2. Trends in Food and Resources

World food demand

Global demand for agricultural commodities has grown rapidly since the mid-20th century as a result of growth in population, income, and other factors. The world's population nearly doubled over the past four decades, from 3.1 billion people in 1961 to 6.0 billion in 1999 (fig. 1.1; FAO, 2000). Most of this growth occurred in developing countries. Growth was particularly rapid in relative terms (2.6-2.7 percent per year) in Africa and Latin America, and in absolute terms (about 50 million people per year) in Asia.

Global population growth has slowed in recent years, from its peak of 2.1 percent per year in the late 1960s to 1.4 percent per year in 1998. (Growth is also slowing in absolute terms, from its peak in the late 1980s.) As a result of both positive developments (in income, education, health, and employment patterns) and negative factors (such as AIDS), world population growth is projected to continue slowing in the coming decades, to 0.7 percent per year by 2030. Even with slower growth, world population is projected to reach 8.9 billion by 2050 under the United Nations' "most likely" medium variant scenario (FAO, 2000).

Demand for agricultural commodities also depends strongly on income levels. Global average per capita income was $5,407 in 1999 (in 1995 U.S. dollars), but regional averages ranged from about $500 in South Asia and Sub-Saharan Africa to nearly $29,000 in high-income countries, and even greater disparities exist within regions (World Bank, 2001). Between 1961 and 1999, global average per capita income grew at an annual average rate of 2.6 percent, and projections by USDA (2001), the World Bank, and IFPRI (Rosegrant et al., 2001) suggest that global average per capita income growth will continue in the range of 2-3 percent per year over the next 10-20 years. As incomes rise from very low levels, demand for basic food staples increases rapidly at first, and then more slowly. Further income growth increases demand for higher value agricultural commodities, including fruits, vegetables, and livestock products (Offutt et al., 2002).

Above and beyond the effects of income growth, IFPRI notes that urbanization, too, is associated with a shift from coarse grains toward increased consumption of rice or wheat, fruits, vegetables, animal products, and processed foods. Of the world population increase of 2.9 billion people between 1961 and 1999, roughly two-thirds occurred in urban areas, and this pattern is likely to continue. The world's urban population today is approaching its total rural population (3.2 billion people) and is expected to surpass it within the next two decades.

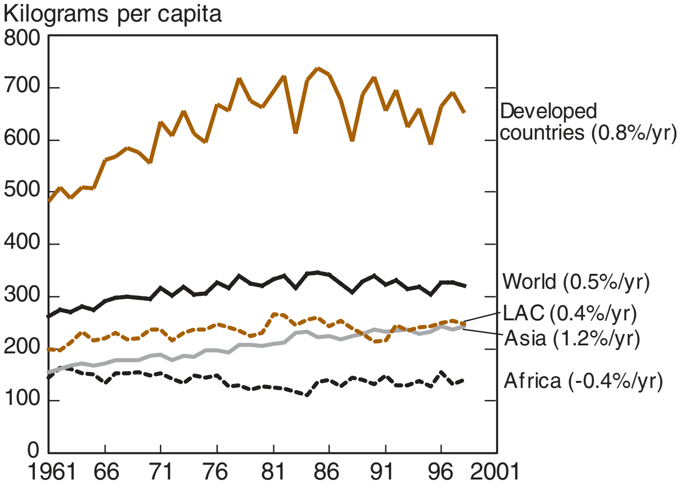
Based on projected changes in population, income, and urbanization, FAO and IFPRI project that global demand for cereals will increase by 1.2-1.3 percent per year over the next two to three decades, while demand for meat is projected to increase slightly faster. Growth rates for both food categories are higher for developing countries and lower for developed countries, but in all cases are lower than the corresponding rates over the past several decades. Most of the increased demand for cereals and meat is projected to come from developing countries, especially in Asia.

World food supply

Demand for agricultural commodities continues to grow, but projected rates of growth in demand are slowing. Demand growth rates are also well within the range of crop production growth rates over the past several decades. Between 1961 and 1999, FAO's aggregate crop production index grew at an average annual rate of 2.3 percent. Relatively rapid and steady annual increases in crop production were reported in Asia (averaging 3.1 percent) and Latin America (2.7 percent). Crop production generally grew more slowly and with greater variation in Sub-Saharan Africa and the developed regions. Total global cereals production grew about 2.3 percent per year, from 0.9 billion tons in 1961 to 2.1 billion tons in 1999 (from 0.8 to 1.9 billion rice-milled-equivalent tons).

FAO's index of crop production per capita has increased more slowly than the index of total crop production, but it has in fact increased for the world as a whole (at an average rate of 0.6 percent per year) and in all regions except Africa. Global cereals production per capita fell from a peak of 342 kilograms in 1984 to 323 kilograms in 1996/98, with steady increases in Asia offset by long-term declines in Sub-Saharan Africa and more recent declines in North America, Europe, Oceania, and the former Soviet Union (fig. 2.1). These more recent declines were due not to binding resource and technology constraints but rather to the combined effects of weak grain prices, deliberate policy reforms (in North America and

Figure 2.1—Cereal production per capita by region (and annual growth rate)



Source: ERS, based on data from FAOSTAT 8May02.

Europe), and institutional change (in the former Soviet Union).

Globally, average per capita food availability for direct human consumption grew 17 percent from the mid-1960s to the mid-1990s, to 2,760 kilocalories (kcal) per person per day. Growth over the period was 15 percent (to 3,374 kcal/day) in the developed countries and 28 percent (to 2,626 kcal/day) in the developing countries, among which China accounts for a substantial portion of the increase. By comparison, national average nutritional requirements for developing countries (varying with demographic and other characteristics, and allowing for moderate physical activity) range from 2,000 to 2,310 kcal/day (FAO, 2000).

Can increases in per capita food availability be sustained? Penning de Vries, Van Keulen, and Rabbinge (1995) have estimated global crop production capacity as a function of biophysical resources (such as land, water, and climate characteristics) and technology levels. Depending on consumption patterns, they argue that enough food could be produced to feed a global population many times the present (or even projected) size. These analyses help to explore biophysical limits, but they do not sufficiently reflect the economic and environmental costs that will influence actual production decisions, practices, and outcomes in the coming decades.

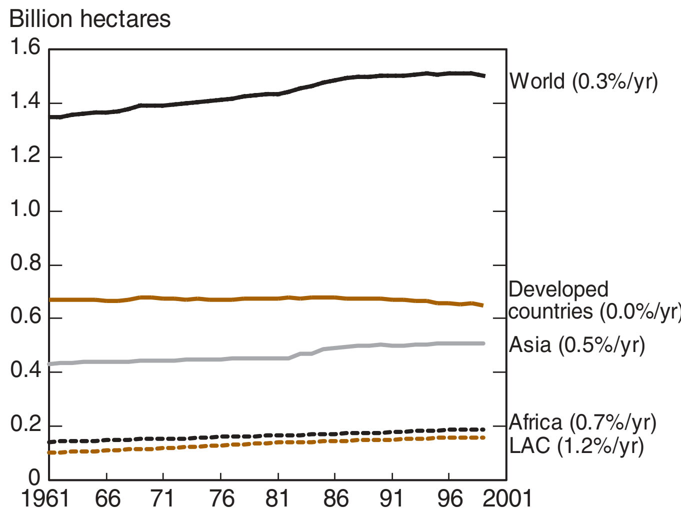
Analyses that attempt to incorporate these costs also indicate that sufficient food can be produced for the foreseeable future but with considerably less excess capacity. As a result of changes in demand and related changes in the extent and intensity of agricultural production, IFPRI projects that world cereal production will increase about 1.3 percent per year through 2020, up 1.6 percent per year (to 1.5 billion tons) in developing countries and 0.8 percent per year (to 1.0 billion tons) in the developed countries (Rosegrant et al., 2001). This will raise per capita cereal production about 0.2 percent annually (to 335 kilograms per person in 2020). Per capita cereal production is projected to grow 0.3 percent per year (to 242 kilograms per person) in developing countries and 0.6 percent per year (to 752 kilograms per person) in developed countries. Based on similar expectations, FAO (2000) projects that per capita food availability will increase 0.3 percent per year (to 3,100 kcal/ day by 2030) for the world as a whole, 0.4 percent per year (to 3,020 kcal/day) in the developing countries, and 0.1 percent per year (to 3,550 kcal/day) in the industrialized countries.

Such increases in production have the potential to satisfy projected food demands (and nutritional requirements) for the foreseeable future. Whether crop production will keep pace with future increases in demand at acceptable economic and environmental costs will depend on the availability and quality of productive resources and on the market incentives, policy measures, and research investments that influence how those resources are used.

Cropland area

The total area devoted to annual and permanent crops worldwide increased from 1.35 billion hectares in 1961 to 1.51 billion hectares in 1998, an increase of about 0.3 percent per year (FAO, 2000) (fig. 2.2). Most of this expansion took place in developing countries (where

Figure 2.2—Cropland area by region (and annual growth rate)



Source: ERS, based on data from FAOSTAT 10May02.

cropland expanded 1.0 percent annually). Due to weak grain prices, policy reforms, and institutional change (as noted earlier), growth in global cropland area slowed markedly in the past decade, to about 0.1 percent per year in the 1990s. Area in cereals increased in developing countries over the past two decades but declined by a larger amount in the rest of the world. By contrast, oilcrops area increased worldwide due to rising demand and policy measures; oilcrops account for nearly 90 percent of the increase in world harvested area since the 1970s.

Urban populations are growing rapidly, often in areas with high-quality agricultural land, but urban and built-up areas cover only about 4 percent (471 million hectares) of the earth's land surface (World Resources Institute, 2000). Citing estimates from the U.S. Agency for International Development (USAID) that urban expansion in developing countries will result in the conversion of less than 500,000 hectares of arable land annually, Rosegrant et al. (2001) argue that land losses to urbanization will not threaten global food production in the foreseeable future.

FAO estimates that the 1.5 billion hectares of land currently in crops represents only about 35 percent of the 4.2 billion hectares of the world's land judged to be suitable for crop production. The remaining land suitable for crops, however, is unevenly distributed among regions; 90 percent is located in Latin America and Sub-Saharan Africa, whereas pressure on land is greatest in Asia. Furthermore, FAO's estimate of suitable land includes all land with the potential to generate yields as low as 20 percent of those on the best land already in production, suggesting that the economic returns to bringing additional land into crop production would typically be low. Bringing additional land into crop production may also involve significant environmental costs, such as lost wildlife habitat and biodiversity and increased soil erosion and downstream flooding.

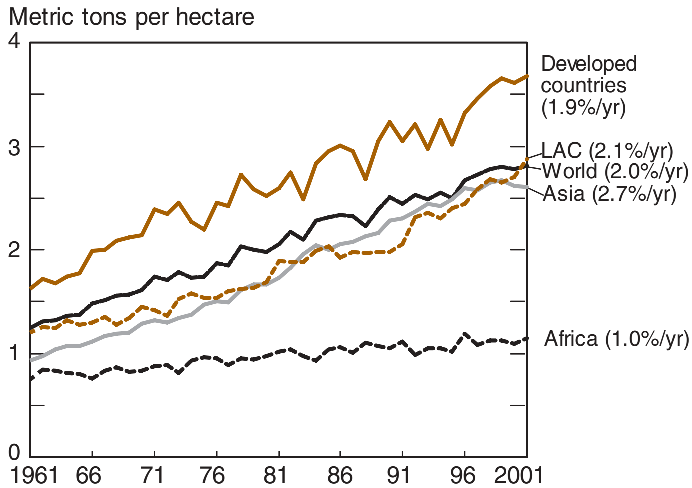
For these reasons, most analysts predict that cropland area will expand only slightly over the next several decades. FAO projects that arable (i.e., cropped) land in the developing countries will increase by about 120 million hectares (0.3 percent per year) by 2030, most of it in Sub-Saharan Africa and Latin America. This growth rate represents a marked slowdown in the developing countries relative to recent decades. (Harvested area is projected to expand more rapidly, however, due to an increase in the number of crops produced per year on a single parcel of land.) Cropland in the developed countries is not expected to increase.

FAO (2000) estimates indicate that about one-quarter of the global increase in production of wheat, rice, and maize over the last four decades was due to expansion of harvested area; increased yields accounted for the remainder. Pinstrup-Andersen et al. (1999) project that increases in cultivated area will contribute a smaller share (only about one-fifth) to increased grain production in the future. Given economic and environmental constraints on cropland expansion, the bulk of increased production in the future will need to continue to come from increased yields.

Yields

FAO data indicate that cereal yields currently average about 2.5 tons per hectare in developing countries, up 2.3 percent per year since the early 1960s. (Recall that the earlier discussion of figure 1.5 held other inputs constant. In fact, use of other inputs has changed considerably over time, allowing steady growth in average yields regardless of land degradation.) About half of all gains in crop yields in recent decades are attributable to genetic improvements (Byerlee et al., 2000); the remainder is due to increased use of conventional inputs, especially fertilizer and irrigation water. World cereal yield growth has slowed to 1.2 percent per year over the past decade, due in part to changes in input use (reflecting low and falling cereal prices) and poorly functioning markets and infrastructure, but also due to reduced growth in agricultural research (Wood et al., 2000; Pingali and Heisey, 2001). (While yield growth rates have been declining, global cereal yields have continued to rise in roughly linear fashion in absolute terms since 1950 (Dyson 1999; fig. 2.3.)

Figure 2.3—Cereal yields by region (and annual growth rate)



Source: ERS, based on data from FAOSTAT 8May02.

Yields vary significantly both across regions and within regions, due in part to differences in resource quality and to different patterns of technology and input use that arise from differences in market incentives and property rights. In developing countries, for example, FAO reports that cereal yields are more than twice as high in irrigated areas (3.8 tons per hectare) as they are in rainfed areas (1.7 tons per hectare). Cereal yields in the lowest yielding countries average only a fifth (or less) of yields in the highest yielding countries.

Potential wheat yields vary even among countries using high-input technology on land of similar high quality, ranging from 11.6 tons per hectare in France to 8.2 tons per hectare in Argentina (FAO, 2000). Actual yields are lower and range even more widely (7.1 tons per hectare in France and 2.4 tons per hectare in Argentina), due to differences in technologies and management practices that are themselves influenced by differences in policies and market conditions. Some inherent differences in resource quality can be mitigated through changes in input use (e.g., by increased use of irrigation and fertilizer), but a portion of observed yield differences is essentially fixed.

IFPRI and FAO project that cereal (and average crop) yield growth rates will decline further to about 1.0 percent per year over the next several decades, both in developing countries and for the world as a whole. Over the next three decades, FAO projects yield growth will account for about half of production increases in land-abundant Latin America and the Caribbean, about two-thirds of production growth in Africa and the Middle East, over four-fifths of production growth in land-constrained Asia, and nearly all production growth in the developed countries.

Genetic resources

Genetic improvements have contributed greatly to gains in yields and production of major crops, beginning with wheat, rice, and maize (which together provide more than half the world's plant-derived calories) in the 1960s. As noted, about half of all recent gains in crop yields are attributable to genetic improvements (Byerlee et al., 2000). Genetic improvements that enhance input responsiveness, resistance to pests and diseases, and tolerance to other stresses have been the sources of many of the gains in yield achieved to date. By the 1990s, 90 percent of land in wheat in the developing countries was in scientifically bred varieties, as was 74 percent of land in rice and 62 percent of land in maize. As a result, production of the three crops increased faster than population in Latin America and Asia, even though population in those regions grew at unprecedented rates. Other cereals and noncereal crops, including beans, potatoes, cassava, and lentils, have also benefited from significant genetic improvements (Evenson and Gollin, 2003). In the developed countries, 100 percent of land in wheat, maize, and rice was in scientifically bred varieties by the 1990s (and probably even earlier). Gains from genetic improvements will continue in the future but likely at slower rates and increasing costs, particularly because gains in input responsiveness have already been relatively fully exploited (Byerlee et al., 2000).

Fertilizer

Global fertilizer consumption increased by 4.1 percent annually between 1961 and 1998 and accounted for one-third of the growth in world cereal production in the 1970s and 1980s (FAO, 2000). Growth in fertilizer consumption per hectare of cropland has been slowing, however, from a global average annual increase of about 9 percent in the 1960s to an average annual decline of about 0.1 percent in the 1990s (FAOSTAT). On a global scale, 55 percent of global fertilizer consumption is applied to cereals, but per hectare application rates are highest for vegetables (Wood et al., 2000).

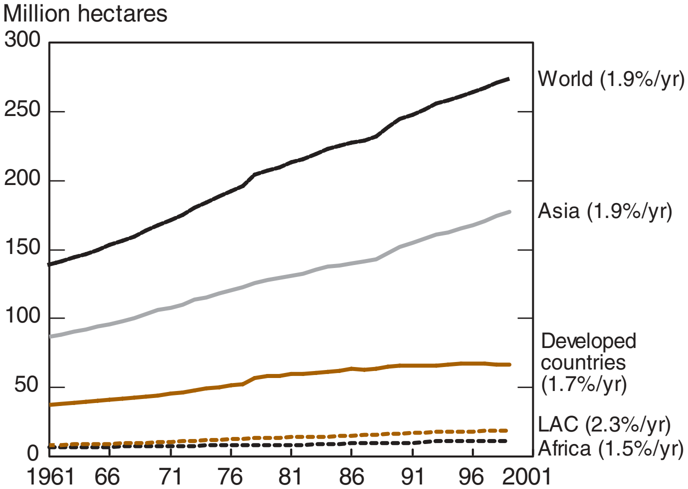
Among developing regions, per hectare fertilizer consumption increased most rapidly in land-scarce Asia (at 7.5 percent annually, to about 130 kilograms in 1998) and most slowly in Africa (at 3.7 percent annually, to just 19 kilograms in 1998—application rates in Sub-Saharan Africa are just half the average for Africa as a whole). Growth in fertilizer consumption also slowed (and even declined) in the developed regions but remains at relatively high levels (about 100 kilograms per hectare in North America and 200 kilograms per hectare in Western Europe).

World fertilizer consumption is projected to increase by an average rate of 0.9 percent annually through 2030, with the most rapid increases being applied to soybeans and other oilcrops (FAO, 2000). As fertilizer use increases, its potential to mitigate onsite land degradation (in the form of soil fertility depletion) will need to be balanced with the risk of increased offsite degradation (e.g., in the form of impacts on water quality).

Water

Water will be a critical factor limiting increased crop production in the 21st century. Fresh water is abundant globally, but most of it is locked up in ice caps, glaciers,

Figure 2.4—Irrigated land by region (and annual growth rate)



Source: ERS, based on data from FAOSTAT 9May02.

permafrost, swamps, and deep aquifers (Seckler et al., 1998). Furthermore, because of evaporation and flooding, only a tenth of annual precipitation over land—about 10,000 cubic kilometers per year—is available for human use, and this portion is distributed unevenly between countries, within countries, and across seasons and years. Of this portion, about one-third is currently withdrawn for human use—up sixfold over the past century (World Resources Institute, 2000).

Agriculture accounts for more than 70 percent of water withdrawals worldwide, and over 90 percent of withdrawals in low-income developing countries (Rosegrant et al., 2001). The total extent of irrigated cropland worldwide has grown at an average annual rate of 1.9 percent since 1961 (about six times the pace of growth in total cropland area), although this rate has been declining (FAO, 2000). About 18 percent of total cropland area is now irrigated, most of it in Asia (fig. 2.4).

Population growth and the increasing cost of developing new sources of water will place increasing pressure on world water supplies in the coming decades. Even as demand for irrigation water increases, farmers face growing competition for water from urban and industrial users, and from demands to protect in-stream ecological functions by imposing minimum in-stream flows. In addition, waterlogging and salinization of irrigated land threaten future crop yields in some areas (Rosegrant et al., 2002).

Climate

The Intergovernmental Panel on Climate Change (IPCC), representing a broad scientific consensus, projects that the earth's climate will change significantly over the course of the 21st century because of increasing concentrations of carbon dioxide and other "greenhouse" gases in the atmosphere (Reilly, 1996 and 2002). Changing patterns of precipitation, temperature, and length of growing season resulting from a doubling of atmospheric concentrations of carbon dioxide would tend to increase agricultural production in temperate latitudes and decrease it in the Tropics (where most developing countries are located). In aggregate, global crop production would be little affected. This conclusion is strengthened when the productivity-enhancing effects of a more carbon-enriched atmosphere and farmers' responses to climate change are considered. Nevertheless, potential impacts and adjustment costs are likely to vary widely among regions and over time and could be quite high in some areas.

Land quality

Constraints on area expansion and rising costs associated with other traditional sources of growth in agricultural production make it especially important to consider land quality's role in determining agricultural productivity. The concept of land, while seemingly simple, refers to the complex association of soil, terrain, water, climate, and biotic resources that characterize any particular location on the earth's surface. Land quality thus refers to the quality of these component resources and is generally defined in terms of the capacity of these resources to produce economic and environmental goods and services that are important to humans (Dumanski et al., 1998).

Similarly, soil quality is generally defined in terms of the capacity of a soil to perform specific functions in relation to human needs or purposes, including maintaining environmental quality and sustaining plant and animal production (Lal, 1998a). Soil quality, in turn, derives from a variety of particular physical, chemical, and biological properties that support these functions, including topsoil depth, texture, bulk density, and water-holding capacity; organic matter, pH level, and extractable nitrogen, phosphorus, and potassium; and microbial biomass (Mausbach and Seybold, 1998). Some of these properties (e.g., pH, N, P, and K) are characterized by optimum levels; departures from these optima (in either direction) are associated with reduced soil quality. Other properties (e.g., topsoil depth and microbial biomass) contribute positively to soil quality at all levels, while some (e.g., bulk density) are inversely related to soil quality.

In addition to soil properties, other characteristics also play a critical role in determining land quality, including aspects of terrain (such as slope) and climate (such as temperature and precipitation, and thus the length of growing period).

On any particular parcel of land, some properties of soil and other resources may limit land quality while others do not. It is important to somehow aggregate or summarize these diverse characteristics into measures of land quality that can provide useful indicators of the suitability of land for specified purposes, such as agricultural production.

Such aggregation can be conducted at a variety of spatial scales. Using data from Iowa and Minnesota, for example, Pierce et al. (1983) created a soil productivity index for deep-rooted crops (such as corn and soybeans) in the Corn Belt, based on available water capacity, bulk density, and pH to a depth of 100 centimeters (assuming that nutrients are not limiting and that factors such as climate are constant). Peterson (1986) used State-level data on inherent characteristics (e.g., soil fertility and precipitation) as well as factors influenced by human choice (e.g., population density and the share of land that is irrigated) to evaluate land quality in the United States.

Two soil-based measures that are commonly used in the United States to assess the quality of land for agricultural purposes are the Land Capability Classification (LCC) system and USDA's "prime farmland" designation (Magleby, 2002). Information about these measures is collected in the National Resources Inventory (NRI) every 5 years by USDA's Natural Resources Conservation Service (NRCS). The LCC system ranks land according to its suitability for crop production based on soil criteria, such as depth and fertility, climate, wetness, and susceptibility to erosion (Heimlich, 1989a). About 7 percent of U.S. cropland was classified in LCC Class 1 in 1997, with no significant limitations on crop production, and another 76 percent was in LCC Classes 2 or 3, with few significant limitations on crop production. Prime farmland designation requires several additional criteria (including favorable soil temperature, acidity, and electrical conductivity) and accounted for about 54 percent of U.S. cropland in 1997.

On a global scale, FAO and the International Institute for Applied Systems Analysis (IIASA) have collaborated in an effort to classify agro-ecological zones in terms of soil, terrain, and climate characteristics (Fischer et al., 2000 and 2001). Based on the FAO/UNESCO Digital Soil Map of the World and associated soil characteristics, along with data on slope and climate, FAO and IIASA evaluated land's capacity to support crop production under a variety of assumptions about technology levels and climate change. They concluded that about three-quarters of the world's land surface is too cold, dry, steep, or poorly endowed with soils suitable for crop production; the remaining one-quarter (3.3 billion hectares out of a total of 13.4 billion hectares) is at least moderately suitable for rainfed production of 1 or more of the 28 major crops analyzed.

In a similar analysis by NRCS, Eswaran et al. (various years) combined FAO/UNESCO's Digital Soil Map of the World and associated soil characteristics with a global climate database, used a water-balance model to estimate soil moisture and temperature regimes, and converted the FAO soil classes into a Soil Taxonomy consistent with NRCS definitions. About two dozen soil stress categories were identified, with continuous moisture stress and continuous low temperatures being the most extensive (table 2.1). Only about 3 percent of global land area was identified as having few constraints to agricultural production.

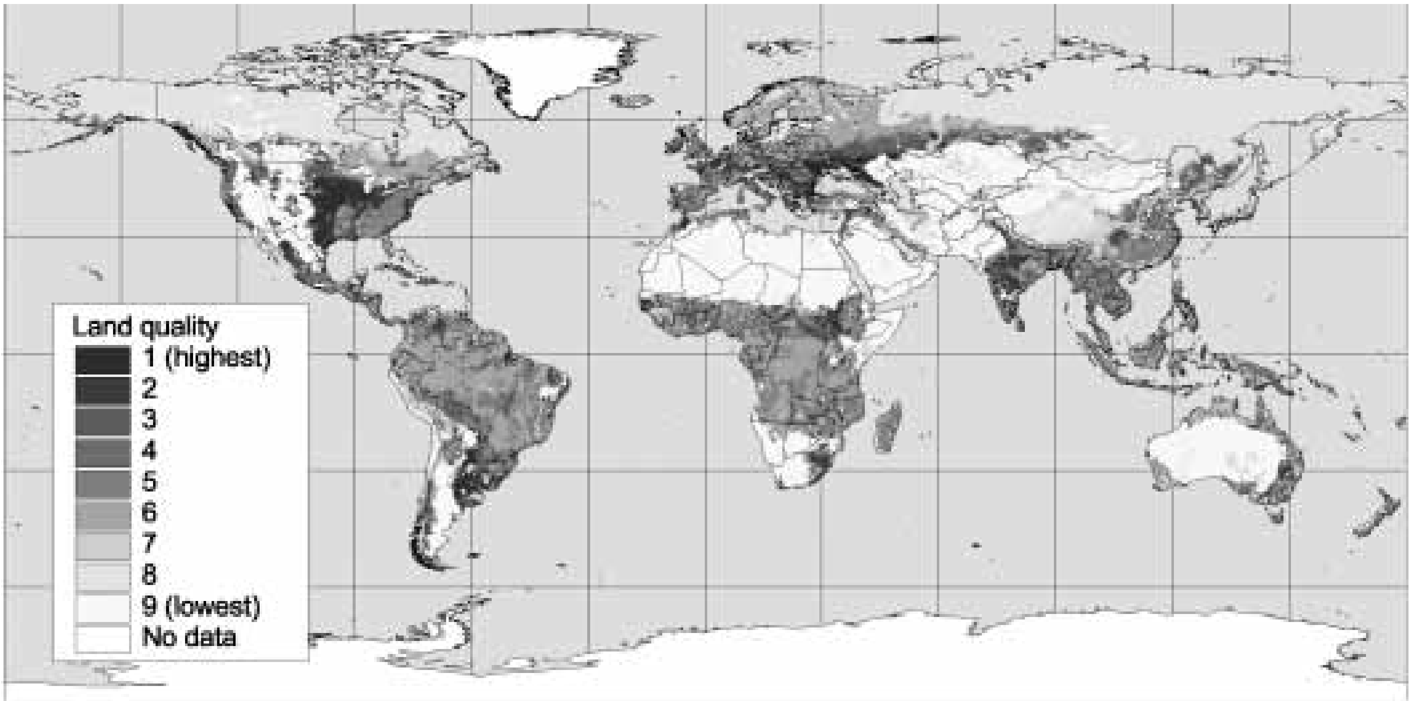
Such results raise questions about the cost of overcoming constraints to expanded (or intensified) agricultural production. To address such questions, Eswaran et al. (various) prioritized these soil stresses in terms of severity and the expenditure needed to make land suitable for sustainable crop production under rainfed conditions. Areas were then classified in descending order of suitability for rainfed crop production, from class 1 (consisting of the 3 percent with few constraints) to class 9 (con-

Table 2.1—Dominant soil stresses

Dominant soil stress	Global land area	
	Million km²	*% of total*
Continuous moisture stress	36.5	27.9
Continuous low temperatures	21.8	16.7
Seasonal moisture stress	10.3	7.9
Low nutrient-holding capacity	7.8	6.0
Shallow soils	7.4	5.6
Excessive nutrient leaching	4.5	3.4
High aluminum	4.1	3.1
Low moisture and nutrient status	3.5	2.7
Low water-holding capacity	3.4	2.6
Other stresses	27.2	20.8
Few constraints	4.1	3.1
Total	130.6	100.0

Source: Eswaran et al. (various years).

Figure 2.5—Land quality classes



Source: ERS, based on data from USDA Natural Resources Conservation Service, World Soil Resources Office.

sisting of the 28 percent subject to continuous moisture stress). (These classes closely parallel the Land Capability Classes used in the United States but are not identical since they are based on a larger set of soil stress categories.) The top three land quality classes together account for 13 percent of global land area. Relatively extensive areas of high-quality land are evident in the Midwestern United States, Argentina, Uruguay, Eastern Europe, and the former Soviet Union, with smaller concentrations in Asia and Africa (fig. 2.5).

In a recent analysis for IFPRI and the World Resources Institute, Wood et al. (2000) overlaid the same underlining soil stress data with spatially referenced data on land cover. They estimated that of the 3.6 billion hectares of agricultural land (cropland and pasture) identified from satellite imagery in the early 1990s, 16 percent (about 580 million hectares) is free of major soil constraints; most of this land is located in temperate areas. About half of agricultural land is estimated to be free of slope constraints (with an incline of less than 8 percent); again, most of this land is in the temperate regions. About 36 percent of agricultural area is characterized by both significant soil constraints and slopes of 8 percent or more; these marginal lands support roughly one-third of the world's population.

Analysis of the soil stress data by USDA's Economic Research Service (ERS) explored regional variations in the quality of cropland in particular. Among the countries of Sub-Saharan Africa, an average of 6 percent of cropland identified from satellite imagery had soils and climate well-suited for agricultural production. The proportion of high-quality cropland was higher in other regions, ranging from an average of 20 percent among Asian countries to 30 percent among the countries of Latin America and the Caribbean.

Improved biophysical measures of land quality are essential for accurate assessment of agricultural productivity. It is important to note that high quality in biophysical terms is neither necessary nor sufficient for high productivity in economic terms (Heimlich, 1989a and 1989b). Some biophysical constraints may be overcome relatively easily, for example, allowing high net returns to production of certain crops. Conversely, some land of high quality in biophysical terms may generate relatively low net returns to agricultural production, perhaps because it is located far from transportation or markets. Alternatively, land may be of high quality but vulnerable to degradation, allowing high returns initially but low returns over the long run. In assessing agricultural productivity, these factors require us to consider economic factors in addition to biophysical constraints, and changes in biophysical factors in addition to inherent/initial conditions.

Land degradation

Land degradation can be defined as a change in one or more of land's properties that results in a decline in land quality. As soil is a fundamental component of land, soil degradation is a fundamental component of land degradation. Lindert (2000) defines soil degradation more specifically as "any chemical, physical, or biological change in the soil's condition that lowers its agricultural productivity, defined as its contribution to the economic value of yields per unit of land area, holding other agricultural inputs the same." (Lindert notes that "[a] synonym for the soil's 'agricultural productivity' is soil 'quality.'") Examples of soil degradation include loss of topsoil through erosion by water or wind, depletion of soil nutrients, loss of soil organic matter, compaction, waterlogging, salinization, and acidification. Soil degradation occurs as a result of both natural and human-induced processes, such as agricultural production.

Some forms of soil degradation are reversible; others are not. Whether a particular form of degradation is reversible or irreversible depends on whether or not there exists an economically feasible substitute for the degraded soil property. Soil nutrient depletion, for example, is largely reversible because organic or inorganic fertilizers can substitute for nutrients taken up in harvested crops or lost through other processes. Soil erosion, on the other hand, is effectively irreversible because there is no economically feasible substitute for such properties as soil depth or water-holding capacity—although the productivity impact of soil erosion will depend critically on initial topsoil depth.

Data on land degradation are extremely limited and uneven in quality. Only one comprehensive assessment has been done on a global scale to date: the Global Assessment of Soil Degradation (GLASOD) by Oldeman et al. (1991). (A 1992 study by Dregne and Chou was global in extent but limited to dry areas.) Based on the judgment of over 250 experts around the world, GLASOD estimated that nearly 2 billion hectares of land (15 percent of total global land area of 13 billion hectares, or 23 percent of the 8.7 billion hectares used by humans for crops, pasture, and forest and woodlands) had been degraded as a result of human activity since World War II. GLASOD estimated that about 749 million hectares had been lightly degraded, indicating that productivity had been reduced somewhat but could be restored through modifications in farm management. Another 910 million hectares had been moderately degraded, indicating greater losses in productivity that would require costlier improvements to reverse. A final 305 million hectares were identified as strongly or extremely degraded, implying losses in productivity that are virtually irreversible.

GLASOD estimated that 38 percent of the world's cropland had been degraded to some extent since 1945. Degradation had affected 65 percent of cropland in Africa, 51 percent of cropland in Latin America, 38 percent of cropland in Asia, and 25 percent of cropland in North America, Europe, and Oceania. GLASOD identified erosion (primarily due to water) as the principal cause of cropland degradation, affecting 1.6 billion hectares (mostly in Asia and Africa). Loss of soil nutrients was the primary cause of degradation on 136 million hectares (mostly in South America and Africa); salinization affected 77 million hectares (mostly in Asia); compaction, sealing, or crusting affected 68 million hectares (mostly in Europe); and other physical and chemical processes affected 42 million hectares.

A related study, the Assessment of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD), applied a similar methodology at a finer spatial scale. Defining degradation in terms of the impact of soil quality changes on crop yields, ASSOD identified more degraded land in South and Southeast Asia than GLASOD but found that this land was often degraded to a lesser degree than had been reported by GLASOD (Wood et al., 2000).

Focusing on arid, semiarid, and dry subhumid zones worldwide, Dregne and Chou (1992) estimated that 30 percent of irrigated cropland and 47 percent of rainfed cropland in dry areas was moderately, severely, or very severely degraded. The severity of degradation in their analysis was defined in terms of reductions in productivity. Slight degradation of cropland, for example, was defined in terms of productivity losses of 0-10 percent. Moderate, severe, and very severe degradation were defined in terms of productivity losses of 10-25 percent, 25-50 percent, and greater than 50 percent, respectively.

Considerable attention has been focused on erosion, perhaps due (at least in part) to the relative ease with which it can be observed and measured (Lindert, 2000). Nevertheless, actual measurements of erosion are scarce, and estimates are highly sensitive to soil, climate, vegetation, and other characteristics. In an effort to use available data on such characteristics to estimate erosion rates when actual measurements are unavailable, many studies rely on such models as the Universal Soil Loss Equation (USLE) developed in the United States in the 1940s and 1950s (Wischmeier and Smith, 1978). USLE estimates average annual soil loss from sheet and rill erosion as a function of rainfall, soil erodibility, slope (both steepness and length of slope), land cover and management, and conservation practices. Bills and Heimlich (1984) partitioned USLE-estimated erosion rates into physical and managerial components to assess inherent erodibility in relation to tolerable erosion rates (which are defined in turn with reference to topsoil formation rates). USLE and related erodibility measures have been used to monitor soil erosion and determine eligibility for Federal program payments in the United States (see box on soil erosion in the United States).

USLE predicts the amount of soil moved on a field but not the amount removed from a field, suggesting that USLE results may overstate the amount of soil actually lost to production (Trimble and Crosson, 2000; Bills and Heimlich, 1984). Estimates of soil removed from fields are also subject to uncertainties about where (and when) sediment is ultimately delivered downstream. Alternatives to USLE range from direct measurement of soil eroded from experimental plots to measurement of Cesium-137 radioactive fallout from nuclear weapons tests beginning in the 1940s, although these involve limitations, too (Nagle et al., 2000).

Soil Erosion in the United States

According to the National Resources Inventory, soil erosion on cropland in the United States declined nearly 40 percent between 1982 and 1997, to 1.9 billion tons, even while cropland area remained roughly constant (Hansen and Claassen, 2001). This resulted in a 1997 average erosion rate of 4.6 tons per acre (or 10.3 metric tons per hectare). Declines were particularly significant in areas of the Western Plains that are vulnerable to wind erosion, and areas of the Upper Midwest that are vulnerable to water erosion.

Much of the decline in soil erosion can be attributed to Federal programs, especially conservation compliance provisions (which require farmers with highly erodible cropland to adopt approved conservation systems in order to receive Federal program payments) and the Conservation Reserve Program (in which environmentally sensitive cropland is voluntarily removed from crop production for 10-year periods in exchange for Federal rental payments). Improvements in conservation technology and awareness also contributed to the decline.

As a result of such problems, Lal (1998a) notes the difficulty of obtaining reliable estimates of soil erosion and reports a wide range of estimates from national and regional studies in Asia, Africa, North America, and Europe. Boardman (1998) cautions against applying site-specific estimates to wider areas even when careful estimates of erosion rates have been made in specific areas, citing the uncritical use of Belgian plot-level data to represent a European average. To estimate erosion rates at a broader scale, NRCS has assessed vulnerability to water erosion and wind erosion based on soil- and site-specific properties.

Despite the emphasis on erosion, other forms of land degradation are also important. As noted earlier, soil nutrient depletion is relatively easily reversible because organic and inorganic fertilizers can be added to compensate for nutrients taken up by harvested crops. Careful analysis of nutrient balances must also consider applications and removal of manure and other organic materials, erosion, sedimentation, atmospheric deposition, and biological nitrogen fixation. Low and declining soil fertility is a serious problem in many countries in Sub-Saharan Africa, most of which have average annual nutrient (NPK) depletion in excess of 30 kilograms per hectare (Stoorvogel et al., 1993; Henao and Baanante, 1999). Soil nutrient depletion is also a significant problem in Latin America, where average annual nutrient depletion exceeds 50 kilograms per hectare (Wood et al., 2000).

Salinization refers to the accumulation of salts in soils, often as a result of irrigation with improper drainage in dry areas (Eynard et al., forthcoming). About 20 percent of world irrigated area (up to 50 million hectares) suffers from salinization (Wood et al., 2000). An additional 0.2 to 1.5 million hectares of irrigated land may be lost to agricultural production each year through salinization, mostly in areas with high crop-production potential.

Productivity impacts of land degradation—evidence to date

Data limitations and differences in methods have resulted in a wide range of estimates of past or potential impacts of land degradation on agricultural productivity and production at various scales. Several studies of productivity impacts have been conducted at a global scale (e.g., Dregne and Chou, 1992; Crosson, various; Oldeman, 1998), some based on GLASOD degradation data. GLASOD did not assign rates of productivity loss to the various categories of land degradation identified. To evaluate how land degradation might affect agricultural productivity at a global scale, Crosson (1995a, 1995b, 1997) applied the productivity loss rates used by Dregne and Chou to the GLASOD estimates of degradation's extent and severity—using midpoints of 5, 18, and 50 percent (cumulative yield loss) for lightly, moderately, and severely or very severely degraded land, respectively. Crosson concluded that productivity had declined by a cumulative global average of 17 percent on GLASOD's degraded lands between 1945 and 1990, implying an average annual productivity loss of 0.4 percent. On all 8.7 billion hectares used by humans, both degraded and undegraded, cumulative productivity losses averaged 5 percent over the period, for an average annual loss of 0.1 percent.

Using the same productivity loss rates that Crosson drew from Dregne and Chou, and applying them to the GLASOD data at a regional level, Oldeman (1998) reached similar conclusions. Cumulative productivity losses for cropland and pasture ranged from 5 to 9 percent over the 45-year period (0.1 to 0.2 percent per year), depending on the productivity loss rates assumed. When higher loss rates were used, estimated losses were considerably higher for cropland in particular areas, averaging 25 percent (0.5 percent per year) in Africa and 37 percent (0.7 percent per year) in Central America.

Lal (1998a) and Scherr (1999b) report similar variation in impacts across crops, soils, and regions elsewhere in the world, with corresponding variation in the potential impact of soil degradation on food security. Reviewing plot-level experiments over periods of 4-7 years in Africa, Asia, and Latin America, Tengberg and Stocking (1997) find that crop yields generally decline in a negative exponential or logarithmic form with soil erosion, but that both erosion rates and yield impacts vary widely with soil, slope, cover, and other site-specific properties.

Bojö (1996) reviews 12 studies of the cost of land degradation in seven Sub-Saharan African countries and concludes that annual productivity losses are generally modest (1 percent or less in most studies, with higher estimates in two studies that applied yield loss coefficients from research in Nigeria to erosion estimates for Malawi and Mali). Using a crop growth simulation model, Pagiola (1994) found that erosion reduced yields in Morocco only on steeper slopes (exceeding 8 percent), where yields fell 20-30 percent over 50 years, implying annual losses of 0.4-0.7 percent. Using a locally relevant version of the Universal Soil Loss Equation, Pagiola (1996) estimated that erosion on a 15-percent slope reduced maize and bean yields by 20 percent after 10 years in Machakos, Kenya, implying annual losses of 2.2 percent.

Building on case studies from Africa, Lal (1995) estimated productivity impacts of soil erosion for the continent as a whole. Acknowledging the difficulties inherent in extrapolation from limited data, Lal first estimated cumulative soil erosion for 1970-90 from data on sediment transport and combined these with data on erosion-induced yield losses from experimental studies. Cumulative yield losses to erosion over the period for cereals, pulses, and roots and tubers were estimated at 6.2 percent (0.3 percent per year) for Sub-Saharan Africa and 9.0 percent (0.5 percent per year) for Africa as a whole.

Huang (2000) reports that about 34 percent of China's cultivated land area is eroded to some extent, and about 8 percent suffers from salinization. Controlling for agricultural inputs and institutional changes, Huang and Rozelle (1995) found that environmental degradation, primarily in the form of erosion and salinization, reduced grain yields in China by about 5 percent between 1976 and 1989 (about 0.4 percent per year). Rozelle et al. (1997) note that degradation's impacts vary by crop and region; losses to erosion are especially high in northern China.

Lindert (1996, 1999, 2000) notes concerns about the accuracy of statistics, perceptions, and analysis of cultivated land and land quality in China. In an econometric analysis of the interaction between crop production and soil quality parameters between the 1930s and the 1980s, he found that agricultural intensification in China has depleted nitrogen and organic matter in some cases but increased soil endowments of phosphorus and potassium, while concerns about soil erosion have been greatly exaggerated. Losses in nitrogen and organic matter have had no clear effect on crop yields in China because of the ability of commercial fertilizer to compensate for those properties. Lindert found similar results for Indonesia.

Ali and Byerlee (2001) argue that a positive trend in total factor productivity (TFP) is inadequate as an indicator of sustainable production growth because the effects of resource degradation may be masked by improvements in technology. Using district-level data on irrigated agriculture in Pakistan's Punjab province for 1971-94, they found that both land and labor productivity grew about

2.5 percent annually over the period, the former due to the introduction of Green Revolution technologies (such as improved seeds, fertilizer, and water control) and the latter due to subsequent mechanization. TFP growth in the province averaged 1.3 percent per year for crops as a whole but declined in the rice-wheat system. Resource degradation (in the form of depletion of soil organic matter and available phosphorus, increased soluble salts and pH, and reduced water quality) was found to have lowered TFP 58 percent on average and to have more than cancelled the positive effects of technological change in the rice-wheat system.

Pagiola (1995b) notes that rice yields in Bangladesh are stagnant or declining despite rising input use, strongly suggesting that yields are being reduced by land degradation in the form of nutrient imbalances and other suboptimal soil properties.

Pagiola (1998) argues that erosion problems in El Salvador have been exaggerated. Perhaps one-third of fields on moderate slopes and two-thirds of those on steep slopes experience productivity problems due to erosion. Productivity losses are difficult to quantify due to a lack of data, but it appears that it has thus far been possible to overcome these effects by increases in input use.

Focusing on the United States, Pimentel et al. (1995) used an empirical model (not described) to estimate losses of water, organic matter, available nitrogen, and other properties associated with soil erosion at a rate of 17 tons per hectare per year (characteristic of U.S. cropland in the early 1980s). These losses were in turn associated with a decline in crop productivity (maize yields) of 8 percent per year. (The authors did note that their model assumed an initial soil depth of 15 centimeters and no replacement of soil nutrients and water.) These assumptions and the authors' results have been questioned by Crosson (1995b) and others.

In an econometric analysis of cross-sectional county-level data from the United States, controlling for fertilizer and irrigation, Crosson (1986) found that several measures of erosion (estimated erosion rate, loss of at least 75 percent of topsoil, and topsoil depth) were significantly related to yields of corn and soybeans (and, to a lesser extent, wheat). If 1982 erosion rates were to continue for 50 years, however, Crosson estimated that yield losses would be only 5.1 percent (0.1 percent per year) for corn and 3.4 percent (0.07 percent per year) for soybeans. Erosion-induced yield losses for wheat would be negligible.

Analyzing their productivity index in conjunction with erosion rates in Minnesota, Pierce et al. (1983) found similar productivity losses after 100 years for most land: cumulative losses of 0-5 percent (0.0-0.1 percent per year) on land with slope of 12 percent or less (representing 92 percent of their study area) and cumulative losses of 10-56 percent (0.1-0.8 percent per year) on steeper land.

Alt et al. (1989) estimated the effects of soil erosion on agricultural productivity in the United States using the Erosion Productivity Impact Calculator (EPIC) model. They assumed that 1982 erosion rates continue and that applications of fertilizer and lime are adjusted to compensate for chemicals eroded with the soil. They measured productivity losses as the sum of crop yield losses and increased costs for fertilizer and lime. After 100 years, results indicate that about 10 percent of U.S. cropland would experience cumulative yields losses of 8 percent or more, while about 25 percent of U.S. cropland would experience cost increases of greater than 8 percent. Most cropland, however, would experience smaller yield losses and/or smaller cost increases, and net productivity losses (the sum of yield losses and cost increases) would decline on average by about 4 percent (i.e., about 0.04 percent per year).

On the whole, these studies suggest that land degradation to date has had significant impacts on the productivity or quality of cropland in some areas, but not in others. Impacts are sensitive to location-specific biophysical and economic factors and, thus, remain unclear at regional and global scales. How much might continued degradation affect productivity in the future? Given that crop yields are projected to increase more slowly in percentage terms than food demand over the next several decades, even small degradation-induced losses of productivity raise concerns.