemicals, timber, and other non-food industrial raw materials. Non-food crops account for nearly 7% of harvested crop area (Wood et al. 2000). Based on FAOSTAT 2004, the annual value of non-food crops from cultivated systems, excluding timber, is about 3.4% of total agricultural production ($50 billion, compared with $1.4 trillion for food crops).

In 2003, the reported primary production of fiber crops worldwide was about 25 million tons. Cotton is the major fiber crop and is extensively grown in China, the United States, and India, accounting for 15.6 million, 10.4 million, and 6.3 million tons, respectively, and providing 5.2 million, 3.9 million, and 2.1 million tons of cotton lint. Flax, another fiber crop, is widely grown in China and France, which produce around 500,000 and 86,000 tons respectively (FAOSTAT 2004).

In industrial countries, biofuel crops currently represent a relatively small proportion of output from cultivated systems. However, diversion of grain and crop biomass for biofuel and bio-based industrial feedstocks could grow substantially with increasing oil prices and continued improvements in the energy efficiency of crop production and bio-fuel conversion. Another approach is through crop genetic engineering to enhance traits facilitating production of plastics and other bio-based industrial feedstocks. Current U.S. maize production systems produce a net energy surplus based on a complete life-cycle analysis, including the embodied energy content of all inputs and operations (Shapouri et al. 2003). It is likely that future gains in energy yield and in efficiency of biofuel production or conversion to feedstocks will increase competitiveness of these renewable resources, especially if fossil fuel prices rise significantly.

Improvements in crop yields and nitrogen fertilizer efficiency are the most promising avenues through which to achieve increased energy output and overall efficiency. Both these factors would also contribute to reducing the negative impact of cultivation on ecosystem services through reductions in greenhouse gas emissions, replacement of fossil fuel usage with a renewable energy source, reduction of NO_2 emissions, and a decrease in nitrogen losses via leaching, denitrification, and volatilization.

If use of grain and crop biomass for biofuel and bio-based industrial feedstocks were to expand, however, it would place additional burdens on other cultivated systems to continue to meet growing food demand and could promote additional area expansion of cultivation and, perhaps, upward pressure on food prices.

26.2.5 Nutrient Cycling and Soil Fertility

Essential nutrients are required to sustain all life and include the macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, which are present in plant tissues at relatively high concentrations (0.1–2.0% on a dry weight basis), and micronutrients such as iron, zinc, and copper, which are required in very small quantities (1–50 parts per million). (See Chapter 12.) Of the essential nutrients, nitrogen and phosphorus have the greatest impact on environmental quality and ecosystem services because they can easily move from cultivated systems to other ecosystems and accumulate to potentially polluting levels.

Moreover, a large proportion of the total global load of reactive nitrogen and phosphorus cycles through agricultural systems, because these nutrients are required in large quantities to maintain crop yields. For example, nitrogen fertilizer applied to cropland represents more than 50% of the annual load of reactive nitrogen attributable to human activities (Smil 1999). Likewise, phosphorus contained in cultivated plants, livestock manure, and recycled organic matter represents 24–40% of the annual global phosphorus flux in terrestrial ecosystems (Smil 2000). While other nutrients are also important, their use in agriculture and their effects on global ecosystem services are much smaller and more localized. Hence, the discussion of nutrient cycling in this chapter will focus on nitrogen and phosphorus. (See Chapter 12 for a wider discussion on nutrient cycling and Box 26.2 for a discussion of "virtual trade" in crop nutrients.)

26.2.5.1 Nutrient Resources in Cultivated Systems

Nutrients available for uptake by crops are derived from resources and processes that are either internal or external to the cultivated system. Internal sources include the weathering of nutrients from soil minerals, which is a very slow process producing only small amounts of plant-available nutrients, and nutrients released in the decomposition of soil organic matter. All SOM is derived from the decomposition of organic materials that include crop and weed residues returned to soil, and livestock manure, mulch, and

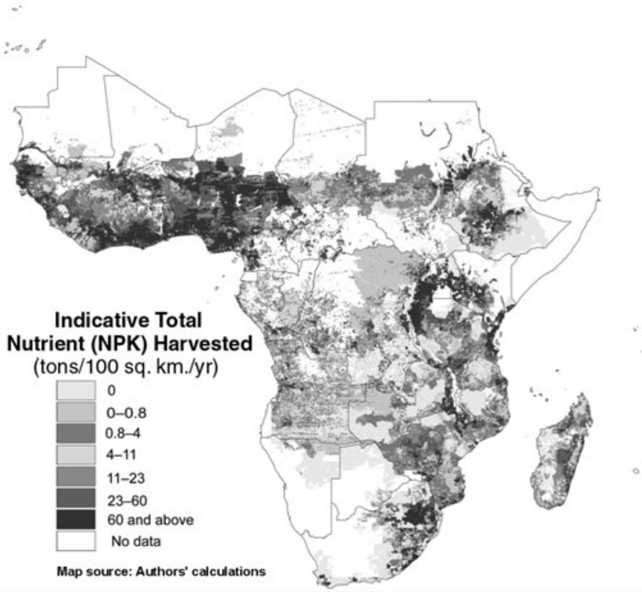
BOX 26.2

Virtual Trade in Crop Nutrients

Nutrients are often a scarce and limiting factor in African cropping systems. Traditionally, farmers have relied on fallow or applied animal and green manure to maintain soil fertility, but pressure to expand output to meet growing food demand has led to shorter fallow periods and increased cropping intensity without corresponding increases in organic nutrient inputs. Since chemical fertilizers are too costly or not available for most farmers, cultivation has progressively led to depletion of soil nutrient stocks over much of sub-Saharan Africa. Here two dimensions of this process are assessed: the total amount of nutrients removed in the harvested component of crops and the net flux (the "virtual trade") of nutrients across national borders by examining the share of domestically produced commodities exported as well as the nutrient composition of imports.

Figure A provides a spatially disaggregated estimate of the total amount of nitrogen, phosphorus, and potassium extracted from agricultural soils each year in the harvested part of crops. Assuming crop residues are recycled, this extraction represents the lower threshold for the amount of nutrients that must be replaced to maintain soil fertility. If crop residues are also removed for fuel, fodder, or building materials, then the nutrients removed in these residues must also be replaced. For each country, the amount of each nutrient removed at harvest was assessed by applying nutrient content/concentration coefficients (amount of nutrient contained in each unit weight of harvested product) to the average annual production (1999–2001) of each of 20 regionally important crops as well as an "other" composite to represent the remaining crops.

The spatial distribution of individual crops was assessed by fusing data from sub-national production statistics; maps of cropland, irrigation, population density, and biophysical crop suitability; and other secondary information, according to the method described by You and Wood (2004). The individual estimates of harvested nutrients for each crop in each (10x10 kilometer) pixel were summed to produce a single NPK total per 100 square kilometers. Areas with larger amounts of nutrient removal are shown in darker shades. Because the amount of nutrients applied in these areas as fertilizer or organic inputs falls far short of these removal rates, failure to adequately replenish soils through the use of applied nutrients is lowering soil fertility and reducing land productivity in many, if not most, of the areas shown.



Map source: Authors' calculations

To assess the overall flux of nutrients attributable to trade, the nutrient content coefficients were applied to the quantities of crops traded. The results for Africa (including north of the Sahara) show that a total of about 7.4 million tons of NPK are contained in the harvested crops of Africa each year (see Table), of which just over 1 million tons (14%) is contained in crop exports from the region. However, crop imports to the region contain around 2.5 million tons of NPK, about 34% of total domestic harvested removal.

This pattern of crop trade provides a net nutrient inflow into Africa of around 1.5 million tons per year. There are major geographical imbalances, however, between locations where nutrient are removed (plots and

compost applied to cropland. SOM contains substantial amounts of nitrogen, phosphorus, and sulfur, although these nutrients are unavailable for plant uptake when they are chemically bound in macro-modules within the organic matter. They only become available when these macro-modules are decomposed by soil microbes and microflora.

Maintaining a high SOM content and the soil microbe and microflora communities supported by SOM is therefore important for preserving soil fertility. Cropping practices that lead to a reduction in SOM result in a proportional decrease in the internal supply of nutrients and greater amounts of external inputs are needed to sustain crop yields. Conversely, cropping systems that increase SOM can reduce the need for applied nutrients. Crop residues and roots that are returned to the soil also decompose through microbial action and release nutrients that are available for crop uptake. A portion of these residues is converted to SOM, and thus the balance of organic matter input relative to SOM decomposition determines whether SOM increases, decreases, or stays the same. Burning of crop residues during fallow periods releases nutrients to the soil through the ash, although most of the nitrogen and some of the phosphorus are lost to the atmosphere in the combustion process.

Another internal source of nutrients, especially nitrogen, is biological nitrogen fixation, which is performed by symbiotic bacteria in association with forage and food legumes and by free-living nitrogen-fixing microorganisms that live in the rhizosphere of plant roots. Prior to the advent of modern farming practices and commercial fertilizers, BNF was the primary source of nitrogen in cultivated systems. In low-input cropping systems and in many natural ecosystems, however, BNF is often limited by a deficiency of phosphorus and other essential nutrients (Vitousek et al. 2002). In addition to BNF, nutrients from livestock manure are another internal source of nutrients in integrated crop-livestock farming systems.

Nutrient sources of external origin include inorganic fertilizers and livestock manure produced in confined feeding operations that are not associated with an integrated crop-livestock farming system. Secondary sources of external nutrient input include wet and dry deposition through nutrients contained, respectively, in rainfall and wind-blown dust, although the amount of nutrient addition from these sources is typically very small. Irrigation can provide substantial external inputs of nitrogen, potassium, calcium, magnesium, and sulfur in areas where groundwater or surface water used for irrigation contains relatively high concen-

BOX 26.2

continued

fields in cultivated systems) and locations where imported nutrients are used, primarily in urban areas and populated rural areas connected to the coast by a few transport corridors. Even within countries there are large movements of nutrients that exacerbate soil fertility problems. In Uganda, for example, *matooke,* the basic food staple produced by cooking the fruit of the East African highland banana, used to be prepared such that skins, stems, and other residues were recycled locally. Now, 30–50% of the country's 9 million tons per year of *matooke* enters the market system, and entire banana bunches with stems are shipped away to urban markets, primarily in Kampala. Here, though, wastes are often used as feed in confined livestock systems, especially for pigs.

	Nutrient Content of Harvested Crop Products			
	N	P	K	Total NPK
	(thousand tons per year)			
Production				
Eastern Africa	714	105	483	1,301
Northern Africa	738	114	383	1,235
Southern Africa	683	127	422	1,232
Western Africa	2,106	420	1,125	3,651
Harvested Product: Africa	4,241	766	2,412	7,419
Exports[a]	550	147	352	1,049
Imports[a]	1,448	439	634	2,522
Net trade flow of embodied crop nutrients[a]	+898	+292	+282	+1,427
Fertilizer consumption	2,462	953	485	3,900

[a] Derived from FAOSTAT (average 1999–2001) and nutrient content database

Comparing harvested nutrients to applied fertilizer estimates, a rough indication of the regional nutrient shortfall is apparent. Both nitrogen and potassium replenishment from fertilizers at the regional scale are significantly less than the nutrients removed in harvested crop product. This shortfall will be even greater to the extent that crop residues are not recycled and applied nutrients are not taken up by the crop (typically, nutrient uptake rates from applied nutrients are quite low). The shortfall is reduced where organic nutrients are applied but, typically, overall nutrient NPK balances in East and West Africa have been estimated at greater than −60 kilograms per hectare per year (Henao and Baanante 1999; Stoorvogel and Smaling 1990). Moreover, in African soils a large share of applied phosphorus fertilizer is fixed in the soil complex and is unavailable for plant use.

Clearly this aggregate assessment hides many important details. One is the lack of complete nutrient balances for specific crops and cropping systems. Some crops such as legumes can improve the nitrogen balance of soils through symbiotic nitrogen fixation in association with nitrogen-fixing bacteria, and high-value crops, often for export, are much more likely to receive fertilizers. Of the primary regional export crops, cotton, groundnuts, and cocoa contain the largest absolute quantities of nutrients, while of the major imports, nutrient totals are largest in wheat, soybean, and maize. Trade in oil palm and sugar accounts for a large share of nutrient flows as both import and export crops in different parts of sub-Saharan Africa. Unless the steady depletion of nutrients is reversed in the region and soil nutrient stocks are restored, it will be very difficult to sustain the rate of growth in food supply that will be required to meet food demand. In fact, Africa currently depends on the net import of more than 30 million tons of the three major cereals—rice, wheat, and maize—and the past two decades indicate an increasing trend of reliance on imported grain.

trations of these nutrients. Irrigation water also delivers sodium and chloride, important salts in the process of soil salinization.

26.2.5.2 Nutrient Balance and Maintenance of Soil Fertility

Maintenance of soil fertility is crucial for sustaining the food production capacity of cultivated systems. Harvesting of plant parts removes nutrients from the system and eventually depletes soil nutrient stocks unless nutrients are replenished through application of fertilizers or manures or, for nitrogen, by leguminous crops. Nutrient losses also occur through soil erosion and leaching of water-soluble nutrients when water percolates below the active root zone. For nitrogen, losses occur as a result of ammonia volatilization and denitrification, the latter releasing nitrous oxide, a potent greenhouse gas. The overall nutrient balance of a cultivated system is therefore determined by the difference between the inputs and outputs of each essential nutrient.

Internally generated nutrients are the primary source of nutrients in subsistence cropping systems where farmers do not have access to or cannot afford fertilizers or manure. The shifting cultivation systems practiced in remote areas in the humid and subhumid tropics are examples of subsistence systems that rely almost entirely on internal nutrient sources (Nye and Greenland 1960). Depletion of soil fertility occurs in many continuously cropped cereal production systems practiced on soils of low inherent fertility in India, Southeast Asia, and sub-Saharan Africa that primarily produce rice, millet, and sometimes sorghum under rain-fed conditions. In these systems, yields are relatively low and highly variable because of low soil fertility and lack of adequate rainfall.

Greater nitrogen input from BNF and increased use of livestock manure are generally not feasible in these continuous cropping systems because high human population density does not allow diversion of arable land away from food crops to non-food legume cover crops or forage crops. Dual-purpose grain legumes such as cowpea and pigeonpea, which can provide an income source to farmers in addition to improving soil fertility, have provided a partial solution to this problem (Giller 2001).

On good soils with adequate rainfall or irrigation, commercial fertilizers are used to support high yields and to maintain soil fertility. From a global perspective, such systems represent the foundation of the human food supply and include the irrigated lowland rice systems of Asia, the rain-fed wheat systems of northern and central Europe, and the maize-soybean rotations in the North American prairies and comparable environments of Argentina and Brazil. Relatively high doses of nitrogen and phosphorus are applied in these systems, which can lead to substantial nutrient losses without skillful management techniques that foster high nutrient use efficiency and nutrient retention in soil. Nitrogen is the most difficult nutrient to control because it is extremely mobile and can be lost rapidly via a number of pathways (Smil 1999). Average uptake efficiency from applied fertilizer is typically only about 30–50% (Cassman et al. 2002), which means there is significant scope for increasing uptake efficiency and reducing the potential for nitrogen losses.

The past half-century has seen large increases in the application of nitrogen and phosphorus fertilizers in high-production cropping systems (Galloway and Cowling 2002; Smil 2000) (see Figure 26.6), although application rates vary markedly by region and crop. This injection of external sources of N and P to cultivated systems has expanded and accelerated global nutrient cycles and, as a result of the inefficiencies in fertilizer application and uptake and the loss of fertilizer nutrients, has played a role in reducing environmental services through decreased water quality (Di and Cameron 2002; Howarth et al. 2002; Sharpley and Halvorson 1994; Spalding and Exner 1993), in the loss of diversity in aquatic plant and animal species (Rabalais 2002), and in emissions of N_2O (Bouwman et al. 2002) and NO_x, which can cause respiratory problems in humans (Wolfe and Patz 2002).

A number of technologies have been developed to increase the efficiency with which applied nutrients are used to produce food. One challenge is to match precisely the amount of nutrients available at any given time to the immediate crop requirements, without deficiency or excess, throughout the crop growth period (Matson et al. 1997; Tilman et al. 2002; Dobermann and Cassman 2002). In small-scale agriculture that is typical of high production systems in developing countries, this precision is best achieved through field-specific management because blanket recommendations cannot account for field-to-field variation in soil conditions and crop nutrient status. In large-scale agriculture that is typical of high-potential systems in industrial countries, site-specific management will be required to accommodate the substantial variation in crop and soil properties within individual large production fields.

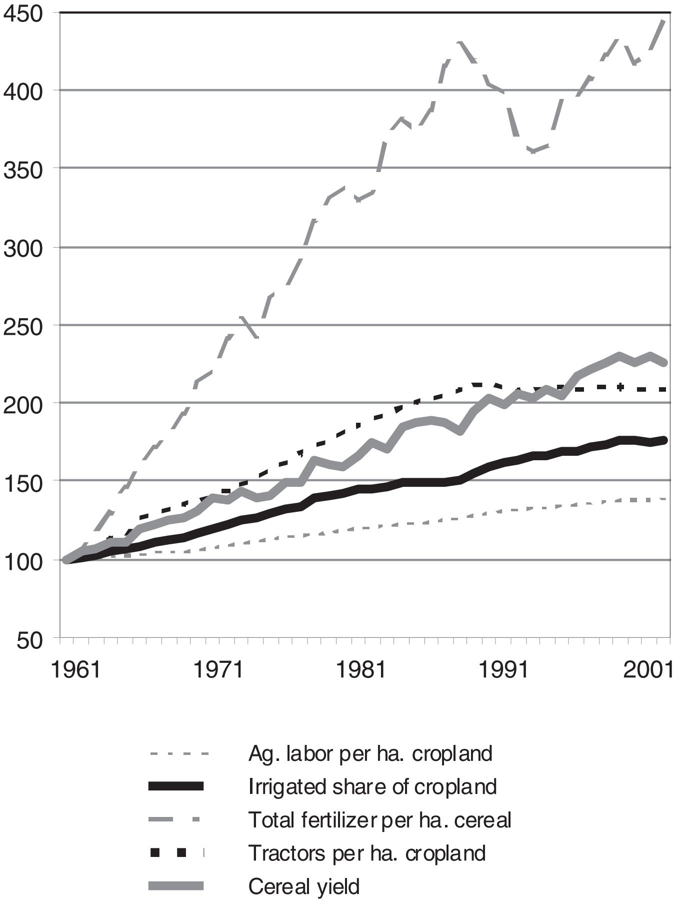


Figure 26.6. Trends in Intensification of Crop Production, 1961–2003. All variables are indexed at 100 in the base year 1961. (FAOSTAT 2004)

Recent research has demonstrated in on-farm studies the potential for significant increases in nitrogen uptake efficiency using these approaches (Dobermann and Cassman 2002). Success in developing these approaches and achieving adoption by farmers, however, requires substantial long-term investments in research and extension to ensure that the improved management practices are well adapted and cost-effective to specific cropping systems and agroecological zones.

While organic nitrogen sources, such as livestock manure and legume cover crops used in ''organic'' agricultural production systems, can be substituted for commercial nitrogen fertilizers, these practices are not feasible in the high-potential cereal production systems of developing countries, where population density is high and arable land resources are limited. Moreover, net profit was found to decrease when organic nitrogen sources were used in place of N fertilizer; which has limited adoption of such practices in tropical lowland rice systems (Ali 1999).

In contrast, ''organic'' production systems that rely entirely on organic nitrogen sources are becoming more popular in Europe and North America, although they still account for less than 2% of crop production. Between 1992 and 2001, the extent of organic cropland in the United States grew by over 200%, from about 163,000 hectares to 526,000 hectares. Organic systems are feasible, and even profitable, in these countries because people can afford to pay higher prices for their food, and there is adequate land to support the crop rotations, legume cover crops, and forages that are needed to supply adequate nitrogen.

It is not clear, however, that environmental benefits would accrue from widespread adoption of organic agriculture if these systems were forced to produce as much grain as conventional systems do today, because it is just as difficult to control the fate of nitrogen from organic sources as it is from nitrogen fertilizer (Cassman et al. 2003). But use of both organic or fertilizer nitrogen need not be an ''either-or'' decision. In most conventional systems, farmers use organic nitrogen sources and rotate with legume crops to minimize the need for nitrogen fertilizer when it is cost-effective to do so.

Although nutrients obtained from livestock manure remain a significant source of nutrient input to cultivated land, their relative contribution has declined substantially in association with the increase in availability and use of commercial fertilizers. On a global basis, Sheldrick et al. (2003) estimate that the contribution of nutrients from livestock manure has decreased from 60% in 1961 to 25% in 1996 for nitrogen, from 50% to 38% for phosphorus, and from 75% to 57% for potassium. However, because livestock manure also contains substantial quantities of organic matter, it can help improve soil physical and chemical properties that determine soil quality. The total amount of nutrients recovered in livestock manure in 2000 was estimated to be 34 million tons of N, 9 million tons of phosphorus, and 23 million tons of potassium.

While livestock in developing countries of Africa and Latin America produce substantial quantities of nutrients in livestock manure, most of this manure originates from grazing cattle and is therefore difficult to collect and use on cultivated land. In contrast, some industrial countries, such as the Netherlands, with large livestock industries that produce cattle, pigs, and poultry in confined feeding operations produce as much nitrogen in manure as their farmers use in nitrogen fertilizer, and the phosphorus and potassium content of this manure exceeds the amount used in fertilizer. (Environmental concerns associated with nutrient losses from large-scale, confined livestock production systems are discussed in earlier in this chapter.)

In contrast to high-potential systems, environmental damage from nutrient losses is not a concern in subsistence cropping systems that are practiced on soils of low inherent fertility in large areas in the tropics. Instead, severe nutrient deficiencies and depletion of soil fertility are the major threats to ecosystem services. Deficient nutrient supply limits food production capacity and profit, which contributes to malnutrition, susceptibility to disease, and economic insecurity. Severe depletion of soil fertility results in a spiral of soil degradation that can eventually render the land unsuitable for crop production. When abandoned, such degraded land can no longer support the native plant and animal communities it previously hosted, and invasive plant species often take over (Cairns and Garrity 1999; Lumbanraja et al. 1998). Subsistence farmers who abandon such land must then cultivate additional areas, thus expanding the area at risk of degradation.

While it is possible to sustain cropping with judicious use of fertilizers (Nye and Greenland 1960; Reardon et al. 1999), access to external supplies is often limited by lack of roads, infrastructure, and markets. Likewise, it is generally not possible to maintain fertility with only organic sources of nutrients because the inherent soil fertility is too low (Sanchez 2002). Integrated use of both organic nutrient sources and fertilizers appears to be the most promising option. Success in gaining adoption of such approaches has been limited by poverty, land tenure policies, and inadequate investment in the development of basic infrastructure, markets, credit, and extension services.

26.2.6 Atmospheric and Climate Regulation

Although carbon dioxide, nitrous oxide, and methane occur naturally in the atmosphere, their recent increase is largely a result of human activity. This increase has altered the composition of Earth's atmosphere and may affect future global climate (IPCC 1996). (See also Chapter 13.) Agriculture contributes to changes in atmospheric concentrations of each of these three greenhouse gases, significantly so in the case of CH_4 and N_2O, of which it contributes 50% and 70% respectively of the total anthropogenic emissions (Bhatia et al. 2004). Frequent cultivation, irrigated rice production, livestock production, and burning of cleared areas and crop residues now release about 166 million tons of carbon per year in methane and 1,600 ± 800 million tons of carbon per year in CO_2. Agricultural systems emit carbon dioxide through the direct use of fossil fuels in field operations (such as tillage, harvesting, irrigation pumping, transport, and grain drying), the indirect use of embodied energy in inputs that require the combustion of fossil fuels in their production, and the decomposition of soil organic matter and crop residues. The direct effects of land use and land cover change (including conversion of forest and grasslands) also resulted in net emission of 1.7 gigatons of carbon per year in the 1980s and 1.6 gigatons annually in the 1990s (IPCC 2000). Burning of standing biomass is a pivotal component of shifting cultivation that emits nitrous oxide in addition to carbon dioxide.

Cultivated fields can be a source or a sink for carbon, depending on the specific circumstances of carbon dynamics during cultivation. Factors having the greatest impact on the carbon balance include crop yield levels, removal of crop residues for fuel or livestock forage, crop rotations that include a pasture phase or perennial forage legume, and tillage. During much of the past century, most cropping systems have undergone a steady net loss of soil organic matter (Lal et al. 2003; Paustian et al. 1997; Lal 2004; Lugo and Brown 1993). Global average soil organic carbon density is estimated at 102 tons of carbon per hectare of land within the extent of agriculture (Wood et al. 2000), and the total global store of soil organic carbon within the extent of agriculture is estimated at 368 gigatons, with 43% of this in temperate zones.

However, with the steady increase in crop yields, which increases crop biomass and the amount of residue returned to the soil, and with the adoption of conservation tillage and no-till cropping systems, net carbon sequestration is estimated to occur in the maize-soybean systems of North America (Paustian et al. 1997), as well as in continuous irrigated lowland rice systems where soils remain flooded for most of the year, reducing the rate of soil organic matter decomposition because of anoxic soil conditions (Bronson et al. 1998; Witt et al. 2000). Estimates of the potential to sequester carbon in cultivated systems on a global basis range from 400 million to 800 million tons per year, assuming that best management practices that foster net carbon storage are widely adopted (Paustian et al. 1997; Lal 2003), although adoption has been limited to U.S. maize-soybean and wheat systems and similar cropping systems in Argentina and Brazil.

Large quantities of agricultural crop wastes are produced from cultivated systems. Disposal systems for these wastes include burning them in the field; plowing them back into soil; composting, landfilling, and using as a biomass fuel; or selling them in supplemental feed markets. Burning crop residues releases a number of greenhouse gases, including carbon dioxide, methane, carbon monoxide, nitrous oxide, and oxides of nitrogen.

An additional impact of cultivation on greenhouse gases occurs from erosion. One ecological off-site impact of accelerated erosion is the emission of erosion-induced greenhouse gases into the atmosphere. While some of the organic carbon transported to depositional sites and aquatic ecosystems is buried and sequestered (Stallard 1998; Smith et al. 2001), a large fraction may be emitted into the atmosphere. Erosion-induced emission of CO_2 into the atmosphere may be about 1 billion tons of carbon a year (Lal 2003). Wind-borne sediments, which transport particulate matter over long distances, also adversely affect air quality.

Agriculture can also contribute to mitigation of greenhouse gases emissions by adopting practices that promote the retention of carbon in stable forms of SOM (called humus) or in standing biomass such as occurs in forest trees. These carbon sinks are promoted by the use of less aggressive tillage and by a reduction in the rate of deforestation to support an expansion of cultivated area. Further reductions could also be achieved in the more efficient use of fossil fuels in all aspects of crop and soil management, which would include greater fertilizer and irrigation efficiency as well as reduced tillage.

26.2.6.1 Methane Emissions

Atmospheric methane is second only to CO_2 as an anthropogenic source of greenhouse gases in the atmosphere, and agriculture accounts for between 44% (IPCC 1996) and 50% (Bhatia et al. 2004) of those anthropogenic emissions. The concentration of methane in the atmosphere has more than doubled over the last two centuries, with enteric fermentation in domestic livestock, manure management, rice cultivation, and field burning of agricultural crop wastes as the main causes. Several other agricultural activities, such as irrigation and tillage practices, may also contribute to methane emissions. About 80% of methane from agricultural sources is produced biologically (IPCC 1992; Yang and Chang 1999, 2001).

During digestion of feed intake, methane is produced through enteric fermentation in the rumen of cattle, buffalo, sheep, and goats, a process in which microbes that reside in the digestive system break down the feed consumed by the animal. These animals have the highest methane emissions among all animal types because they have a rumen, or large "fore-stomach," in which a significant amount of methane-producing fermentation occurs. The amount of methane produced and excreted by an individual animal also depends on the amount and type of feed it consumes and other environmental factors.

The need to increase food production in order to keep pace with population growth and changing consumer tastes has led to a large increase in animal production (FAOSTAT 1999), as noted earlier, and to problems related to disposing of increasing quantities of dung and urine. The problem is exacerbated by disassociation of crop and livestock production (Bouwman and Booij 1998; Ke 1998) such that the animal wastes cannot be directly returned to fields where the feed was grown, which recycles the nutrients for succeeding crops. Instead, livestock manures from large confined feeding operations must be transported greater distances to surrounding farmland. But the nutrient content of the manure is low relative to commercial fertilizers, which increases the cost of handling and transporting it. Moreover, care must be taken to ensure that the amount of applied manure does not lead to excessive accumulation of phosphorus in the soil, which can lead to phosphorus losses via erosion and runoff, resulting in degradation of water quality and health concerns (Burton et al. 1997).

The decomposition of organic material in animal manure in an anaerobic environment produces methane. The most important factor affecting the amount of methane produced is how the manure is managed, since certain types of storage and treatment systems promote an oxygen-free environment. In particular, liquid systems (ponds, tanks, or pits) tend to produce a significant quantity of methane. However, when manure is handled as a solid or is deposited on pastures and rangelands, it tends to decompose aerobically and produce little or no methane. Higher temperatures and moist climatic conditions also promote methane production.

Applying manure to agricultural land can lead to groundwater contamination by nitrates after nitrification of the ammonium nitrogen (NH_4–N) present and to emissions of ammonia (European Centre for Ecotoxicology and Toxicology of Chemicals 1994), methane (Chadwick and Pain 1997), and N_2O (Jarvis et al. 1994)—all of which contribute to climate change. Ammonia, after deposition on land surfaces and water bodies, and nitrification act as a secondary source of N_2O and may also decrease the capacity of soils to absorb CH_4 and act as a sink for this gas (Mosier et al. 1996).

Rice fields are large producers of methane, accounting for as much as one third of total anthropogenic methane emissions. When fields are flooded, anaerobic conditions develop in the soils, and methane is produced through anaerobic decomposition of soil organic matter mediated by soil microbes. In fact, both methane and nitrous oxide are simultaneously emitted, as irrigated rice fields offer favorable conditions for their production and emission (Cai et al. 1997; Bronson et al. 1997; Ghosh and Bhat 1998; Majumdar et al. 2000). Global methane emissions from rice fields are estimated to be 37 teragrams per year, while N_2O emissions are much lower, at 1.8–5.3 teragrams per year, although N_2O is a much more potent greenhouse gas (IPCC 1996).

26.2.6.2 Nitrous Oxide Emissions

Agriculture is the main source of nitrous oxide, a chemically active greenhouse gas, accounting for about 70% of anthropogenic emissions. Atmospheric concentration of N_2O is increasing at a rate of $0.22 \pm 0.02\%$ per year. Concern over N_2O emissions is particularly great because of its long atmospheric lifetime and high climate change potential (Bhatia et al. 2004). Although global atmospheric loading of N_2O is less than CH_4, the former is 310 times more potent as a greenhouse gas than CO_2 on a 100-year time-scale, while CH_4 is only 21 times more potent (Majumdar 2003). N_2O is produced naturally from a wide variety of biological sources in soil, water, and animal wastes and contributes to the depletion of stratospheric ozone. The release of nitrous oxide has increased in recent years due to more intensive agricultural practices, in particular land conversion and application of nitrogen fertilizer. A wide range of other agricultural and soil management practices can also affect N_2O fluxes, including irrigation, tillage practices, the burning of agricultural crop residues, and changes in land use, such as loss and reclamation of freshwater wetland areas, conversion of grasslands to pasture and cropland, and conversion of managed lands to grasslands or the fallowing of land (Mosier et al. 2004).

From the agricultural perspective, N_2O emissions from soil represent a loss of N from the soil system and a decrease in N use efficiency. Soil is considered to be one of the major sources of nitrous oxide, contributing 65% of the global emissions. Annual emissions of N due to N_2O emissions from agricultural systems amounts to 6.3 teragrams. Soil receiving chemical fertilizers and biologically fixed nitrogen contributes to nitrous oxide emissions during the processes of nitrification and denitrification, and the increasing use of fertilizers will lead to increased N_2O emissions unless N fertilizer efficiency can be increased as well.

Use of organic nitrogen sources instead of nitrogen fertilizer causes a substantial increase in methane emissions in irrigated rice systems, and it may not decrease nitrous oxide emissions (when both are applied at levels that achieve similar yields). Thus, from a purely climate change perspective, organic fertilizers should be used with caution in such systems.

In summary, agriculture may be contributing about 20% of current annual greenhouse gas–forcing potential. It is the largest source of anthropogenic CH_4 and a significant contributor to increases in atmospheric N_2O concentration. In contrast, cultivated systems play a relatively small role in total CO_2 emissions, and some systems have the potential to sequester carbon by use of improved crop and soil management practices, thus becoming a sink for carbon dioxide.

26.3 Drivers of Change in Cultivated Systems

Many factors have influenced the evolution of cultivated systems and their capacity to meet the increasing demands placed on them. (See Figure 26.7.) These factors have driven the changes that have occurred in cultivated systems and will continue to do so in the future. This section reviews the nature these drivers, their interactions and extent, and their impact on system performance.

Although the Figure is a simplification of the context and dynamics of cultivation, it illustrates three key points: that the number of drivers and interactions among them are potentially large; that important feedback mechanisms exist that influence the ability of cultivated systems to generate desired cultivated products and ecosystem services; and that individual drivers can simultaneously have positive and negative impacts (for example, a new

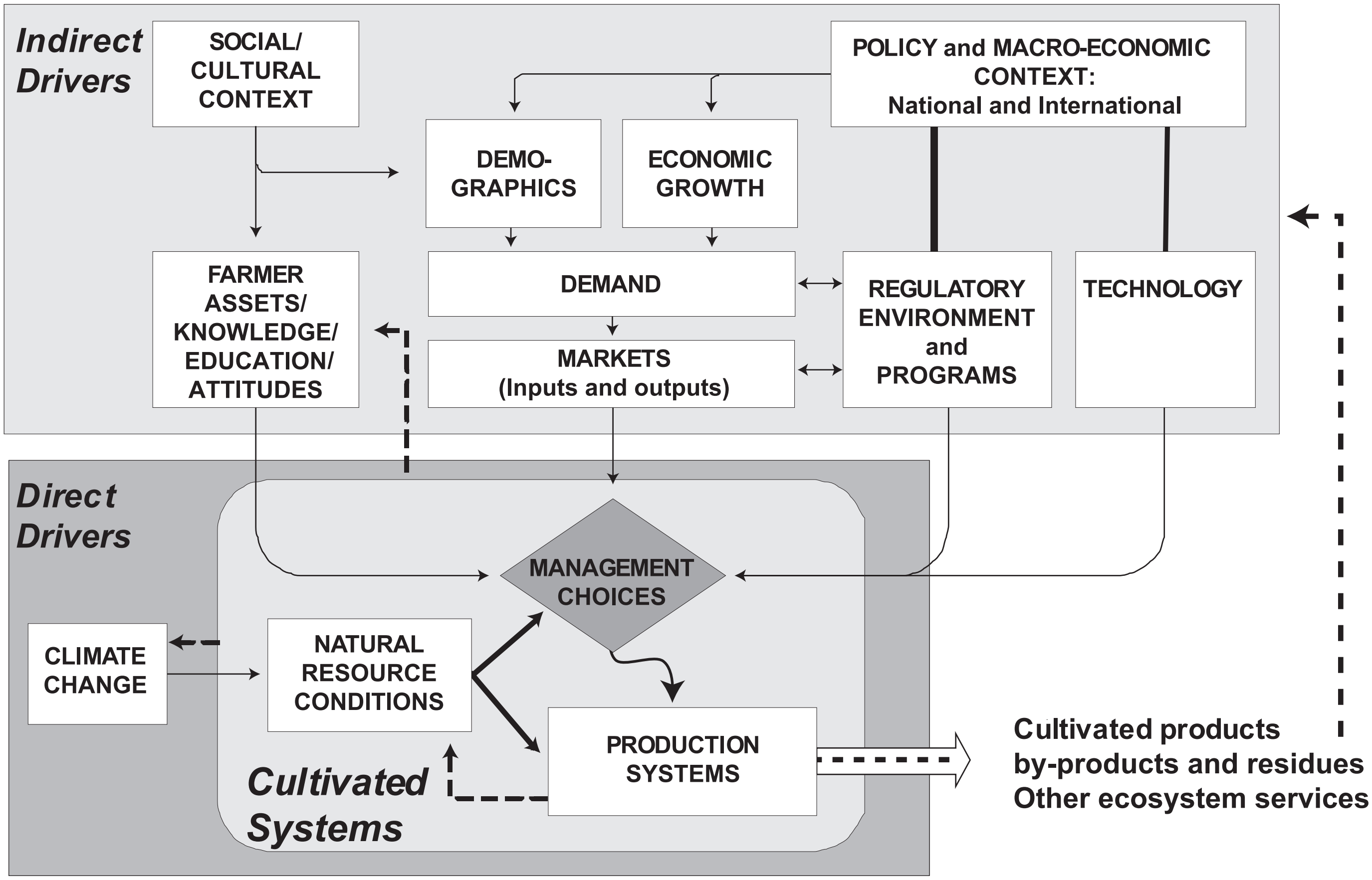


Figure 26.7. Interactions between Drivers of Cultivated Systems

technology that increases the yield of outputs might also generate a negative impact on ecosystem services).

The central role of the "manager" of the cultivated system is also highlighted in this conceptual model, whether the manager is an impoverished subsistence farmer with two or three hectares of remote hillside in East Africa or a professional agronomist in a multinational corporation that cultivates a 5,000-hectare cash crop plantation in Southeast Asia. Within any given socioeconomic and environmental context, it is the sequence of choices made by these managers about what to produce and how to produce it that drives the long-term capacity of cultivated systems to deliver products and ecosystem services. These choices are driven by farmers' incentives to take particular courses of action and by their capacity to act on those incentives. Through a better understanding of the key drivers of change, decision-makers are better placed to target policy and investment interventions for improving the economic and environmental outcomes of cultivation.

In keeping with the MA conceptual framework, drivers are grouped into two broad categories: indirect—those that influence the demand for both cultivated products and other ecosystem services, as well as the overall feasibility and attractiveness of different cultivation options—and direct—those that come into play at the actual site of cultivation.

26.3.1 Indirect Drivers

Many of the indirect drivers of change relevant to cultivated systems have already been described in Chapters 3 and 8, so this section focuses on a selective synthesis together with complementary material of more specific relevance to a cultivated systems perspective.

26.3.1.1 Demand for Cultivated Products and Other Ecosystem Services

The scale and structure of demand for cultivated products as well for other ecosystem services from agricultural landscapes has been broadly shaped by three drivers: demographic change, economic growth, and changing consumer preferences.

Over the past 50 years population growth has been the single most important global driver determining the aggregate demand for food and other cultivated products and shaping the extent and intensity of cultivation. Between 1960 and 1999, world population doubled to 6 billion, with an average growth rate of around 1.7% per year, while aggregate per capita food energy consumption grew at just over 0.5% per year. In industrial as well as developing countries, 60–70% of the total increase in calories consumed between 1961 and 2002 was accounted for by population growth (FAOSTAT 2004).

Population growth rates are declining, however, and currently stand at around 1.4% per year globally, although with major regional differences. Developing countries now account for over 95% of global population growth and hence a correspondingly greater share of the pressure to expand food output from cultivated systems. High population growth rates are negatively correlated with income levels. Hence, the population in poorer countries are typically less well nourished or even undernourished compared with populations in rich countries. Food insecurity in poor countries or regions often results from the low productivity of local cultivated systems (UN Hunger Task Force 2005). In Europe and some richer developing countries, population growth rates are stagnant or negative, so population growth is no longer a driver of food demand, and this trend will continue globally as economic development proceeds and population growth rates continue to fall (United Nations Population Fund 2004).

Economic growth is another strong stimulus of demand. As incomes rise in many developing countries, a large share of the increased income is used to purchase a greater and more diverse food supply. Compounding both population growth and increased purchasing power, social and cultural change—often linked to urbanization, increased female participation in the workplace, and increased exposure to food industry advertising and to public health and nutrition information—have changed consumer preferences with regard to the type, amount, and quality of food they demand. This includes growing preference for animal protein, (particularly chicken and pork), for fruits, vegetables, and oils, and for more processed and convenience foods and declining preference—as a share of per capita consumption—for starchy staples and cereals (FAOSTAT 2004). The rapid growth in industrial-scale, confined livestock systems and aquaculture have been direct consequences of these trends. Urbanization not only alters food preferences, it also changes the age and sex structure of rural populations and increases remittances—both factors that influence cultivation practices. (See Chapters 3 and 8.)

Many of the same demographic and socioeconomic changes have also increased the demand for a broader range of ecosystem services beyond food, such as fresh water, clean air, wildlife conservation, and recreation. Since cultivated systems now dominate many of the populated landscapes of the world, they have come under increasing pressure to play a greater role in delivering more (or consuming less) of these other services, while at the same time continuing to meet growing food needs (Wood et al. 2000).

Cutting across demographic and economic factors is the issue of poverty, which severely curtails livelihood opportunities. From a cultivation perspective, poverty limits access to production inputs such as credit and to new technologies that improve crop and soil management. Poverty is also often associated with a lack of security in terms of access to or title to land and other natural resources, in turn diminishing farmers' incentives and ability to choose production practices with long-term payoffs. Without such incentives, cultivated systems are focused on meeting short-term needs, and increasingly intensive cultivation under such conditions has often resulted in the degradation of soil and water resources that are required to maintain even low levels of productivity. This process has been called a ''downward spiral'' of productivity and degradation (Scherr 2000; Ehui and Pender 2005; Wiebe 2003). Ultimately such a degradation spiral can lead to abandonment of the cultivated system and migration to other locations that are likely to be of more even more marginal production potential (Barbier 1997; Chopra and Gulati 1997).

26.3.1.2 Policy, Legal, and Sociocultural Context of Cultivation

The policy, regulatory, and cultural environment have profound impacts on the incentives to produce more and higher-quality food, to engage in local, regional, and international trade, to invest in long-term productivity and enhanced cultivated system capacity, and to reduce the off-farm impacts (the externalities) of cultivation. The distinct and evolving nature of policies and institutions across and within countries influences the effectiveness of markets and hence choices about where, what, how, and how much to cultivate as well as the incentives, if any, for farmers to reduce or eliminate negative externalities caused by their cultivation practices (Uri 2001; Eicher 2000).

Agricultural, trade, and food security policies can distort incentives to produce and trade cultivated products in one way or other. These include price policies that favor either domestic rural producers (such as the U.S. Farm Bill and the EU Common Agricultural Policy) or urban consumers (such as the food price control schemes prevalent in many developing countries). The level and effectiveness of investments in education, infrastructure (roads, irrigation, rural electrification, and telecommunications), and credit have been shown to be strongly related to improvements in agricultural productivity and rural incomes (Fan et al. 2000; Fan and Hazell 2001; Zeller and Sharma 1998; Wiebe 2003). Investments in agricultural research and technology transfer have been especially strong drivers of change in cultivated systems, as described later in this section.

Resettlement policies, though now less common and certainly of lesser scale, have had significant impact on the conversion of natural ecosystems over very large areas for cultivation, with consequent, large-scale environmental consequences. The massive transmigration program from Java to the outer islands of Indonesia and the colonization policies of the Brazilian government, implemented largely during the 1960s and 1980s, are two notable examples (Fearnside 1997).

The nature and strength of land tenure and resource use laws and customs have been shown to strongly influence the willingness of farmers to engage in cultivation beyond meeting subsistence needs, as well as to invest in sustainable land management practices (Soulé et al. 2000; Meinzen-Dick et al. 2002). Similarly, the effectiveness of collective action can significantly affect the productivity and sustainability of cultivated systems. This is true not only for proper management and utilization of open access and common property resources such as pastures or woodlots, but also where the productivity of individually managed plots and fields would benefit from collective action, such as coordination of agronomic activities so as to pool labor, minimize pest and disease problems, or make the best use of available water resources (Meinzen-Dick et al. 2002).

Inheritance laws and customs are also relevant. The practice of dividing land among heirs, particularly common in Asia, has so fragmented holdings in some areas that the scale of cultivation operations limits their economic viability over the long term (Maxwell and Wiebe 1999).

In recognition of the potential environmental costs of cultivation, the growing demand for improved environmental services, and the lack of incentives for farmers to consider externalities, governments have played an increasing role in influencing crop selection and cultivation practices through both regulatory and voluntary incentive schemes. Regulatory policies have included systems of wildlife and watershed protection and conservation that have sought to exclude or restrict cultivation in areas considered to have high biodiversity, hydrological, watershed protection, or amenity value. Where cultivation pre-existed in such areas, or where land and population pressure external to such areas has been high, these policies have often created conflict with farming communities (Gillingham and Lee 2003; Maikhuri et al. 2000). This has led to the emergence of more enlightened and participatory approaches to the design and management of conservation areas in partnership with local communities (Farrington and Boyd 1997).

Other approaches have included the zoning and regulation of certain types of cultivation or cultivation practices, such as large-scale confined livestock feeding operations, that present local waste and odor problems or use of certain categories of pesticides. While such restrictions are often associated with punitive sanctions, their effectiveness has varied depending on the technical and economic validity of the regulation standards applied, the deterrent value of the sanctions, and the rigor of enforcement (Kleijn et al. 2004).

Voluntary strategies, particularly in richer countries, involve incentive payments to farmers linked to production or conservation practices that are considered to be more environmentally sound (Dobbs and Pretty 2004; Wu et al. 2004). Increasingly these policies are being aligned with the ''boxes'' established under the auspices of the World Trade Organization that govern permitted levels and types of domestic support to agriculture. One goal of the WTO is to ''decouple'' support to farmers from production and price level, as a means of reducing trade distortion (WTO 2004). The U.S. 2002 Farm Bill provides for support to farmers related to programs for resource conservation, wildlife habitats, and wetlands within cultivated systems (National Resources Conservation Service 2002), and similar programs operate in most, if not all, OECD countries. But the WTO provisions that accommodate such programs are still controversial among many developing countries: they see them as an indirect means of providing otherwise restricted or disallowed income support, which places their own farmers at a competitive disadvantage (*The Economist* 2003).

It is difficult to generalize about the net effect that national policies have had on cultivated systems. However, in those countries where policies tend to expand production to levels that would otherwise be uneconomic—such as cotton in the United States, sugar in the European Union, and rice in Japan—it is likely that more land is being kept in production and more agricultural pollution is taking place than would otherwise be the case. Another implication is that, to the extent that such subsidies distort trade, less area is allocated to the cultivation of these crops in competitor countries, such as cotton in West Africa and India, sugar in the Brazil and Australia, and rice in Viet Nam.

As subsidies and other barriers to trade are removed in these and other commodity sectors, adjustments in global patterns of production will take place. The net local and global consequences of such changes on cultivated systems and ecosystems services depends primarily on the relative yield levels (as those determine the harvested area required for a given level of production) and the specific production inputs and practices used in each location, such as the nature, management, and mix of inputs and practices for plant, soil fertility, water, and pest and weed management. These in turn depend on local markets, farmer characteristics, resource conditions, and management choices.

26.3.1.3 Markets

The existence and efficiency of markets, and the extent to which farmers are able to participate in them, provide perhaps the strongest signals shaping cultivation decisions for an ever increasing number of farmers. Even where subsistence goals dominate household production strategies, survey data indicate that households frequently engage in markets to varying degrees. Markets include those for cultivated outputs (main products and by-products), inputs (such as labor, land, seeds, fertilizers, and pesticides) and those, often at a nascent stage, for ecosystem-related services such as carbon sequestration and habitat conservation.

Essential ingredients for the development of markets include a stable monetary system, accepted procedures for establishing and enforcing contracts, viable entry costs for market participation, financially acceptable search and transaction costs, and adequate access to physical infrastructure and transportation. As described earlier, incentives for market development and participation have also been shaped by policy factors that directly affect markets through transfers (taxes or subsidies) or other barriers related to production, consumption, or trade.

High transaction and transport costs limit market opportunities since they increase the farmgate cost of inputs and reduce the farmgate value of outputs. The geographic scope of market potential is also influenced by the bulk density and perishability of cultivated products and by the unit value of the product itself. Where markets function effectively, where products can be cultivated competitively, and where demand exists, the geographic distances between production and consumption can be very large, as seen in the global cereal markets. Other examples include the cultivation of high-value horticultural crops, of flowers and ornamentals in the cool tropical highlands of Central and northern South America for the U.S. market and in Kenya and Uganda for UK supermarkets, of out-grower schemes in Indonesia for the Dutch flower industry—all of which use air transportation—as well as the production, packaging, and shipping of fresh fruit and vegetables in California to all parts of the United States by rail and road transportation.

Thus, where it has been possible to lower marketing and transportation costs, the geographic distances between production and consumption becomes less relevant, and producers, and the cultivation systems they manage, are exposed to an increasingly broad range of market opportunities. This is often a double-edged sword—on the one hand, providing increased incentives to expand or intensify production with possible negative ecosystems consequences, while on the other hand providing greater incentives to preserve the long-term sustainability of the production base that might foster more positive outcomes for ecosystem management (Lopez 1998; Kaimowitz and Angelsen 2000).

But there remain significant obstacles for smallholders in developing countries to engage more in local, regional, and international markets. Many relate to constraints to market entry through insufficient access to credit or information about market needs and to the insufficiency and variability of the quantity and quality of farm outputs to engage in stable marketing arrangements. At the same time, there appear to be growing barriers to trade arising from stricter sanitary and phytosanitary standards being imposed by importing countries. While fears of pest, virus, and disease consequences for plant, animal, and human health are undoubtedly genuine and call for effective safeguards, these regulations have become another contentious issue under the WTO. As with subsidies and environmental payments, many developing countries regard the sanitary and phytosanitary requirements and regulations imposed by richer countries as another mechanism for imposing indirect trade barriers (Henson and Loader 1999; Athukorala and Jayasuriya 2003).

There are several market niches that link cultivated products with what are considered to be improved standards of cultivation with regard to ecosystem outcomes or ethical issues. These are products designated as, for example, organic, bird-friendly, shade-grown, fair-trade, and humane from an animal welfare perspective (Harper and Makatouni 2002; Lockie et al. 2002). The organic food movement is perhaps most developed in Europe, but it can probably be considered a global scale phenomenon, especially with richer consumers.

The term ''organic'' is open to many different interpretations but can include avoiding or minimizing the use of pesticides, inorganic fertilizers, antibiotics, GMOs, fossil fuels, and so on as well as promoting biodiversity at various levels. Broadly accepted standards are beginning to emerge in some markets (Guthman 1998; European Union 2000; USDA 2004), as well as widely-accepted market certification procedures, such as those of the UK's Soil Association (2004). Currently, almost 23 million hectares globally are reportedly explicitly managed according to organic principles (IFOAM 2004). Of this total, some 46% are reported in Australia/Oceania, 23% in Europe, and 21% in Latin America. While the United Kingdom and Germany have about 4% of cultivated land under organic production, the United States has less than half a percent, although these systems contribute some 3–5% of fruit and vegetable production (Greene and Kremen 2003).

26.3.1.4 Prices

The ability of farmers to respond to changes in prices of inputs and products is an important indicator of the resilience of food production systems. Producer decisions about what and how much to produce (or to harvest, in the case of wild fisheries) are strongly influenced by the relative prices of outputs (maize versus beans, for instance, or cod versus plaice), as well as of essential inputs (such as the maize/nitrogen fertilizer price ratios). Consideration of time frames and the need to maximize return on fixed assets are important determinants of the willingness and ability of producers to respond to price signals.

Output responses are quicker and stronger for short-term production cycles than for longer ones. Thus adjustments in annual cropping can be made in a short time frame, whereas decisions about changing animal herds or perennial crops that take longer to develop their economic potential are more complex. The average price of food has been on a downward trend for some 40 years, and many poor smallholders who have limited access to productivity-raising technologies and practices often face situations in which their on-farm costs per unit of product, plus the unit costs of transportation and marketing, are higher than the market price of their products. In the case of marine fisheries, prices have increased, reflecting the scarcity as more and more fisheries are fully exploited, as well as increased costs because of increased fishing effort.

Increased farmgate prices—for example, for higher-quality or better-timed products or brought about by temporary shortfall in supply—can raise producer incomes and increase incentives for more investment in the underlying production system. This could have positive or negative outcomes for ecosystem services other than food, depending on the type of investment. Furthermore, increased profits from increased productivity might be a spur to bring more land into production, including more conversion of natural ecosystems (Kaimowitz and Angelsen 2000). Ironically, falling prices can also have equally ambiguous outcomes, ranging from providing incentives to raise productivity to removing incentives to make any further investments—likely with negative ecosystem impacts.

26.3.1.5 Technology and Information

One of the most widely researched areas in the field of agriculture is the impact of technical change on the productivity of cultivated systems. Assessments at programmatic and national scales typically suggest that the contribution of technical change to overall productivity growth is in the range of 30% to 50% (Evenson and Gollin 2003; Ruttan 2002; Roe and Gopinath 2001). Technologies include better-quality inputs such as improved crop varieties with higher genetic potential and increased pest and disease resistance, improved livestock breeds and fish species, better cultivation techniques such as zero tillage, improved agronomic practices such as the timing and placement of applied nutrients and water, and better storage and other post-harvest technologies. In countries where a sufficiently large base of commercial farmers exist, the private sector plays an important role in technology development and delivery, but in virtually all countries public investment in agricultural research and extension are important and well established if not always adequately funded areas of public policy (Pardey and Beintema 2001). These investments reflect both the importance of the agricultural sector to the rural economy and the generally high levels of economic payoff to agricultural R&D investments.

During the past 50 years, crop genetic improvement and improved technologies for managing soil nutrients and pests have come predominantly from investment in research and extension conducted by public-sector institutions such as universities and national and international agricultural research centers (Pardey and Beintema 2001). In recent decades, however, investment in private-sector research has increased markedly, especially for improvement of commercial crops such as maize, soybean, and cotton that require purchase of new seeds each cropping season for achieving optimal yields.

Today, agricultural research investment in the private sector exceeds that in the public sector, with consequences on research priorities (Pardey and Beintema 2001). The private sector focuses on improving crop traits that result in greater seed sales, emphasizing relatively short-term research successes. Private-sector research has also given greater emphasis to use of modern tools of molecular genetics to develop crop varieties with traits controlled by single genes. (See Box 26.3.) Many of the major crop development constraints, such as yield potential, drought tolerance, and nitrogen use efficiency, however, are controlled by numerous genes, and progress will require greater scientific effort and longer-term investment. The private sector has few incentives at present to invest in technologies aimed at improving environmental services.

The focus of public investment is on research producing ''public goods'' (knowledge and technologies that can be used by all, without exclusion, such as a new soil conservation practice), as well as research that is too long-term, risky, or otherwise financially unattractive to the private sector but that would yield social benefits, such as more environmentally sustainable production practices. In the past, publicly-funded research has focused on understanding and increasing crop yield potential, achieving greater fertilizer use efficiency, protection of water and soil quality using conservation tillage systems, and reducing pesticide use through integrated pest management.

BOX 26.3

Crop Breeding and Genetics

Plant types and agricultural techniques that are better suited to farmers' needs could go a long way toward improving the productivity of cultivated systems and thus the livelihoods of farmers. Genetically modified crops provide economic gains to farmers that have shown to be large in the case of cotton and soybeans. Extending these gains to other "orphan" crops that are planted by smallholders could, in the presence of appropriate regulatory policies, have significant poverty-reducing effects. Stress-tolerant varieties have the potential to benefit producers; nutritionally enriched varieties have the potential to benefit consumers as well.

Many people are concerned about the prospects of biotechnology. Concerns center on the science itself, control over the science, access to the science, environmental effects, and human and animal health effects (FAO 2004a). Addressing these concerns separately and in a case-specific manner is essential for analyzing the costs and benefits of genetic technologies as they are applied to crops.

Studies of economic returns into public-sector agricultural research have documented substantial and consistent returns on investment as a result of higher yields and farm profits, increased labor productivity and prices, and lower prices of staple grains for consumers (Alston et al. 2000). Despite this evidence, recent trends in public funding of research and technology transfer in both industrial and developing countries show general decline at a time when constraints to sustaining yield growth while protecting environmental services are becoming more complex and scientifically challenging. If maintained, this decline will affect agricultural research outputs globally, with serious consequences for the ability of crop productivity growth to keep pace with food demand and for opportunities to improve the environmental characteristics of new technologies.

The overall efficiency of converting research investment into yield gains at the farm level is an important driver of food supply. For example, the total research investment in both public and private sector for maize genetic improvement increased 3.4-fold in inflation-adjusted dollars from the mid-1970s to the mid-1990s in the United States while the rate of gain in U.S. maize yields remained constant at about 100 kilograms per hectare per year during this period (Duvick and Cassman 1999). Therefore, the efficiency of converting investment in maize genetic improvement to greater yields at the farm level has decreased by about 70%.[3] (See Chapters 4 and 8 for further extensive treatment of the role of science and technology.)

A particular area of concern has been the relatively low adoption of many technologies designed to improve soil and water conservation or provide other improvements in ecosystem service delivery from cultivated systems. Many of these technologies—such as use of the nitrogen-fixing azolla plant to replace nitrogen fertilizer in lowland rice production, alley-cropping with leguminous trees on plot borders, use of the tree leaf mulch on subsistence cereal crops in sub-Saharan Africa, and contour bunds and vegetative field border strips to reduce erosion for hillside cropping systems—are often labor-intensive, provide benefits after several years, or provide benefits off-site. These characteristics often make them unattractive to farmers in countries where conservation efforts are not subsidized and in situations of limited assets (including labor) and insecure land tenure (Lutz et al. 1994; Antle and Diagana 2003).

Changes in cultivation systems are driven by access to various types of information: market data on prices, grades, and standards; advances in cultivation practices and technologies (both for farmers and for researchers); current weather conditions and forecasts; and information on current pest and disease threats and recommended responses. Where they are available and accessible to farmers, and farmers have the capacity to use them, all these types of information have economic value (Solow et al. 1998).

26.3.1.6 Farmer Characteristics

Ultimately, it is farmers who make decisions about the nature and management of cultivated systems, decisions that affect the delivery of both cultivated products and ecosystem services. Thus the cultural, socioeconomic, and educational background as well as the expectations, preferences, and risk attitudes of farmers and farm households all play a role in shaping cultivation decisions.

In the case of subsistence, resource-poor farmers, it is the reduction of production risks while best using family labor that is the driving force behind decision-making (Willock et al. 1999). There may also be different attitudes to risk, crop management, and even crop selection and cropping patterns on the landscape among men and women farmers. In general, women-headed households focus more on meeting food self-sufficiency needs using a diverse portfolio of products to meet a range of nutritional and domestic needs. Male-headed households have generally been shown to be less risk-averse and often focus on the production of cash crops. Farmer age and education level are also considered to be important factors in conditioning willingness to accept new ideas and technologies (Soulé et al. 2000).

Often farmers and farming communities have a very large amount of accumulated indigenous and science-based knowledge, but experience and new knowledge continue to evolve. Indeed, it is the interplay between indigenous knowledge, access to new technologies, and risk aversion that are major determinants of decisions about cultivation practices and evolution of farming systems. Considerable effort is being made to improve understanding of this process (e.g., Röling and Wagemakers 1998) and to advance it through better designed interactions between farmers, researchers, and technology support specialists (Loevinsohn et al. 2002).

26.3.2 Direct Drivers

Direct drivers are those that manifest themselves at the point of cultivation. As shown earlier in Figure 26.7, we can broadly identify three types of direct drivers:

- management choices made at plot, field, pen, or pond level about the scale of cultivation and what to cultivate and how;
- the production system itself—its specific mix of inputs including labor, production practices, and outputs in terms of cultivated products as well as other residues; and
- the natural resource base (including the local impacts of climate change) that underpins and is affected by the cultivation process.

26.3.2.1 Management Choices

To a large extent the potential productivity and ecosystem service impacts of a cultivated system are pre-determined by the crop and resource management choices farmers make, which are often extremely constrained in the case of poor farmers. Key drivers involve strategic decisions about which crops to produce and the cropping pattern in time and space, how much area to devote to cropping, and tactical decisions about specific production practices involving crop and soil management involving nutrients, water, and pest control.

In the face of growing demand for cultivated outputs, several key factors are involved in these choices from an ecosystem service perspective. First, the choice about what to produce often has direct implications on services. For example, perennial crops reduce cultivation needs and are often associated with more ground cover and less soil disturbance, which may result in less soil erosion and lower carbon emissions. The more uniform landscapes of annual crops grown in monoculture reduce biodiversity and can increase the risk of erosion on sloping land unless conservation tillage practices are used that leave adequate crop residues to protect the soil surface. Cultivation of high-value cotton and horticultural crops often uses substantial amounts of pesticides to ensure adequate product quality to meet consumer demand, and growing tobacco in some developing countries is frequently associated with high consumption of fuelwood for drying purposes.

A second strategic factor with a large impact on ecosystem services relates to choices about how much area to cultivate, and especially whether to expand production into as yet uncultivated areas—that is whether to transform natural ecosystems or semi-natural rangeland plant communities into cultivated systems. Pressures to expand are larger if land suitable for cultivation is available at low cost and if land currently under cultivation has low or declining productivity.

The third set of choices is related to production technologies and practices, which in turn are strongly linked to strategies adopted for the intensification of production. Intensification can be achieved through increased inputs and outputs (increased yields) per hectare per harvest, or by increasing the number of harvests in a given time (such as reducing fallow periods or sequential cropping within a single growing season). This is generally termed increasing the cropping intensity. Increasing cropping intensity is often the first stage in the transformation from swidden to permanently cultivated systems, and it can be one of the major consequences of irrigation in regions where rainfall is uni-modal and sufficient for only one cropping season per year.

It is the accumulation of such management decisions by many rural households over time that ultimately drives the aggregate extent and condition of cultivated systems and their impact on ecosystem services—both within the agroecosystem in question and in adjacent or even distant ecosystems that are affected by the externalities of cultivation.

Globally, 78% of the increase in crop output between 1961 and 1999 was attributable to yield increases and 22% to expansion of harvested area. Of the expansion in area harvested, roughly two thirds was accounted for by physical expansion of arable land and the remainder was due to increases in cropping intensity (Bruinsma 2003). While the pattern of yield increases outpacing harvested area increases was true for most regions, the proportions varied. For example, only 55% of total output growth was derived from yield increases in Latin American and the Caribbean compared with 80% in South Asia. In contrast, only 34% of increased output was derived from yield increases in sub-Saharan Africa and 66% from harvested area expansion. In industrial countries where the amount of cultivated land has been stable or declining, increased output was derived predominantly through increased yield and cropping intensities.

In both physical land area and proportional terms, the largest expansion of arable land took place in Latin America and the Caribbean, where expansion of the agricultural frontier accounted for about half of the increase in crop output, with cropping intensities static (Bruinsma 2003). For, example soybean production expanded by some 25 million hectares in Brazil and Argentina between 1981 and 2004, largely through expansion of arable land (Fearnside 2001; James 2004). And conversion of forest and savanna to agropastoral systems was widespread throughout South and Central America. By contrast, of the 66% of increased crop output that was due to increased harvested area in sub-Saharan Africa, about half was attributed to increase in cropping intensity and the rest to increased cultivated area.

Some of the factors that drove these trends have been described earlier: the Green Revolution in Asia; resettlement policies in Brazil; environmental conservation programs in Europe, North America, and Oceania; and so on. But a key underpinning factor in all these cases is the difference in relative endowment or scarcity of land, labor, and capital in the various regions. These endowments have, for example, shaped national technology generation strategies, such as investment in land-saving R&D in Asia and labor-saving R&D in North America (Hayami and Ruttan 1985). At the farm level, area expansion has been pursued in regions of relative land abundance, and intensification has been the preferred strategy where land or labor are scarce and capital more abundant.

Figure 26.8 illustrates the distinct levels and trends in land productivity (total value of crop and livestock outputs per unit of arable land) and labor productivity (total value of crop and livestock output per agricultural worker) from 1961 to 2001 for different regions. Western Europe, with extreme land constraints, shows high land and improving labor productivity. The United States, with high capital and limited labor, has shown high and increasing land and labor productivity. Asia, with little additional land and abundant labor, has shown high and increasing land productivity but low labor productivity. Sub-Saharan Africa remains low in both dimensions, and while some limited progress has been made in land productivity (but by 2001, only reaching levels that are still below or equal to the starting point of all other regions in 1961), virtually no gains have been made in labor productivity.

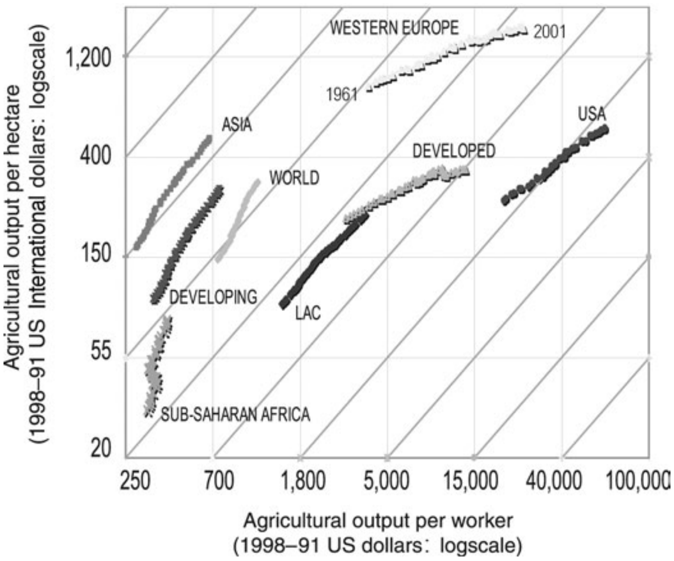


Figure 26.8. Growth in Land and Labor Productivity by Region, 1961–2001. The graph is derived from an assessment of crops and livestock only. Output values were computed for individual commodities using the FAOSTAT production time series and average world prices estimated by FAO for the period 1989–91 (FAO 1997). "Land" is the sum of arable and permanent cropland and pasture in each year. "Labor" is the population economically active in agriculture: as defined by FAO. The diagonal lines represent pathways of equal growth in land and labor productivity.

26.3.2.2 Natural Resource Conditions and Production Systems

Natural resource conditions are described briefly here because the impact of production processes, ecosystem services, and cultivated system management that influence natural resources have been covered in greater detail elsewhere in the chapter. Furthermore, many production system practices represent direct responses to changes in natural resource conditions described in previous sections (declining soil productivity, for example).

The range of feasible cultivation options open to farmers is fashioned by a number of indirect drivers: input and output markets, the regulatory environment, accessibility of usable and profitable technologies and information, the cultural context and socioeconomic condition of the farm household, and the farmer's knowledge base, goals, and attitudes to risk. But specific cultivation decisions for each site are made taking into account the set of prevailing local natural resource conditions, particularly the availability of land and water; the type and variability weather conditions; the quality of soil and water; the prevalence of pests, diseases, and weeds; and other potential natural hazards such as erosion and flooding. Key among these factors for crop-based systems are the availability of land suitable for cultivation and the depth, water-holding capacity, fertility, and workability of soils. The quality and reliability of water are important for all forms of cultivation but are most critical for irrigated systems. Rain-fed systems are subject to the usual uncertainties of weather, exacerbated by the impacts of climate change—increasing temperatures, shifting rainfall patterns, and greater variability in seasonal rainfall.

As a result of the high degree of heterogeneity of natural resource endowments and climatic variability over relatively short distances, it is difficult to make uniform management recommendations for production technologies or practices at scales above the field level. For example, recent results from on-farm tests in intensive irrigated rice systems of South and Southeast Asia confirm the benefits of taking a "field-specific" approach for nutrient management to optimize yield, fertilizer efficiency, and profit (Cassman et al. 1996; Dobermann et al. 2002). Such specificity highlights the challenge of developing and scaling up the adoption of new technologies from field to district/county and to regional scales, and the magnitude of this challenge increases in proportion to the complexity and sophistication of crop and soil management practices. In less favorable production environments where natural resource endowments are relatively poor and there is little infrastructure or market development, it is particularly difficult to support farmer adoption of new technologies. Such is the case in sub-Saharan Africa, where not only are production conditions extremely heterogenous but public and private institutions that support technology generation and transfer are often quite weak.

Some drivers related to natural resource condition are unpredictable and largely uncontrollable, such as weather variability, climate change, and the emergence of new pests and diseases, and can at best only be managed once they occur. Others include onsite conditions that both affect and are affected by production, such as soil nutrient dynamics, soil water status, erosion, and weeds. These are mostly controllable conditions if farmers have sufficient resources, access to information, and technologies that provide profitable solutions to address these constraints.

26.3.3 Summary of Drivers as Potential Points of Intervention

The drivers affecting the evolution of cultivated systems and their capacity to produce cultivated outputs and services are many and are interrelated. It is tempting to simplify the complexity of these direct and indirect drivers and focus only on the field-level issues that affect provision of food and environmental services. That would be, and indeed has been, a mistaken approach. The literature of technology adoption examined in this assessment is, despite the many significant successes, replete with examples of failed "fixes" at the farm level in broader contexts where income levels, security, property rights, equity, financial and agricultural markets, health, education systems, and so on were inadequate to provide the proper enabling environment and incentives for farmers to make the type of productive, long-term investments that are required to deliver economic and environmental benefits in a sustainable fashion.

Regardless of the productivity and profitability of cultivated systems from a farmer perspective, the central MA concerns of how best to deal with the externalities of cultivation remain a major challenge in all cultivated systems. As described earlier, many of the impacts of cultivation on ecosystem services occur away from the farm, outside the agroecosystem boundaries, which provides little or no incentive to farmers to invest in reducing them. Likewise, consumers are increasingly demanding affordable and safe food, which means continued increase in cultivated yields and product quality at the same time as addressing concerns about negative impact on environmental quality.

Our assessment documents that a number of approaches have been used to address these concerns: the development of productive, environment-friendly, profitable ("win-win-win") technologies or practices, the regulation of farming practices on a statutory or voluntary basis (such as effluent standards and penalties versus watershed stakeholder institutions), and, more recently, payments designed to promote improved environmental outcomes. Continued experimentation with, improvements in, and integration of such strategies, involving several indirect drivers listed in Figure 26.7, will be central to progress from both a food security and environmental sustainability perspective.

26.4 Trade-offs, Synergies, and Interventions in Cultivated Systems

The preceding sections examined the condition and trends of ecosystem services and the major driving forces that shape them, highlighting how it is the response of farmers to these trends and pressures, using means that best match their opportunities and constraints, that largely determines the various outcomes of cultivation. This section summarizes some of the trade-offs that have been faced in balancing between food provision and other ecosystem services and briefly reviews a number of approaches and interventions that appear to reduce such trade-offs: integrated pest management; integrated agriculture-aquaculture; farm-scale options for mitigating carbon emissions, increasing carbon sequestration, and minimizing soil erosion; and agroforestry. Such approaches have shown results both in farmers' fields and in reducing off-site effects, but they are often very knowledge-intensive, require additional land or labor, and take time to yield benefits—all factors that can limit broader adoption unless more cost-effective interventions can be developed or non-distorting incentives can be provided.

26.4.1 Trade-offs

The world's cultivated systems embody a diverse array of biophysical constraints and production strategies. The specific quantity and mix of outputs generated by each system, including the supply of ecosystem services in both the short and the long term, is a consequence of the interaction among natural and managed processes, including the use of external inputs (chemical, physical, mechanical, or biological). The extent to which specific management interventions result in trade-offs or in synergies among system outputs (such as the impact of increased food output efficiency on water and nutrient cycling and biological diversity) is often both system- and location-specific.

Some clear trade-offs have been observed in the evolution of the world's dominant cultivation systems. For example, most flat, well-watered, fertile areas have increasingly been managed to simplify ecosystem function and to specialize in the efficiency of food production. Sustaining the high levels of food output such systems provide has generally and significantly reduced the supply of other ecosystem services from cultivated areas. High food-yielding cultivated systems have often required substantial externally derived inputs to sustain yield levels, such as additional reserves of water and nutrients, as well as the use of herbicides, insecticides, fungicides, and external energy sources.

The integration of cultivated systems into commercial food, feed, and fiber markets has usually provided the knowledge, incentives, and financial resources to maintain and often increase their already high food production capacity. However, the impact of intensive cultivation on the provision of ecosystem services both within and beyond the extent of cultivation has been equally substantial, resulting in the depletion of natural and human-made water reservoirs, water pollution, the disruption of global nutrient (particularly nitrogen) cycles, increased carbon- and nitrogen-based gas emissions, and an accelerated loss of terrestrial and aquatic biodiversity (Merrington et al. 2002). The global extent of farming and the specific trade-offs it entails imply that agriculture is the single largest threat to biodiversity and ecosystem function of any single human activity (Clay 2004).

While the evolution of the world's other dominant crop-based cultivation systems, low-input, smallholder rain-fed systems, has been markedly different, they too have increasingly been faced with significant trade-offs in the provision of ecosystem services. In general, low-input systems consume less energy and emit fewer pollutants. They also tend to accommodate higher levels of agricultural biodiversity with regard to more diverse crop mixtures and crop varieties.

Within many of these systems, increasing the provision of food would have a significant positive effect on human well-being, especially in cases where they support poor rural populations in areas with underdeveloped markets and where a lack of purchasing power prevents farmers from importing food from more-productive systems. Increases in food provision in low-input systems are likely to come from land-clearing and expansion, however, which reduces the services provided by pre-existing forest or grassland systems. (See Box 26.4.) Intensification in such low-input systems sometimes has within-system sustainability trade-offs—reduced soil fertility due to nutrient depletion when fertilizer inputs are underutilized or not available.

26.4.2 Integrated Pest Management

The goal of integrated pest management is to achieve economical protection from pest damage while minimizing hazards to crops, human health, and the environment (Kogan 1998; Bajwa and Kogan 2002). IPM takes advantage of existing ecosystem dynamics or sometimes involves the introduction of new, competing organisms to control pests.

Successful IPM practices achieve multiple goals at once, but careful monitoring and high levels of technical expertise are necessary. IPM farmers must choose from a wide array of options: cultural, biological, chemical, physical, mechanical, and genetic techniques. They must also have detailed understanding of numerous key factors:

- cropping histories (variety, seeding date, fertilization, seed treatment, tillage system); the timing and date of any pest control methods; environmental conditions before, during, and after treatment; past, present, and future plans for cropping; pesticide use history; and yield results;
- pest information, such as pest identity, growth conditions, development, reproduction and spreading modes, damage symptoms, and natural enemies; and
- field scouting, which involves systematic sampling of pest populations.

Only by understanding the ecology and economics of their cultivated systems can farmers make informed choices about appropriate levels of pesticide use (Kenmore 1996).

Following the Green Revolution, IPM scored several striking successes, notably in Indonesia, where the introduction of simple methods allowed farmers to halve the money they spent on pesticides (Orr and Ritchie 2004). Attempts to generate such successes in Africa have been mixed. In the 1970s, mealybug infestations caused crop losses of up to 80% in African cassava plants; today, cassava mealybug damage is minimal thanks to the introduction of a parasitic wasp predator that maintains mealybug populations at a low level. This biological control method was free to farmers and environmentally benign (Herren and Neuenschwander 1991). Results were more limited elsewhere. In Malawi, for example, the major field pests of maize, beans, pigeon pea, and sweet potato were targeted using 18 different IPM strategies, but site variability, risk of reduced profitability, and overly complicated trials were all obstacles to adoption.

IPM has also had some success in industrial countries. In 1993, the U.S. government set a goal of having 75% of U.S. agriculture managed under IPM programs by 2000 (Fernandez-Cornejo and Jans 1999). While IPM has significant potential, however, that potential has yet to be fully realized. Despite extensive research into IPM programs, implementation is lagging (Sorensen 1993; Steffey 1995; Hutchins 1995). Many examples of cost-effective IPM trials exist, but in practice economic and institutional incentives are often not sufficient to encourage farmers to take on the risk of switching to integrated pest management (Sorby et al. 2003).

26.4.3 Integrated Agriculture-Aquaculture

Many freshwater species can adapt to an integrated farming system, where the wastes produced by one species are used by another species cultured in the system. IAA allows farmers to optimize resource flows and increase productivity by recycling nutrients between the various components of the system. In general, livestock manure is used as fertilizer for a crop species, the residues of which are fed to herbivorous fish. Fish excreta and other components of the pond humus are then recycled as manure for crop cultivation.

Such low-waste approaches reduce the discharge of nutrient-charged wastewaters into the environment, thus mitigating eutrophication and lowering net pollution compared with each cultivation component functioning independently. IAA systems also offer greater scope for more-efficient use of perhaps scarce water resources not only within the IAA system and but also by using IAA wastewater for irrigation. This both reuses water and delivers the residual levels of nutrients it contains directly to soil and crops. IAA systems have been developed for fish-duck farming, fish-chicken farming, fish-pig farming, rice-fish farming system in integrated areas, rice-shrimp farming, fish-vegetable farming, or fish-aquaponics farming (Lightfoot 1990).

Pig-grass-fish systems in China are used in both large-scale state-operated farms and in smaller-scale family-operated ones. Excreta from pig production is reused and treated as fertilizer for high-yielding fodder grasses, which serve as the main feed for herbivorous fish. Pig excreta are also applied directly to fish ponds, where it supports the growth of phytophankton—another source of fish feed. Wastes and residues that accumulate at the bottom of the fish ponds are harvested and recycled as manure for grass cultivation, completing the nutrient cycle. Pig-grass-fish systems are more labor-intensive than systems that use purchased feed inputs, and they also require substantial land area to grow the grass; however, their ability to simultaneously capitalize on in situ vitamins and proteins and to minimize waste makes them models of nutrient efficiency (Yang et al. 2001).

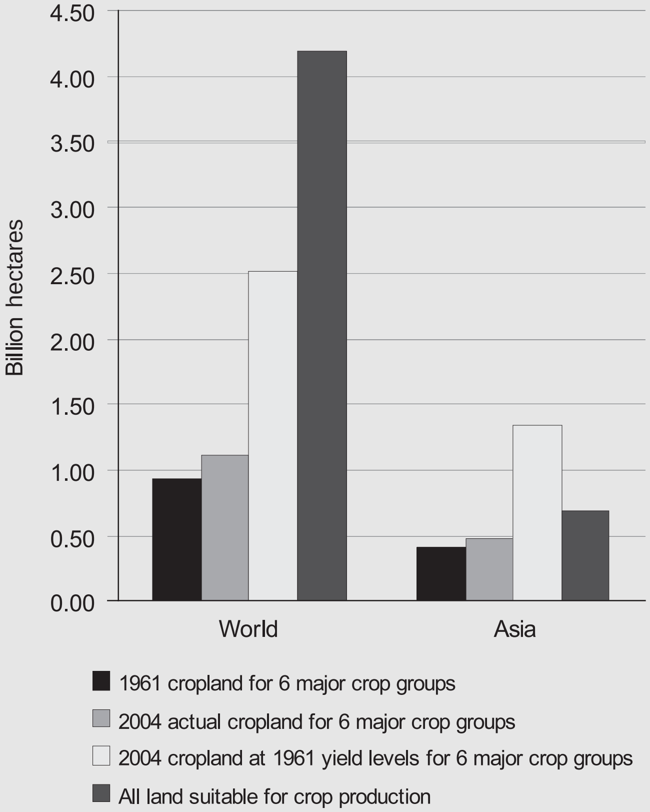
Another example of IAA systems is fish/fruit/vegetable cultivation in India, in which pond embankments are planted with fruit and vegetable crops. This provides several benefits: pond mud can be used as crop fertilizer, thus decreasing the cost of organic manures; pond water can be used to irrigate crops; fruit and vegetable residues can be used as low-cost fish feed; and plants

BOX 26.4

Aggregate Impacts of Trade-offs in Cultivated Systems: Land Use Perspective

At a regional or global scale, one measure of trade-off is the amount of land that needs to be brought into production according to different levels of food productivity. The "land-sparing" impact of modern farming practices has largely been achieved through yield increases brought about by the use of crop monocultures with improved crop varieties, fertilizer inputs, and irrigation where farmers have access to supplemental water. For example, if yields of the six major crop groups that are cultivated on 80% of the total cultivated land area had remained at yield levels farmers achieved in 1961, it would require an additional 1.4 billion hectares of land to meet global food demand in 2004. (See Figure.) This represents 34% of total land area suitable for crop cultivation and would have required conversion of large areas of uncultivated land that currently support rain forests, grassland savannas, and wetlands. In Asia alone, it would require an additional 600 million hectares, which represents 25% more land area than is suitable for cultivation on this continent. Asia would have had to be heavily dependent on food imports if crop yields had remained at 1961 yield levels.

The key ecological question is therefore whether environmental services other than food production at regional and global scales would be enhanced by focusing food production on less land under intensive management with high yields versus expanding cultivated area in lower-yielding systems that use farming practices that seek to preserve environmental services at the field and local levels. Few studies have addressed this issue using sound, ecological analytical methods. One recent study found that farming is already the greatest extinction threat to birds and evaluated the impact of land-sparing high-yield systems with "wildlife-friendly" farming practices on bird species persistence using ecological models (Green et al. 2005). The results suggest that high-yield farming may allow more bird species from a range of taxa to persist in developing countries. More such studies with other threatened fauna and flora species are needed to answer this critical question.



Land Used to Produce Major Crops in 1961 and 2004 and Land That Would be Needed to Produce Them in 2004 at 1961 Yield Levels. The six major crop groups included in this analysis are cereals, oil crops, pulses, root and tuber crops, sugar crops, and fiber crops. They accounted for 87% of all cropland in 1961 and 80% in 2004.

growing on the embankment strengthen the dikes (Tripathi and Sharma 2001).

26.4.4 Options for Mitigating Carbon Emissions and Increasing Carbon Sequestration

Several actions taken by farmers reduce overall greenhouse gas emissions. Those with the greatest potential for reducing emissions include increasing crop yields and return of crop residues; increasing the efficiency with which energy-requiring inputs (such as fertilizers and irrigation) are used; reducing or eliminating tillage operations; modifying crop rotations that include grass pastures and legumes; and increasing renewable energy production from biomass that either substitutes for consumption of fossil fuels (such as ethanol) or replaces the inefficient burning of fuelwood or crop residues and so avoids carbon emissions (Wassmann and Vlek 2004; Lal 2002; Antle et al. 2001). When considering biofuels as substitutes for fossil fuels, the greenhouse gas emissions associated with production and transport must also be taken into account to determine the net effect on greenhouse warming potential of the system.

It is notable that higher yields and input use efficiency result from farmer adoption of the best available crop and soil management technologies, and they contribute to increased profits. Reducing tillage improves yields and profits in rain-fed systems that are often limited by drought. The viability of modified rotations and bio-energy production systems depends on a number of economic factors that are often beyond the control of farmers and typically do not favor adoption.

In addition to the actions just described, there are a wide range of mechanisms and measures for increasing carbon sinks in agriculture. (See Box 26.5.) However, there is considerable scientific uncertainty over the magnitudes and permanence of carbon sinks and emissions in cultivated systems. In addition, the economic potential for sequestration is considerably less than the technical potential, since sequestration practices are often costly (Lewandrowski et al. 2004).

26.4.5 Strategies for Minimizing Soil Erosion

Accelerated erosion has numerous adverse ecological and economic impacts to both ecosystems that are sources of erosion and those that receive sediments and sediment-borne contaminant (Lowdermilk 1953; Olson 1981; Oldeman 1998; Scherr 1999; Lal 2001). The on-site ecological impacts lead to disruption in cycles of water, carbon, nitrogen, phosphorus, sulfur, and other elements; a reduction in effective rooting depth; and a decline in soil quality. The on-site economic impacts are associated with reduction in agronomic productivity, which may be caused by reversible productivity effects due to loss of soil fertility, and re-

BOX 26.5

Approaches to Increasing Carbon Storage and Reducing Greenhouse Gas Emissions (Pretty et al. 2002)

Increase carbon sinks in soil organic matter and aboveground biomass.

- Replace inversion ploughing with conservation- and zero-tillage systems.
- Adopt mixed rotations with cover crops and green manures to increase biomass additions to soil.
- Adopt agroforestry in cropping systems to increase aboveground standing biomass.
- Minimize summer fallows and periods with no ground cover to maintain soil organic matter stocks.
- Use soil conservation measures to avoid soil erosion and loss of soil organic matter.
- Apply composts and manures to increase soil organic matter stocks, including crop residue recycling.
- Improve pasture/rangelands through grazing, vegetation, and fire management both to reduce degradation and increase soil organic matter.
- Cultivate perennial grasses (60–80% of biomass belowground) rather than annuals (20% belowground).
- Restore and protect agricultural wetlands.
- Convert marginal agricultural land to woodlands to increase standing biomass of carbon.

Reduce direct and indirect energy use to avoid greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide).

- Conserve fuel and reduce machinery use to avoid fossil fuel consumption.
- Use conservation or zero-tillage to reduce carbon emissions from soils.
- Adopt grass-based grazing systems to reduce methane emissions from ruminant livestock.
- Use composting to reduce manure methane emissions.
- Substitute biofuels for fossil fuels.
- Increase N fertilizer use efficiency (as manufacture of N fertilizer is highly energy-intensive).
- Use integrated pest management to reduce pesticide use (avoid indirect energy consumption).

Increase biomass-based renewable energy production to avoid carbon emissions.

- Cultivate annual crops for biofuel production, such as ethanol from maize and sugarcane.
- Cultivate annual and perennial crops, such as grasses and coppiced trees, for combustion and electricity generation, with crops replanted each cycle for continued energy production.
- Use biogas digesters to produce methane, substituting for fossil fuel sources.
- Use improved cookstoves to increase efficiency of biomass fuels.

duction in soil organic matter and attendant water-holding capacity, versus more permanent, sometimes irreversible adverse impact on soil quality such as reduction in effective rooting depth with an accompanying decline in available water and nutrient retention capacities. While the reversible effects may be mitigated by use of additional inputs (such as fertilizers, organic amendments, and supplemental irrigation), the more permanent changes to soil quality that reduce productivity cannot be easily or economically alleviated.

Estimates of the global impact of erosion on agricultural productivity vary widely because of differences in methodology. Estimates of potential yield losses in the absence of farmers' decisions are greater than estimates that account for farmers' incentives to mitigate the impacts of erosion. In the absence of farmer interventions, erosion would cost the world $523 million per annum in lost agricultural productivity (Den Biggelaar et al. 2004), or 0.3% of agricultural production per year, averaged across crops, soils, and regions. Other estimates are larger: Crosson (1995) calculated the on-farm economic costs of soil erosion on a global level at about 5% of agricultural production. Oldeman (1998) calculated the global productivity loss during the post World War II period at about 13% for cropland and 4% for pastures. Off-site damages to navigation, reservoirs, fishing, and water treatment, industrial, and municipal water facilities was estimated at $2–8 billion per year in the United States (Ribaudo 1997).

Economic analysis by Hopkins et al. (2003) finds that actual losses (when farmers respond to land degradation to maximize net returns over the long term) average 0.1% per year in the north-central United States. Global impacts of erosion are expected to similarly be less as farmers anticipate and respond to land degradation.

A number of effective soil and crop/vegetation management systems have been developed to minimize soil erosion. They include conservation tillage along with use of crop residue mulch and incorporation of cover crops in the rotation cycle on cropland; controlled grazing with appropriate stocking rates and use of improved pasture species on grazing lands; and adoption of methods of timber harvesting and logging operations that cause the least amount of soil disturbance (shear blade, tree extractors) on forestland (Lal 1998, 2001).

Planting choices have a significant impact. Frequent use of cover crops in the rotation cycle, integrated nutrient management, reduced pesticide use (through use of IPM, for instance), and use of agroforestry are important to soil and water conservation. Cover crops can limit erosion and prevent the accumulation of hazardous biogeochemical compounds, such as phenolic acids, that inhibit plant growth (Ryszowski et al. 1998). These ecological measures of minimizing risks of soil erosion may be supplemented by the installation of physical conservation structures, such as terraces and grass waterways, that reduce and direct runoff along with slope stabilization structures (Lal 1991).

Erosion control is enhanced by the adoption of management regimes that reinforce natural ecological cycles and processes in crop and rangeland systems. Soil erosion can be greatly reduced if there are minimal disruptions to water and nutrient cycles and when soil fertility and physical properties are not degraded. In cultivated systems where soils are prone to erosion, development of soil-specific farming systems and use of appropriate management practices are essential components of erosion control, as is the improvement of soil structure and enhancing biotic activity of soil fauna and flora (earthworms, termites, and so on).

26.4.6 Agroforestry

Agroforestry involves the integration of trees into farming systems in ways that create an agroecosystem succession, akin to that in natural systems (Leakey 1996). Biodiversity increases with each stage in the development of this succession (Leakey 1999). Agroforestry systems take many forms—short-term improved fallows with leguminous shrubs, medicinal, or other products in low-input tropical systems of the Amazon basin; enriched forest fallows in Southeast Asia; intensive cash crop agroforestry systems with indigenous fruits and nuts in cocoa and coffee in West Africa; and contour strips in high-input maize/soybean systems in North America that mitigate erosion and runoff. The specific benefits of agroforestry vary by system but have included more profitable and nutritious food production, biodiversity conservation, improved soil resources, improved water quality, and carbon sequestration. Agroforestry systems have shown the ability to achieve multiple goals simultaneously, thus reducing the ecosystem service trade-offs inherent in crop production (Leakey 2001; Sanchez 1995, 2002).

Agroforestry systems have been shown to increase farmer incomes in sloped areas of Nepal (Neupane and Thapa 2001), in nutrient-poor farmlands of Africa (Sanchez 2002), and in Thailand (Wannawong et al. 1991), Cameroon (Palm et al. 2004), and Indonesia (Palm et al. 2004). Indigenous tree species are increasingly being domesticated to produce improved agroforestry tree products for local and regional food and medicinal markets. These improved species have been shown to generate household income, diversify production and the local economy, provide environmental services such as the mitigation of soil erosion, enhance carbon sequestration and biodiversity, and improve agroecosystem processes, like nutrient and water cycling. These multiple attributes of agroforestry are particularly valuable to subsistence-based livelihoods and simultaneously enhance the sustainability of crop production.

In the Philippines, the primary agroforestry practice is contour hedgerows, in which food crops are planted between hedges of woody perennials established along the contours of upland sloping farm plots. Prunings from the hedgerow trees or shrubs are placed at the up-slope base of the hedges to trap eroding soil so that, over time, natural terraces are formed (Pattanayak and Mercer 2002). Such hedgerows can improve soil conservation by 15–20% for a typical small farmer (Pattanayak and Mercer 2002). In addition to erosion control, biophysical effects of contour hedgerows on soil include maintenance or increase of organic matter and diversity, nitrogen fixation, enhancement of physical properties such as soil structure, porosity, and moisture retention, and enhanced efficiency of nutrient use (Nair 1993).

Besides agroforestry systems that combine trees with annual crops, there are those that combine trees with animals. Silvopastoral systems (defined as the integration of trees and pasture) are the most common form of agroforestry in the southern United States (Zinkhan and Mercer 1997). Silvopastoral systems are increasingly important in the developing world, especially in areas where perennial crops such as coconuts, oil palm, rubber, and fruit trees are found. In Southeast Asia, the integration of oil palm plantations with cattle and goats resulted in increased production of 3.52 tons of fresh fruit bunches per hectare, equivalent to 0.7 tons of palm oil per hectare. In Central America, most livestock farms include some silvopastoral systems that improve economic returns through diversification and the timing of cash flows (Henderson 1991).

Despite the potential benefits of agroforestry techniques, adoption has been relatively limited. Impediments fall into five categories: economic incentives, biophysical conditions, risk and uncertainty, household preferences, and resource endowments (Pattanayak et al. 2003). Additional research is required to domesticate novel tree species (and other crops) that can further enhance agroforestry systems. Identifying and domesticating such species could, for example, increase the availability and quality of traditional fruits and nuts rich in vitamins and minerals, which would improve the nutrition of smallholder farmers and their families (Leakey in press).

26.4.7 Constraints and Opportunities for Improved Interventions and Outcomes

The interventions just described span notions of high and low input or of tropical versus temperate agriculture. IPM, reduced tillage, agroforestry, and soil conservation, for example, have all been used in a range of agroecological and socioeconomic contexts globally. To these farm-scale interventions could be added the emergence of landscape-scale approaches that recognize and respond to the scale at which water and nutrient cycling and energy fluxes take place. Landscape approaches involve complementary and coordinated farm- and landscape-scale interventions as a means of improving long-term productivity and environmental sustainability (Baudry et al. 2000; Ryszkowski et al. 1999; Thenail 1996). Achieving the full potential of such approaches, however, requires continued development and integration of knowledge, strengthening of institutions, and improved feasibility and profitability for farmers. (See Box 26.6.)

Most approaches that seek to reduce food versus environment trade-offs require intensive use and integration of knowledge from the biological, agronomic, and ecological sciences together with farmer knowledge. Thus, the greater role and impact of such interventions is conditional on bridging perspectives of often productivity-focused scientific research with more ecosystem-focused perspectives—encompassing, for example the role of agroecological and eco-agriculture approaches (Conway 1999; Altieri 2002; McNeely and Scherr 2002). There is both much to learn and likely much to gain from, for example, improved understanding of the role of soil microbiology in improving water and nutrient efficiency in high-input systems (Matson et al. 1997; Woomer and Swift 1994), as well as rich possibilities of using biotechnology tools to enhance the productivity of low-input systems or orphan crops (Naylor et al. 2004).

Ultimately, decisions about the use of specific technologies and practices will depend on the opportunities and constraints of farmers, and there is evidence that here, too, more needs to be done to foster the adoption of practices that minimize trade-offs. Even where technologies have the potential to be profitable, many adoption decisions are affected by local institutions, particularly the effectiveness of local property rights systems and capacity for organizing and sustaining collective action.

Figure 26.9 plots increasingly secure property rights on the horizontal axis and increasing levels of collective action on the vertical axis. Some of the most successful agricultural technologies lie close to the origin in this figure. For example, the benefits of high yielding cereal varieties—the cornerstone of the Green Revolution—could be captured within a single agricultural season by individual farmers and hence did not require secure property rights or collective action. In tackling more complex objectives that include both yield and conservation goals, however, local institutional issues are more prominent.

Integrated pest management requires that farmers in an area work together to control pesticide use and to synchronize planting dates. The returns are relatively quick, however, so secure property rights are still not a major issue, and IPM appears in the upper left corner of the Figure. In contrast, planting of trees on farms (agroforestry) is a long-term investment that requires secure property rights. But since trees can be planted by individual farmers, agroforestry appears in the lower right-hand corner. Still other approaches, however, such as watershed conservation, require both secure property rights and effective collective action, and therefore appear in the upper right-hand quadrant. If these institutional conditions are not met, then the technology is not likely

BOX 26.6

Service Trade-offs in Cultivated Systems: A Case Study from the Argentine Pampas

The pampas agroecological zone is a vast, flat region of Argentina extending more than 50 million hectares and used predominantly for crop and cattle production (Satorre 2001). Agriculture in the pampas has a relatively short history (a little more than 100 years) comparable with that of the American Great Plains (Hall et al. 1992). Both agroecological zones were mostly native rangelands until the end of the nineteenth and the beginning of the century centuries, when lands were initially transformed for crop (cereals and oil seeds) and cattle production under rain-fed conditions. Where European tillage methods with a conventional plow were used, heavy erosion (dust bowls) occurred the first half of the last century, especially on the more fragile lands (Covas 1989).

Mixed-grain, crop-cattle production systems have now expanded to occupy most of the pampas and involve rotations of maize, wheat, and soybeans, with cattle pastures being integrated in various ways depending on local soil and climate conditions. Cattle operations vary from cow-calf to cattle finishing. The pampas suffers occasional droughts and floods that temporarily affect both crop and cattle production (Viglizzo et al. 1997).

A major challenge in sustaining the economic viability of the pampas low-input agroecosystems is to maintain soil quality that supports crop production and environmental services. Soil organic matter content is a key component of soil quality since it serves as a reservoir of nitrogen, phosphorus, and sulfur and has a large impact on soil physical properties that promote water infiltration, storage, and root function, all essential to support crop growth (Viglizzo and Roberto 1998).

Intensification of agricultural systems in the pampas during the past 50 years has involved a steady increase in farm area devoted to annual crop production and a consequent reduction in area allocated to perennial and annual pastures. Similar trends have occurred in the U.S. Corn Belt. From 1960 to 2001, grain production in the pampean provinces increased from 11.1 million to 43.5 million tons. Changes in soil organic matter and nitrogen dynamics associated with intensification provide an illustration of environmental service trade-offs. For example, leguminous pastures in a pasture-crop rotation can promote biological nitrogen fixation such that the soil nitrogen supply fluctuates around a value determined by the length of the leguminous pasture phase. Changes in land use that reduce or eliminate leguminous pasture decrease soil organic matter and nitrogen and phosphorus supply unless there are compensating applications of fertilizer or livestock manure (Viglizzo et al. 2001). Because current levels of N fertilizer use efficiency achieved by farmers are relatively low, there is substantial risk that nitrogen losses can damage environmental services in off-farm ecosystems.

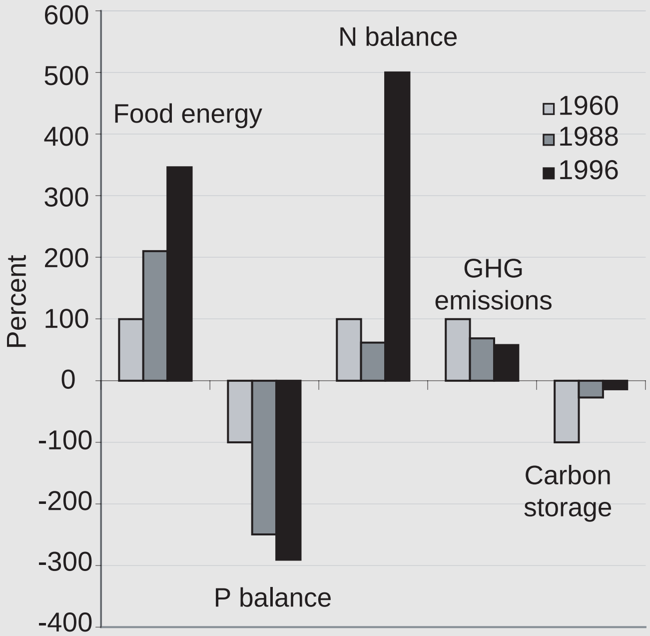


Figure A

to be adopted and maintained, regardless of its profitability and scientific soundness.

26.5 Cultivated Systems and Human Well-being

The ability of humans to convert natural systems to cultivated systems and to derive more food from each hectare of land has, for millennia, supported the growth of civilizations. Indeed, the first civilizations developed in the Fertile Crescent of the Middle East because local conditions were well suited to cultivation and the domestication of animals for livestock (Smith 1998; Diamond 1999). Similarly, in many parts of Asia, efficient and sustainable irrigated paddy fields have supported a number of prosperous cultures with high population densities over thousands of years. A stable food supply has always been the foundation on which human civilizations are built. Moreover, adequate nutrition is fundamental for human development and health.

For all the benefits they provide, cultivated systems can also pose risks to human well-being, most notably via direct health effects from, for example, the handling and use of pesticides and zoonotic diseases associated with certain cultivation practices, as well as through pollution of air and water. Cultural and amenity services of natural ecosystems are diminished when they are converted for cultivation, and that loss may or may not be compensated for by cultural and amenity services associated with cultivated systems.

This section deals with the linkages between human well-being and cultivated systems, noting that the largest single source of human well-being derived from cultivation is through the production and consumption of affordable food, fiber, and other products. The human well-being impacts mediated through food consumption are dealt with separately and in detail in Chapter 8.

26.5.1 Economic Component of Human Well-being

Cultivated systems play a vital role in global economic well-being, especially in poorer countries. In 2000, agriculture (including forestry and fishing) represented 24% of total GDP in countries with per capita incomes less the $765 (the low-income developing countries, as defined by the World Bank) (World Bank 2003). About 2.6 billion people depend on agriculture for their livelihoods, either as actively engaged workers or as dependants (FAOSTAT 2004). In 2000, just over half (52%) of the world's population were living in rural areas and, of these, about 2.5 billion people were estimated to be living in agriculturally based households (World Bank 2003). The global agricultural labor force includes approximately 1.3 billion people, about a fourth (22%) of the world's population and half (46%) of the total labor force (Deen 2000).

BOX 26.6

continued

Analysis of 85 pampas farm systems differing in their land use patterns and level of intensification (measured in terms of energy use) reveals trade-offs between the share of land used for crop production and the provision of ecosystem services. Results show that carbon storage, greenhouse gases emissions, and annual nitrogen and phosphorus balances decrease as the cropping area, use of energy derived from fossil fuels, and the net primary productivity of systems increase. Risk of pesticide contamination and soil erosion and the human disturbance of the habitat also increase, although both risk of erosion and disturbance stabilized or decreased somewhat at the highest levels of cropping intensity.

In contrast, GHG forcing potential decreases because removal of pastures and livestock grazing is associated with a reduction in methane emissions and fire used to improve vegetation quality in pastures and grazing land. The nature of trade-offs observed in the pampas varies not only by local agroecological conditions and production systems but also over time. Figure A shows how the average level and mix of ecosystem services have changed across the pampas over time. Compared with 1960, food output has increased significantly, while phosphorus balances have worsened. Nitrogen balances were positive but declining as pasture was converted to low-input cropland, but they have surged as urea application to cropland has become increasingly necessary. GHG emissions have fallen in line with pasture and livestock decreases, while carbon stocks continue to be depleted, but at a declining rate. Given the broad adoption of no-tillage cultivation practices in recent times, carbon stocks might now be increasing (Viglizzo 2002a, 2002b).

Both agricultural production and ecosystem services have economic value that can contribute to human welfare. Hence, the costs associated with the loss of ecosystem services caused by crop intensification should be weighed against the benefits obtained from farming. The ecosystem service valuation techniques developed by Costanza et al. (1997) were used to estimate both the market and nonmarket components of ecosystem services in pampas agricultural systems. The gross margins of crop and livestock production operations during the 1990s were assessed using standard economic valuation approaches. A comparison of the dynamics of crop and livestock gross margins and ecosystem service values related to the intensity of cropping is shown in Figure B. While the gross margin of farming production increases proportionately to the intensification of cropland, there is a relatively sharp decline in the value of ecosystem services at the earlier stages of intensification, such that about half the value of ecosystem services is lost when around 40% of the area is used for crop cultivation.

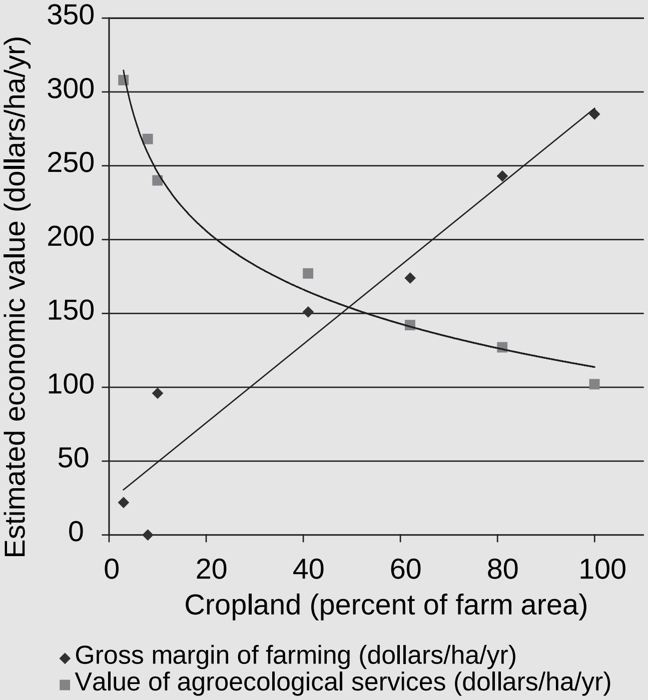


Figure B

This analysis considers only the implications of intensification within the pampas and does not examine broader geographic effects. Globally, the pampas has become a major source of grain for countries and regions where local food supply is insufficient to meet demand. Thus while reducing cropping intensity and increasing the percentage of land devoted to pastures in the pampas might improve ecosystem services locally, the loss of grain output would need to be offset by yield increases elsewhere in the pampas or by expansion of cultivated area and yields elsewhere in the world. In both cases, there would likely be negative effects on environmental services in these other locations that any comprehensive assessment of ecosystem service trade-offs would need to take into account.

In Africa, agriculture provides two thirds of all employment and half of all exports and accounts for 37% of GNP. Despite rapid urbanization and economic diversification in South Asia, agriculture continues to provide employment for over 60% of the population and generates 27% of GNP (DFID 2002). In 2000, globally, cultivated systems produced approximately $815 billion worth of food crops and $50 billion worth of non-food crops. In the same year, fisheries output was valued at $156 billion and livestock products at $576 billion. (See Chapter 8.)

Measuring the economic benefits of employment is difficult because globally comparable agricultural wage rates do not exist. One very rough proxy of gross agricultural income is the total value of agricultural production divided by the number of agricultural workers. This provides a rough estimate of the gross economic returns to labor. Globally, the average annual value of agricultural production per agricultural laborer for 1995–97 was approximately $1,027 per person (using 1989–91 average international prices). The range of estimates is quite broad—from about $50,500 per person per year for the United States down to $411 for sub-Saharan Africa (Wood et al. 2000).

Livestock provides the main source of livelihood for 650 million farmers worldwide. Despite low productivity, livestock husbandry is one of the few means for the poor to generate income, acquire assets, and escape from poverty. Sales of livestock, animal-source food, hides, and fibers through both formal and informal markets make major contributions to household income. Evidence from in-depth field studies in Asia and Africa indicates that livestock contribute as much as 76% of household incomes in some regions, and generally a higher percentage to the incomes of poorer households (Delgado et al. 1999; Kaufmann and Fitzhugh 2004).

There is a growing consensus that poverty, hunger reduction, and increased economic growth cannot be achieved in most poor countries without more fully exploiting the productive capacity of the agricultural sector (Timmer 1989; Sarris 2001; Hazell and Haddad 2001). Agricultural growth can reduce poverty through

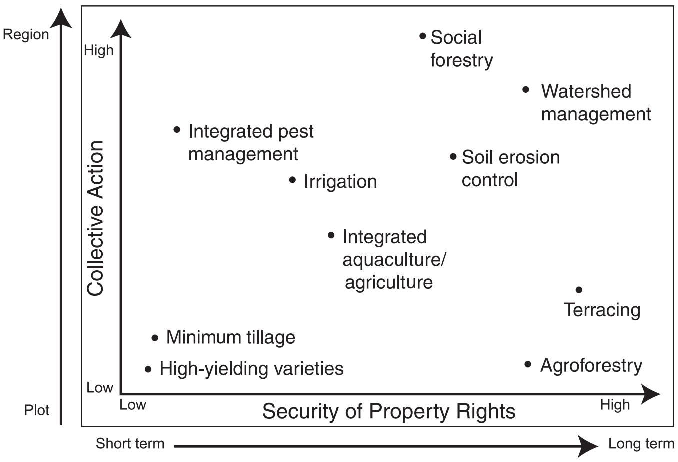


Figure 26.9. Links between Property Rights, Collective Action, and Technology Adoption in Cultivated Systems (adapted from Knox et al. 2002)

increased employment and wages and through income generated by the sale of goods produced by the poor (Datt and Ravaillon 1998). It also results in increased demand for food, services, and unskilled labor (Mellor 2000). The relationship between agricultural wages, higher yields, and poverty in the case of India is shown in Figure 26.10. Timmer (1997) has shown for 27 countries from the period 1960 to 1992 that agricultural growth reduced poverty more than growth in manufacturing did, while López and Valdéz (2000) have shown that rural growth is more effective than urban growth in reducing poverty in Peru. Growth in Peruvian agriculture was also shown to have reduced urban poverty through slower rural-to-urban migration and more affordable food prices.

Beyond the direct economic impact on employment and incomes, there are several indirect economic benefits of cultivated systems that can be even greater. These are mediated through rural growth linkages, inter-sectoral linkages including the post-harvest agribusiness sector, consumer income effects, and trade. Rural growth linkages are an important mechanism by which agricultural growth spurs growth in non-farm incomes and employment (Hazell and Roell 1983; Mellor 1966). Growth in the use of farm inputs, processing, marketing, and transport services serve to increase rural non-farm incomes. The increasing household expenditure that results enhances consumer spending and triggers a further rise in non-farm incomes and employment. For example, a $1 increase in agricultural income resulted in increases in rural income of an additional $1.88 in Burkina Faso, $1.48 in Zambia, $0.96 in Niger, and $1.24–$1.48 in two locations in Senegal (Delgado et al. 1998).

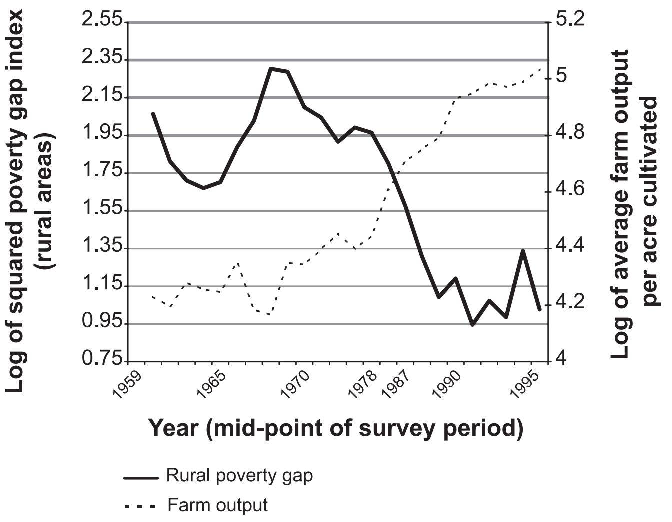


Figure 26.10. Yield Growth and Poverty Reduction in India, 1959–94 (Datt and Ravaillon 1998)

In an analysis of Asia and the Near East, Timmer (1989) concluded that linked growth between industrial and service sectors and the rural economy could lead to increases in rural wages and more equitable income distribution. Mellor (2000) contends that the substantial lags between accelerated agricultural growth and reduction in poverty are strong evidence that agricultural growth reduces poverty more through indirect processes than direct ones. Furthermore, these linkages enhance overall economic growth. Rural growth linkages are particularly important because they benefit small labor-intensive enterprises and thus contribute to the alleviation of rural poverty.

It is increasingly recognized that estimates of agriculture's contribution to economic growth and human well-being at national levels are underestimated by economic indexes that focus only on farm-level added value. Upstream and downstream linkages with agro-industries, services, and trade are not properly accounted for. In Argentina, for example, primary agriculture is estimated to represent about 5% of total GDP, but this increases to 32% when the linkages with the food and agro-industry sectors are considered (IDB 2004). Similarly, agriculture in Brazil and the United States is estimated to contribute about 4% and 1%, respectively, to national GDP, while full accounting of food chain linkages gives estimates of 26% and 8% (IICA 2004).

The economic well-being generated from cultivated systems is not limited to those employed in the food supply sector. Food consumers have benefited enormously from the long-term decline in food prices. Cereal prices have fallen by about 40% in real terms during the past 40 years, resulting in increased disposable incomes for consumers. (See Chapter 8.) This allows increased expenditures on education, health, and better nutrition (Hazell and Roell 1983).

Economic well-being can be further improved through international agricultural and food markets. Trade in food not only broadens choices but also provides access to foods year-round that often can be grown locally only on a seasonal basis. It provides local farmers with new market opportunities, resulting in higher living standards for those able to participate. Food trade also helps provide more stable and secure access to food at competitive prices, but it cannot play such an effective role where prices are distorted or significant market barriers exist. A major limit to agriculture's role in the global economy is that agricultural trade barriers are on average 10 times higher than industrial trade barriers (Abbott 2005; Charlton and Stiglitz 2005).

Agriculture's effects on economic well-being are not all positive, and other sections of this chapter have described the negative impacts, including loss of biodiversity; soil, water, and airborne pollution; and health risks. Although it is difficult to quantify the costs of these externalities from agriculture, there can be significant financial and economic consequences that are explicitly and implicitly borne by society. Pretty et al. (2000) have estimated the external environmental and health costs of agriculture in the United Kingdom at £2.3 billion in 1996 using ecosystem service values derived from Costanza et al. (1997). These costs represent 13% of average gross farm returns and 89% of average net farm income in the country.

Improving formal measures of productivity by accounting properly for the full social costs and benefits of all inputs and outputs from cultivated systems, including environmental services and health as well as the economic multipliers from agricultural productivity, is critical for making more informed decisions about policies and investment in the agricultural sector, especially in developing countries, where sustainable agricultural development is the foundation for broader economic development.

26.5.2 Linkages between Cultivated Systems and Nutrition and Health

Cultivated systems contribute to human health and nutrition primarily by providing food either through subsistence agriculture or through commercial agriculture and food markets. The magnitude of the human well-being benefits derived from an adequate and nutritious food supply are so large that they are often taken for granted, especially in wealthy countries in which food costs represent a small proportion of disposable income. Likewise, it is very difficult to protect against environmental degradation and loss of ecological services in regions where people experience chronic food shortages. Unless chronic hunger and food insecurity are reduced, the poor will continue to exploit natural resources in the short run, thereby undermining the sustainability of natural ecosystems and consequent food security in the long run (Webb 2002).

The important linkages between food consumption, health, and nutrition are assessed in detail in Chapter 8. This section focuses on linkages between human health and factors other than food supply per se, such as the impact of production systems, production practices, and associated environmental externalities. The linkages are grouped into the health of farm workers and farm families and that of the broader population potentially affected by cultivation practices.

Agriculture is a hazardous occupation. Globally it is estimated that farm workers run at least twice the risk of dying on the job than workers in other sectors and that around 170,000 people die per year because of these work hazards (Forastieri 1999). In the United States, for example, the death rate among agricultural workers was an estimated 20.9 per 100,000 workers in 1996—more than five times the average for all industries (Reeves and Schafer 2003). Not only are mortality rates higher, but so are rates of accident and illness. In the United States, farmers and farm workers account for only 3% of the workforce but for nearly 8% of all work-related accidents; in Italy, some 10% of workers in agricultural production account for some 29% of workplace accidents, often related to the use of tractors, harvesting machinery, and power tools (Forastieri 1999). In developing countries, where farmers use smaller and less powerful equipment, there are likely to be fewer serious work-related accidents, although few data on these are available.

Apart from accidents, two other linkages between production and health are respiratory problems caused by working in barns and confined livestock systems and a variety of health problems linked to pesticide handling and use. A compilation of studies from Australia, Finland, Denmark, Sweden, Scotland, the United States, and Canada indicated very high levels of occupational respiratory problems in farm workers. In intensive dairy systems, about 20% of farm workers were reported to suffer bronchitis problems directly related to in-barn air quality, 5% from asthma problems, and just under 5% each with symptoms of organic dust toxic syndrome and "farmer's lung" disease. Health effects are comparable or larger for pig and poultry operations and arise largely through the presence of dust from the use and handling of hay, straw, and dry animal feeds (Omland 2002). Kansas farmers were found to be at an increased risk of death from prostate cancer, brain cancer, non-Hodgkin's lymphoma, and leukemia in a 1983–89 study; they were also at elevated risk of death from motor vehicle accidents, accidents resulting from falling objects, and machinery accidents (Frey 1991).

In addition to high risk of physical injury, the estimated 2 million farm workers in the United States face a greater risk of pesticide exposure than any other segment of the population (Reeves and Schafer 2003). On a global scale, it is estimated that 20,000 people die of adverse effects of pesticide exposure each year, 3 million are poisoned, and there are nearly 750,000 new cases of chronic pesticide exposure, such as cancer, each year (WHO and UNEP 1990). There are limited reliable data on the extent of pesticide-related illness anywhere due to poor identification of such illnesses, which leads to underestimations. The magnitude of health damage caused by agrochemical exposure will vary according to the type of agrochemical used, the mode of application/exposure, the individual susceptibility, and the climatic conditions—and each of these factors is related to the type of crop grown and specific pesticide use practices.

Pingali and Roger (1995) documented that pesticide use had an adverse impact on human health and subsequently on farmer productivity for rice farmers in the Philippines in 1991. Eye, pulmonary, and neurological problems are significantly associated with long-term pesticide exposure. In Northern Ecuador, heavy use of pesticides by potato farmers was the principal cause of death after traffic accidents for both men and women (Yanggen et al. 2004). In China, in 2001, decreased use of pesticide as a result of growing *Bacillus thuringiensis* cotton resulted in a lower incidence of poisonings (Hossain et al. 2004).

Farm workers and farm families are particularly susceptible to zoonoses—animal diseases that can be transmitted to humans through contact with infected animals. There are approximately 150 kinds of zoonoses, and many are transmitted by livestock. For example, avian influenza, or "bird flu," is a disease that humans may contract through direct contact with live poultry infected with the flu virus or direct contact with the feces, nasal, or eye discharges from infected birds (WHO 2004). In contrast, the risk of infection from consumption of poultry product is extremely low. Because there is no viable treatment, recent outbreaks caused by the H5N1 strain are considered to be one of the greatest potential threats to human health if human-to-human transmission of the disease becomes widespread (WHO 2004). The first documented infection of humans with an avian influenza virus occurred in Hong Kong in 1997, when the H5N1 strain caused severe respiratory disease in 18 humans, 6 of whom died. Cases have also recently been reported in Viet Nam, Thailand, and Cambodia (WHO 2004).

The incidence of zoonoses is high in developing countries because social and economic factors contribute to their spread (Langoni 2004). Poor sanitation can exacerbate these diseases in children by allowing the zoonotic agent to be disseminated through rainwater, streams, and brooks where children often play. Bovine brucellosis can be transmitted to humans and is a major zoonosis associated with livestock. Human brucellosis is characterized by fever and back/joint pain (Unger 2003). Further complications due to human brucellosis may include hepatitis (Masouridou et al. 2003). According to WHO data, the number of cases of human brucellosis worldwide was estimated to be about 500,000 (WHO 2005). The advent of HIV/AIDS has increased the prevalence of many zoonoses in humans because HIV can increase susceptibility to zoonotic agents by depressing the human immune system (Langoni 2004).

Contamination of surface and groundwater by pesticides and fertilizers is also reported to affect public health (Ongley 1996). Excessive waterborne nitrogen has been linked to respiratory ailments, cardiac disease, and several cancers (Townsend et al. 2003). Nitrate levels have grown in some countries to the point where more than 10% of the population is exposed to nitrate levels in drinking water that are above the 10 milligrams per liter guideline (WHO 1993). Although WHO finds no significant links between nitrates and nitrites and human cancers, the drinking water guideline is established to prevent methemoglobinemia in infants (blue baby syndrome) (WHO 1993). Water polluted by waste and runoff from grazing areas and stockyards can also cause disease. The most common diseases associated with contaminated waters are cholera, typhoid, ascariasis, amebiasis, giardiasis, and enteroinvasive *Escherichia coli*. Four million children die every year as a result of diarrhea caused by waterborne infection, although the share attributable to agriculture is unknown (Ongley 1996).

Irrigation systems provide sources of water that can improve sanitation, and thus human health, but they can also serve as a breeding ground for disease vectors. Increases in malaria have been linked to reservoir construction (De Plaen 1997; Reiff 1987). Schistosomiasis (bilharziasis), a parasitic disease that spends part of its lifecycle in a snail species and that affects more than 200 million people in 70 tropical and sub-tropical countries, has also been demonstrated to increase significantly following reservoir construction for irrigation and hydroelectric power production (DFID 1997). The two groups at greatest risk of schistosomiasis infection are farm workers involved in the production of rice, sugarcane, and vegetables and children who bathe in infested water.

Water contamination is not restricted to the developing world. The total cost of drinking water contamination from agriculture has been estimated at £120 million in the United Kingdom due to pesticides and £16 million due to nitrate from fertilizers (Pretty et al. 2000).

Recently, HIV/AIDS has added another dimension to the relationship between agriculture and human health. Gillespie and Haddad (2002) suggest that improved nutrition for agricultural workers with HIV/AIDS is important for improving their quality of life. However, ill health as a result of HIV/AIDS also affects agricultural production through reduced stamina and strength of sick farm workers and the diversion of household resources and time to care for the sick and for funerals. Subsequent decreased labor productivity can in turn affect human well-being since households may resort to growing less nutritious or less lucrative crops because they are less labor-intensive.

26.5.3 Equity and Distributional Aspects of Cultivation

At the scale of the farm and community, linkages with equity and distribution are conditioned by the existing distribution of assets and the limited access of poor people and vulnerable groups to cultivation-related resources and opportunities such as land, credit, extension, and markets. At the scale of the country and region, there are often biases in political and economic power against rural areas and against specific marginalized groups. At the international scale, there are imbalances among richer and poorer countries with regard to their ability to promote competitive agriculture through publicly-funded domestic farm support, influence on trading patterns, and the strength of public and private systems delivering improved production technologies and practices.

In theory, agricultural growth should eventually lead to more equitable distribution of both income and resources (Kuznets 1955). However, empirical evidence of agriculture's effects on promoting equity is ambiguous (von Braun 2003) or marginal at best (Deininger et al. 2004; Tsur and Dinar 1995; Bautista et al. 1998). For example, a number of studies have shown that administrative land reform was not effective in transferring land to the poor in Colombia and Ethiopia (Castagnini et al. 2004; Adenew et al. 2003). In Viet Nam, despite the rapid growth of agricultural wages in the 1990s, wage inequality fell modestly (Gallup 2002). In China, however, long-term government investments across multiple sectors, including agricultural research and development, irrigation, rural education, and infrastructure (including roads, electricity, and telecommunications) contributed not only to agricultural growth but also to the reduction of rural poverty and regional inequality (Fan et al. 2002).

The marginalization of vulnerable groups such as women and children is also a constraint to more equitable sharing of benefits from farming. Women are especially vulnerable to existing inequities in terms of wages, access to and control of production technologies, gender segregation in labor markets, and access to property and entitlement in their own right (Quisumbing and Meinzen-Dick 2001).The central role of improving gender equity in African agriculture, where women are productive farmers and key food producers, is now widely recognized (Kabutha 1999). And in Cambodia, 90% of children worked in agriculture or agriculturally related activities during 1996 (ILO 1997). Lack of education propagates vulnerability and promotes widening inequality. While widespread use of child labor in agriculture is an economic necessity in many countries as families are too poor to pay for schooling, adult males often migrate to urban areas seeking employment. In addition, sickness and care-giving—especially related to HIV/AIDS—reduces the pool of family labor in sub-Saharan Africa.

Persistent barriers to agricultural trade across international boundaries, such as export subsidies and import restrictions, limit more equitable agricultural income distribution among countries by, for instance, limiting developing-country access to EU and U.S. markets, as described earlier. But the impact of trade liberalization on the distribution of income within developing countries varies according to country-specific policy conditions and socioeconomic structure. In Latin America, for example, analysis suggests that trade liberalization has had positive effects on income equality in nine countries and negative effects in five countries (von Braun 2003).

There are growing concerns about inequalities with regard to the capacity to generate and gain access to new scientific information and technology (von Braun 2003). An increasing share of agricultural R&D globally is being funded by the private sector at the same time that the science needed to make key advances becomes more complex, costly, and, particularly for biotechnology, increasingly proprietary in nature. The fear is that large bioscience companies have few incentives to focus on the crops, constraints, and technologies most appropriate for poor farmers in tropical areas but have proprietary rights over processes and components of technologies that need to be used (Pardey and Beintema 2001).

These trends, compounded by the long-term underinvestment in agricultural R&D by most developing countries despite the economic importance of agriculture, are widening already significant gaps in scientific capacity compared with industrial countries. Increasingly it is only the larger developing countries, such as Brazil, China, India and South Africa, who can muster the investments in R&D and human capacity needed to keep their farmers competitive.

As trade liberalization proceeds, increased reliance is placed on knowledge, science and technology, and technology transfer to keep farmers in business. In addition, emerging trends in global food retail and agro-processing markets, increasing demand for food safety, and shifts in diets and preferences toward processed foods are raising concerns about the long-term future of smallholder farmers in developing countries (Lipton 2005). In part, these concerns arise from the disproportionately negative impact of structural adjustment programs on smallholders during the 1980s and 1990s brought about by the wholesale withdrawal of public-sector services (disappearing market, input services, and credit).

With regard to the specific case of genetically modified crops, recent studies have documented substantial economic benefits from the most widely adopted transgenic crops—*Bt* cotton and herbicide-resistant soybean. Non-GMO cotton varieties are highly susceptible to yield loss from bollworm and boll weevil insect pests that require as many as five or six applications of highly toxic pesticides to avoid severe yield loss. In contrast, the *Bt* cotton varieties have been transformed to contain a bacterial gene that produces a protein that is toxic to these insect pests when they feed on the plant's tissues.

Reduced cost of insecticide applications and higher yields contribute to substantial increases in profit for the farmer and lower prices for cotton, which benefit the consumer. As a result, the economic benefits from use of insect-resistant *Bt* cotton varieties were found to be evenly distributed among farmers, private-sector seed companies, and consumers in both industrial and developing countries (Huang et al. 2002; Falck-Zepeda et al. 2000). Similar studies of the distribution of economic benefits from herbicide-resistant GMO soybean have also documented balanced distribution among farmers, seed companies, and consumers (Qaim and Traxler 2005).

There are also linkages between the impact of cultivation on ecosystems services and equity. The poor and the vulnerable are likely to suffer most from environmental externalities of production, such as downstream water depletion and pollution and loss of habitat and biodiversity—particularly since the landless rely more on wild sources of food (Grimble et al. 2002).

26.5.4 Cultural Aspects of Cultivation

Cultivated systems and human culture are inextricably linked. Religious and ethical values, cultural backgrounds, and philosophical convictions are important factors linked to the sustainability of cultivated systems, rural development, and food security. Cultural practices and traditions are often integrated into cultivation norms and practices, into land inheritance, ownership, and access, and into access to other productive resources. Cultural factors and preferences can have a large influence on the demand and value of various food products in the marketplace. Likewise, traditional food taboos and food distribution along age and gender lines can have a substantial impact on nutrition by affecting the types of food that are available or culturally acceptable. (Chapter 8 contains more discussion on food and culture.)

Farmers' close ties to the land and their intimate relationship with it is an intangible aspect of farming that can outweigh maximizing short-term economic gain. In northern New Mexico, for example, small livestock operations are a critical aspect of families' and communities' way of life, maintaining cultural heritage and traditional values as well as passing those values on to future generations. Keeping land in the family and upholding traditional values are regarded more highly than material possessions or monetary gain (Raish and McSweeny 2003). Despite the commercialization of agriculture, agricultural societies still exist that value the cultural aspects of farming and, as a result, have created homesteads, communities, collective action mechanisms, and alternative technologies that allow continuation of traditional peasant agriculture (Schwarz and Schwarz 1999). It is not just farm households who value the existence of agriculture—in richer countries, the policy of publicly funded payments to farmers for "environmental stewardship" is broadly supported, reflecting findings of formal studies of the public's willingness to pay for maintained agricultural landscapes (Drake 1992; Olsson and Ronningen 1999).

Changing cultural attitudes toward agriculture can be traced back to the Industrial Revolution, when technological innovations that control the environment began replacing the spiritual relationship of farmers to the land. Ultimately, the evolution of agriculture in industrial countries has profoundly changed culture, eliminating the need for millions of farmers and farm workers and displacing entire communities (Bailey 1999).

The farming of animals involves a culture of its own, and ancient myths surrounding animals have deeply influenced animal production (Fraser 2001). Nurturing animals is an integral part of the ecology and economy of many farming systems; it was and is regarded as a moral responsibility in many religious and cultural traditions, with different species serving important and complementary functions. Animals are also important for moral education, because children often learn responsibility by caring for animals. These values are now embodied in broader social concerns for animal welfare, particularly with regard to industrial livestock systems.

Just one example of the strong sense of rural community spirit can be seen in *gotong royong,* Indonesia's traditional spirit of mutual help. The underlying philosophy is that people cannot live a solitary existence; they need each other, particularly family members and relatives. The practice of *gotong royong* originates from the traditional peasant subculture, which is characterized by subsistence farming, family-oriented grouping, and strong social interdependence. Even in commercial smallholder areas of Indonesia, *gotong royong* is still practiced widely in farming operations—including during land preparation, pest management, water management, weeding, and harvesting.

An example of the strong spiritual connection to cultivation is the growing of rice in Asia. For the Balinese, rice is much more than just a staple food; it is an integral part of the Balinese culture. The rituals associated with the cycle of planting, maintaining, irrigating, and harvesting continue to enrich the cultural life of Bali after thousands of years and despite the strong external cultural influences associated with tourism. Before planting, throughout the growing season, and at harvest, ceremonies are held and offerings are presented to Dewi Sri, the goddess of rice. In the middle of most rice fields, even far from villages, shrines are well maintained with flowers, fruit, and other offerings for Dewi Sri.

Gender-related cultural norms and practices also play an important role in the functioning of cultivated systems. For example, in the rural Philippines land is preferentially given to sons because rice farming requires intensive male labor (Estudillo et al. 2001). In many patrilineal African communities, the cultural custom of *lévirat* dictates that if a woman becomes a widow, she has to remarry one of her husband's brothers, which allows the woman continued access to land and food security; otherwise she would have to leave the family on the death of her husband (Estudillo et al. 2001).

Cultivated systems have a long history. Since as early as 10,000 years ago, crops have been carefully and deliberately managed by people, who in turn have reaped the benefits of increased food production. It has been argued that domesticated seed varieties and agricultural technologies were some of the most important factors in shaping the evolutionary course of civilizations (Diamond 1999). Domesticated, nutritious crops are capable of supporting larger populations, which in turn promotes innovation and technological advances. The social, cultural, economic, and political patterns and institutions that underlie both traditional rural societies and modern nation-states are in many ways products of humans' evolving ability to manage plants and animals for the production of food and other services (Diamond 1999).

Notes

1. If inland waters, Greenland, and Antarctica are excluded from this analysis, the coverage rises to approximately 27%. According to the MA definition, an area is considered cultivated if at least 30% of the underlying 1x1-kilometer land cover grid cell has been classified as cropland. This definition seeks to identify landscapes where a significant degree of ecosystem transformation has already taken place. The MA definitions of ecosystems allow for overlapping geographical extents of terrestrial systems.

2. The AVHRR-derived Global Land Cover Characterization Database V1.2 was produced by the EROS Data Center of the U.S. Geological Survey (Loveland et al. 2000) with revisions for Latin America (USGS EDC 1999). This dataset identifies approximately 200 seasonal land cover regions per continent (for example, 167 for South America and 205 for North America) based on the interpretation of a series of satellite images captured every 10 days from April 1992 to March 1993.

3. This conversion efficiency is embedded in the IFPRI IMPACT model, which was used to provide the food supply projections for the MA scenarios. (See MA *Scenarios,* Chapter 6). The conversion efficiency used in the IMPACT model was estimated by evaluating the impact of research investment on genetic improvement of major crops over the past 30 years. The recent evidence cited, however, suggests that conversion efficiencies have decreased markedly as average crop yields have increased.

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