United States
Department of
Agriculture

Economic
Research
Service

Agricultural
Economic
Report
Number 823

Linking Land Quality, Agricultural Productivity, and Food Security

Keith Wiebe

Linking Land Quality, Agricultural Productivity, and Food Security. By Keith Wiebe, Resource Economics Division, Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report No. 823.

Abstract

Land quality and land degradation affect agricultural productivity, but quantifying these relationships has been difficult. Data are limited, and impacts are sensitive to the choices that farmers make. Summarizing new research by economists, soil scientists, and geographers, this report explores the extent to which land quality and land degradation affect agricultural productivity, how farmers' responses to land degradation are influenced by economic, environmental, and institutional factors, and whether land degradation poses a threat to productivity growth and food security. Results suggest that land degradation does not threaten food security at the global scale, but does pose problems in areas where soils are fragile, property rights are insecure, and farmers have limited access to information and markets.

Keywords: Land quality, land degradation, soil erosion, agricultural productivity, food security.

Acknowledgments

Many colleagues at ERS and elsewhere made valuable contributions to this report. Vince Breneman developed the spatial data on land quality and other variables; Meredith Soule, Clare Narrod, and Abebayehu Tegene collaborated in the multicountry econometric analysis; Rattan Lal and Christoffel den Biggelaar led the analysis of soil erosion's potential impacts on crop yields; Hari Eswaran and Paul Reich provided the estimates of crop production areas and erosion rates; Jeffrey Hopkins conducted the dynamic analysis of farmer decisionmaking; Meredith Soule and Abebayehu Tegene collaborated in the analysis of land tenure and adoption of conservation practices; and Stacey Rosen and Shahla Shapouri incorporated land degradation impacts into their food security assessment model. These colleagues also provided valuable feedback on other parts of the manuscript. In addition, valuable comments were provided by Eldon Ball, Clara Cohen, Pierre Crosson, Anna Eynard, Paul Heisey, Carol Jones, Scott Malcolm, Will Masters, Greg Nagle, Rich Nehring, Stefano Pagiola, Mitch Renkow, Sara Scherr, Kate Sebastian, Robbin Shoemaker, Charles Sloger, and Stanley Wood. Finally, I thank John Weber and Susan DeGeorge for their expertise in editing and laying out the report.

Cover photos:
Women building contour terraces, Peru: FAO photo, I. Valdez.
Family returning home with rice harvest, Cambodia: FAO photo, G. Bizzarri.
Children being weighed and measured, Burkina Faso: FAO photo, R. Faidutti.
Background photo of terraces and buffer strips, Iowa: courtesy of USDA NRCS.

1800 M Street, NW
Washington, DC 20036-5831 June 2003

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Executive Summary

As rising populations and incomes increase pressure on land and other resources around the world, agricultural productivity plays an increasingly important role in improving food supplies and food security. Agronomic studies and conventional wisdom have long recognized that land quality affects agricultural productivity, but it has been difficult to disentangle land quality's effects from those of other factors, such as changes in input use. Advances in spatially referenced data and geographic information systems offer new insights on land quality's role in shaping patterns of agricultural productivity and food security.

First, econometric analysis using new data on soils and climate, and controlling for the effects of agricultural inputs and other measures of resource quality, confirms that differences in land quality contribute to significant differences in agricultural productivity among countries. Some of these differences can be mitigated (e.g., by increasing fertilizer use to reduce or reverse soil nutrient depletion in Sub-Saharan Africa), but others may not be reversible at reasonable economic or environmental cost.

Second, land degradation appears to generate productivity losses that are relatively small on a global scale (although their relative importance may increase if productivity growth continues to slow). New estimates of productivity losses are consistent with the lower range of previous estimates. For example, potential yield losses to erosion estimated in the soil science literature average 0.3 percent per year across regions and crops. These estimates focus on biophysical relationships in the absence of behavioral response; actual yield losses will be lower to the extent that farmers act to avoid or reduce these losses.

Third, farmers' responses to land degradation affect how potential impacts on yields may translate into actual impacts on agricultural productivity. Econometric and simulation analyses show how differences in land tenure and other factors that affect farmers' planning horizons combine with differences in land quality to influence farmers' decisions to adopt practices that reduce erosion and nutrient depletion. Actual losses under optimal practices will typically be lower than potential losses derived from agronomic studies. Actual losses under optimal practices are difficult to estimate but are generally less than 0.1 percent per year in the north-central United States.

These findings do not imply that degradation-induced yield losses are unimportant—just that they have historically been masked by yield growth (which has averaged over 2 percent per year in recent decades for the world as a whole) spurred by improvements in technology and increases in input use. Degradation-induced yield losses may become more significant in relation to yield growth in the future, as yield growth rates are projected to fall below 1 percent per year over the next few decades. Land degradation's effects on productivity are likely to be more severe in some regions and local areas, due to a combination of resource factors (terrain, soils, and precipitation) and economic factors (poverty, tenure insecurity, and lack of infrastructure).

Finally, land degradation's impacts on productivity may affect food security in some areas both through losses in aggregate production (and thus higher food prices for all consumers) and through losses in income for those who derive their livelihoods from agricultural land or agricultural labor. Model results suggest that the number of people with nutritionally inadequate diets in low-income developing countries would decline by 5 percent if average annual yield losses to land degradation in those countries were reduced from 0.2 percent to 0.1 percent over the next decade. Such improvements would contribute to meeting the 1996 World Food Summit objective of halving the number of undernourished people in the developing world by 2015 but would not be sufficient to meet the Summit goal entirely.

These results suggest that when markets function well, private incentives to reduce land degradation are generally sufficient to address onfarm productivity losses. When markets function poorly (e.g., when property rights are insecure or credit is expensive or unavailable), private incentives to address productivity losses are diminished. In either case, private actions are unlikely to adequately address land degradation's other, and perhaps more significant, effects: offsite impacts on both economic performance and environmental quality. Priorities for further progress in understanding and addressing the links between resource quality, agricultural productivity, and food security include targeted improvements in data, analysis, technology development, and policy.

Linking Land Quality, Agricultural Productivity, and Food Security

Keith Wiebe

1. Old Concerns and New Opportunities

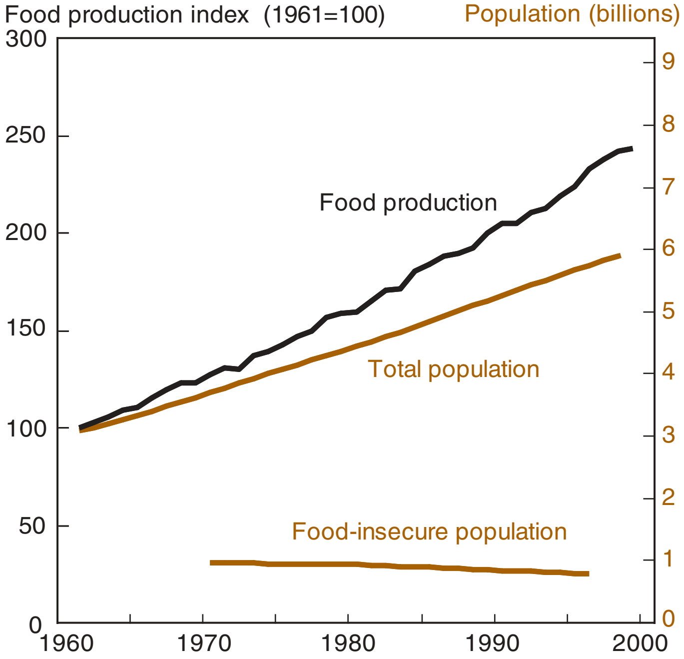
Two hundred years ago, citing limits on the extent and quality of agricultural land and concerns about population dating back to Plato and Aristotle, Thomas Malthus argued that population growth would inevitably outpace food production—unless checked by "moral restraint, vice, [or] misery" (Malthus, 1982 ed.). By 1960, his concerns appeared well founded. Growing at an unprecedented rate, the world's population reached 3 billion, of which about a third were chronically undernourished.

Four decades later, the world's population has doubled to 6 billion, and demand for food has grown with it. But food production has grown even faster, and the number of people who are chronically undernourished has fallen (fig. 1.1). Growth in food demand has generated incentives to increase resource use and improve technology and efficiency much more rapidly than Malthus anticipated, particularly during the second half of the 20th century.

Despite these achievements, enormous challenges remain. More than 800 million people remain chronically undernourished, most of whom live in Asia or Africa. For many of these people, food security depends on income from agriculture, and thus on the quality and productivity of agricultural inputs, such as land and labor. Meanwhile, concerns persist about the effects of increased agricultural production on the quality of land, water, and other environmental resources.

Addressing these challenges requires improved understanding of the links between land quality, land degradation, agricultural productivity, and food security (see box on key concepts)—incorporating biophysical processes as well as choices that farmers make in the context of diverse and changing economic circumstances. Though studied for many years, these links remain shrouded by conceptual difficulties, disciplinary boundaries, and incomplete data. Recent developments in each of these areas have improved our understanding of how land quality and land degradation affect agricultural productivity, how agricultural productivity affects food security through its impacts on both food supplies and farmers' incomes, and how food security, in turn, influences farm-

Figure 1.1—World food production and population, 1960-2000



Note: food insecurity is indicated here by chronic undernourishment.
Source: ERS, based on data from FAO.

ers' choices about practices that affect land quality over the longer term. These developments are the subject of this report.

Biophysical processes and economic choices

Estimating the impact of differences or changes in land quality on agricultural productivity and food security is difficult because data are scarce. Given this scarcity, a wide range of estimates have been offered regarding the magnitude of productivity losses to land degradation at various scales, from 0.1 percent per year to all forms of soil degradation (on a global scale) to 8 percent per year to soil erosion alone (in the United States). These differences make it difficult to assess potential impacts on food security and the environment and, thus, the appropriate nature and magnitude of policy response.

This wide range of estimates is also due to differences in methods of analysis. For example, to isolate the impact of soil erosion on crop yields, soil scientists may conduct biophysical experiments that hold factors other than topsoil depth constant. By contrast, to understand the productivity consequences of erosion in the context of farmer behavior, economists typically analyze data on a number of factors—including topsoil depth as well as fertilizer application and other inputs—and seek to isolate the effects of topsoil loss econometrically.

Soil scientists and economists use different approaches because they seek to answer different questions. The soil science approach focuses on biophysical relationships while the economic approach focuses on behavioral responses of farmers and other decisionmakers. Soil science experiments generate estimates of yield losses to erosion under specific controlled conditions (i.e., those represented by the experiments conducted). Quantitative economic analyses generate estimates of productivity losses to erosion under different conditions—namely, the range of biophysical and economic conditions represented by data available on the factors considered, including farmer behavior.

The possibility of error arises in how the results of these two approaches are interpreted. Both approaches are costly, implying that data are limited and that inferences will generally be necessary if results are to be applied more broadly. The soil science approach can be successfully generalized to the extent that experimental conditions represent actual conditions—including farmer technologies and practices—in the wider area and time period of interest. The economic approach can be successfully generalized to the extent that the data and factors analyzed adequately represent the range of conditions that characterize the area and time period of interest. In general, the economic approach more accurately accounts for differences or changes in farmer practices, but risks omitting critical variables or data. This approach faces an additional challenge: data on some variables, such as fertilizer use, may be readily available at aggregated levels (e.g., as reported by national and subnational political

Key Concepts

Land quality refers to the ability of land to produce goods and services that are valued by humans. This ability derives from inherent/natural attributes of soils (e.g., depth and fertility), water, climate, topography, vegetation, and hydrology as well as "produced" attributes, such as infrastructure (e.g., irrigation) and proximity to population centers.

Land degradation refers to changes in the quality of soil, water, and other characteristics that reduce the ability of land to produce goods and services that are valued by humans. Examples of land degradation include soil erosion, soil nutrient depletion, and salinization. Some forms of land degradation, such as nutrient depletion, can be halted and even reversed rather easily (e.g., by balancing nutrient application with that taken up in harvested crops). Other forms of land degradation, such as soil erosion or salinization, can be slowed or halted through appropriate management practices but are generally very costly to reverse.

Agricultural productivity is a measure of the amount of agricultural output that can be produced with a given level of inputs. Agricultural productivity can be defined and measured in a variety of ways, including the amount of a single output per unit of a single input (e.g., tons of wheat per acre or per worker), or in terms of an index of multiple outputs relative to an index of multiple inputs (e.g., the value of all farm outputs divided by the value of all farm inputs). Land productivity helps determine total food production, incentives for land use change, returns to landowners, and consumer food prices. Labor productivity helps determine returns to agricultural workers—who make up about half of the world's labor force (and even more in developing countries).

Food security is generally defined in terms of access by all people at all times to sufficient food for active, healthy lives (World Bank, 1986). As such, food security depends not only on how much food is available but also on the access that people (e.g., individuals, households, and nations) have to food—whether by purchasing it or by producing it themselves. Access, in turn, depends on economic variables, such as food prices and household incomes, as well as on agricultural productivity and the quality of natural resources.

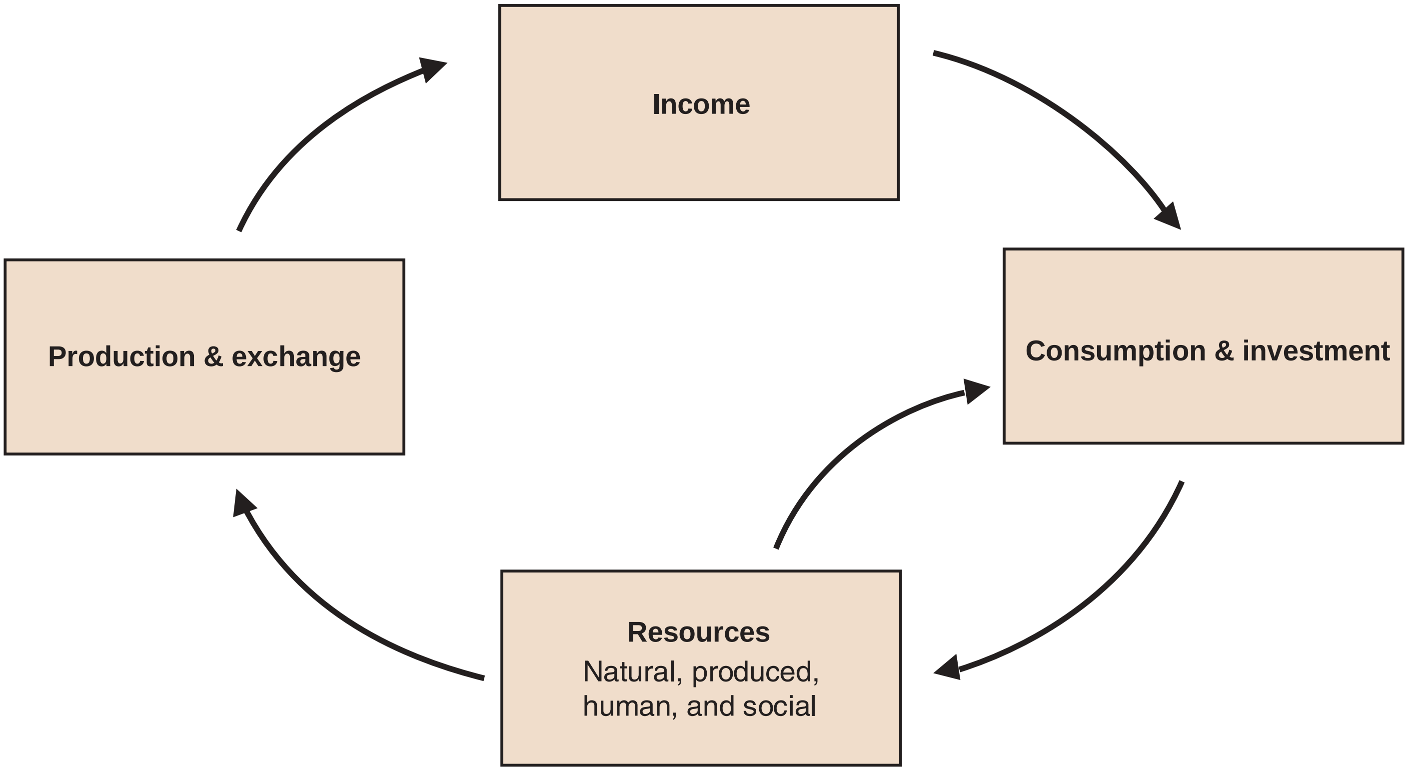
units), but data on biophysical characteristics, such as land quality or land degradation, may be available in only a few locations. Much may be known about selected sites, but little is generally known at the larger scales at which policy measures—if appropriate—become relevant.

These challenges must be met to gain a better understanding of the links between land quality, land degradation, agricultural productivity, and food security at policy-relevant scales. To do so, we need to examine not just the biophysical relationship between land quality and yields but also the role of farmers' decisions in shaping that relationship. Further, we need to consider farmer decisions not just in terms of maximizing income in the short term but also in terms of sustaining income over the longer term by investing in the maintenance or improvement of land quality. The result is not a simple linear relationship that begins with exogenous land quality and traces causality through to agricultural productivity and food security in a single period but rather a dynamic process in which resources, income, and decisions about production, exchange, consumption, and investment influence each other over time (fig. 1.2). Note that if incomes and wealth are insufficient, whether due to degradation-induced productivity losses or unrelated factors, some households may be forced to choose between adequate consumption in the short run (with consequences for the quality of their health and/or labor productivity) or investment in the protection of other resources (including land) on which their food security depends over the longer term.

Farmers' incentives

Farmers' incentives to invest in protecting land quality depend on their perceptions of the costs and benefits associated with such investments. Some forms of land degradation generate impacts both at the location where the degradation occurs and elsewhere. For example, soil erosion involves the removal of soil from one location, by wind and/or water, and its deposition downwind or downstream. The loss of topsoil depth and associated nutrients, organic matter, and water-holding capacity

Figure 1.2—Farm household opportunities and choices



Source: Maxwell and Wiebe (1999).

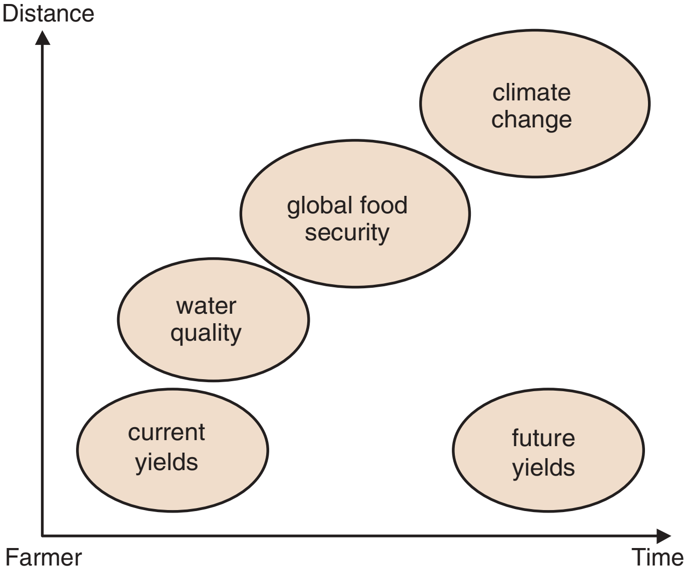
may affect the eroded location’s ability to produce crops, while the deposition of eroded soil may affect the efficiency of measures to provide clean water, irrigation, flood control, and other services downstream.

Similarly, some forms of land degradation generate impacts felt not only in the present but also in the future. For example, cumulative changes in soil quality may progressively reduce a field’s ability to produce crops over time. Changes in the flow of carbon between soils and the earth’s atmosphere may have effects on climate that are felt both at a great distance and far in the future (Lal, 1998a; Pagiola, 1999b).

Determining the incidence of these effects over space and time is critical to understanding the decisions made by farmers. Figure 1.3 illustrates several potential effects of land degradation and their proximity to the farmer whose decisions influence the occurrence of land degradation. The vertical axis represents spatial distance from the farmer, while the horizontal axis represents distance in time. Land degradation may reduce crop yields on farmers’ fields both in the short run and in the future, for example, and may also affect downstream water quality in the (relatively) short run. Impacts on food security and climate may be felt only over time and at a distance.

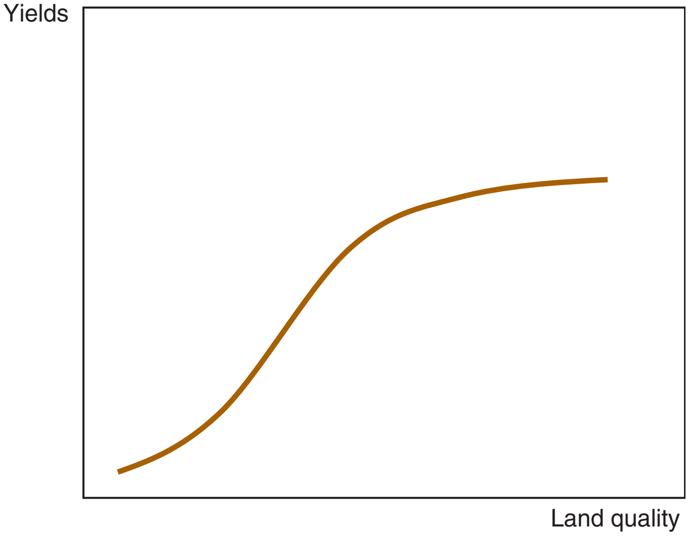
In general, farmers have little direct incentive to address offsite impacts of land degradation. By contrast, farmers have a direct incentive to address onsite productivity losses, particularly if productivity losses occur over a short period of time but also over the long run if property rights provide adequate assurance that the farmer will benefit from his or her investments over time. Actual choices made by farmers in response to these incentives will depend not only on biophysical conditions but also on economic and institutional conditions—such as access to credit to spread onsite costs over the longer term and policy instruments to spread the incidence of downstream costs and benefits over society as a whole.

Figure 1.3—Land degradation effects over space and time



Source: Wiebe (2001).

Figure 1.4—Yields as a function of land quality



Source: ERS.

Farmers’ incentives, in turn, depend on the underlying relationship between land quality and agricultural output. Figure 1.4 depicts a stylized relationship between a measure of output or yields and a measure of land quality, holding all other factors (such as labor and fertilizer) constant. A common feature of such production functions is that output initially rises at an increasing rate as the factor in question (e.g., soil fertility) increases. After a point, however, further increases in the input add progressively smaller increments to output. Such functions may also be characterized by discontinuities due to “lumpy” inputs and technologies.

Such a relationship indicates that output will be higher for a farmer with land of higher quality, everything else being equal. If appropriate data on output, land quality, and other inputs are available, it is possible to examine this relationship empirically. Over the past 40 years, economists have tried to estimate agricultural production functions (using national-level data) while attempting to control for differences in land quality in various ways. Some of these attempts are described later in this report, along with recent efforts that use improved spatially referenced data on land quality.

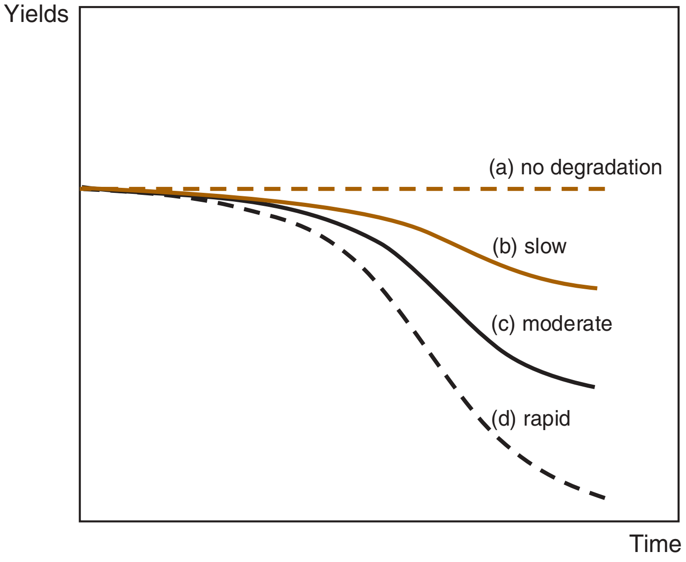
Figure 1.4 also implies that output will fall for a particular farmer if the quality of his or her land declines over time, everything else remaining equal. This proposition is more difficult to examine empirically, requiring not only data on output, land quality, and other inputs but also data on changes in land quality over time. Such data are scarce because changes in land quality are highly sensitive to initial land quality, environmental conditions, farmers' choices regarding management practices, and other factors that vary with location.

If such data are available, it becomes possible to estimate the rate at which land quality (or some component of land quality, such as topsoil depth) changes over time. Changes in output per unit of change in land quality can then be combined with changes in land quality over time to estimate the rate at which output changes as a function of changes in land quality over time.

The hypothetical relationship in figure 1.4 represents a trajectory that output might follow if a farmer allowed land quality to decline over time, everything else remaining equal. If farmers are aware of these potential losses, however, and concerned about impacts on their income (fig. 1.2), they will consider adopting farm management practices (such as conservation tillage) or making investments (such as terracing) that protect land quality by reducing or preventing various forms of land degradation. Choosing among these practices involves making complex decisions that simultaneously affect inputs, output(s), and land quality (and, as suggested by figure 1.2, nonfarm expenditures as well). Figure 1.5 shows the range of possible yield impacts associated with land degradation. Depending on economic and environmental conditions, it may be optimal for a particular farmer to control degradation completely (a), to allow relatively rapid degradation (d), or to manage degradation at some intermediate rate (b or c). (Note that these curves derive from the production function depicted in figure 1.4, adjusted to reflect land degradation over time; time is now shown on the horizontal axis. Also note that the actual shape of these curves is a site-specific empirical question.)

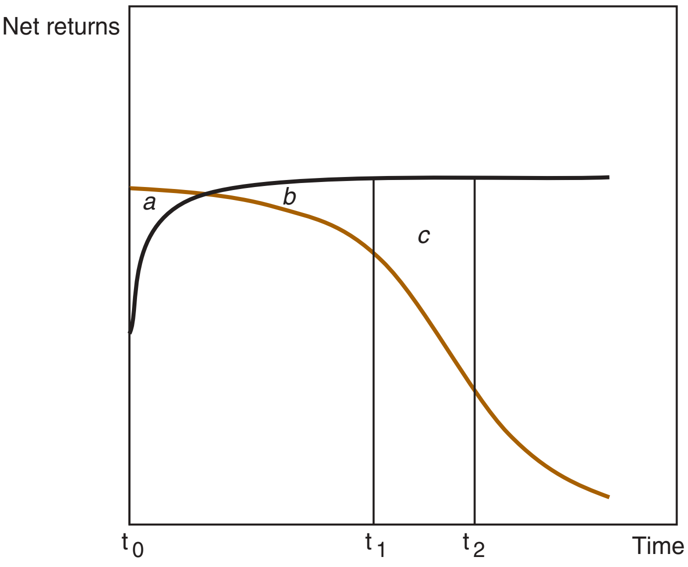
To understand how farmers make these choices, we need to move beyond yields and compare the level and timing of net returns to alternative practices over time, drawing on previous work by Pagiola (e.g., 1999a, 1992) and McConnell (1983). For example, consider two management practices with different streams of net returns over time (fig. 1.6). One stream, based on the degrading practice currently being used, declines over time due to soil erosion or other forms of land degradation. After an initial investment reflecting the cost of switching from the degrading practice, the other stream of net returns, based on the conserving practice, remains constant (or increases or declines less rapidly). Reflecting their differing impacts on land quality, the two streams diverge over time. Differences in net returns at any point in time are represented by the difference in the height of the two curves at that point.

Figure 1.5—Yields at different rates of land degradation



Source: ERS.

Figure 1.6—Net returns under alternative practices



Source: ERS.

In general, the farmer's choice between the two practices is driven not by comparison of net returns at any single point in time but rather by comparison of cumulative returns to the two alternatives over a period of time. Comparison of the two streams is complicated by the fact that net returns in the future must be discounted to reflect the alternative uses to which money might be put if invested today.[1] If the discounted present value of net returns from the conservation practice exceeds that from the degrading practice over the relevant time horizon, it will be optimal for the farmer to adopt the conservation practice. If not, it will be optimal for the farmer to continue using the degrading practice.

The relative magnitude of discounted net returns to the two alternative practices depends on many factors, including the magnitude and timing of the costs of each practice, the returns they are expected to generate, the rate at which future costs and returns are discounted by the farmer, and the farmer's belief that he or she will be able to realize future returns on a particular parcel of land in the future. Each of these factors may vary from one farmer to the next, from one parcel of land to the next, and from one time period to the next—implying that optimal conservation decisions may vary accordingly.

If a farmer holds a lease on a field between the present (t_0) and time t_1, the relevant comparison of net returns is between the discounted present value of *a*, the short-term losses incurred to establish the conserving practice, and that of *b*, the eventual gains from preventing (or reducing) land degradation. If the latter exceeds the former, the farmer will maximize net returns over the period of the lease by switching to the conserving practice. If the reverse is true, it will be optimal (at present) for the farmer to continue using the degrading practice. (It may become optimal for the farmer to change practices in the future.) Alternatively, if the farmer's planning horizon extends from the present through t_2, perhaps as a result of a longer lease, he or she stands to realize additional gains from adopting the conserving practice, and the relevant comparison is then between the discounted present value of *a* and the discounted present value of *b + c*. Such a farmer is more likely to adopt the conserving practice than the farmer with the shorter time horizon, everything else being equal.

Other factors that influence farmers' choices among practices include differences or changes over time in land quality (and thus urgency of conservation), wealth and access to credit (thus discount rates and the cost of financing upfront investment), other aspects of tenure security (thus the likelihood of realizing future returns), and the effectiveness of alternative practices in slowing land degradation. The effect of some of these factors on the adoption of conservation practices, recognizing the importance of long-term costs and benefits, is explored conceptually by Pagiola (1999a) and empirically later in this report.

Policy challenges

The stream of net returns to alternative practices will differ in general for society as a whole and for a private individual. In addition to sustaining yields and net returns on a farmer's field, for example, a conserving practice may reduce downstream pollution and/or sedimentation, with implications for water quality and quantity, irrigation, hydroelectric power generation, flood control, biodiversity, and climate change. Through their effect on agricultural production and prices, private choices may also have potentially far-reaching effects on aggregate income, economic growth, and food security. (Note that these effects are distinct from the effects of land degradation or investment on the farm household's own food security, via changes in its income.) Mitigating these offsite effects, however, generates no direct reward for the farmers whose actions create them, so farmers' choices based on private criteria may not be optimal from the perspective of society as a whole.

A variety of public policy measures can be used to supplement private incentives to protect land quality, including sharing the costs of switching practices (upfront costs as well as operating costs), providing credit on favorable terms for upfront costs, and improving tenure security. These measures would raise net returns to the conservation practice relative to the degrading practice by reducing area *a* in figure 1.6 and/or by increasing areas *b* and *c*. Such policy measures may or may not be warranted in specific contexts, depending on the relative magnitudes of private and public costs and benefits.

Land quality and food security have been the focus of a number of domestic and international policy initiatives in recent years. International attention first focused on land degradation in the early 1970s, following poor harvests in important food-producing areas, global grain price increases, and several years of famine in Sub-Saharan Africa. Particular attention was focused on land degradation in dry areas, which was referred to as "desertification." A United Nations conference on desertification in Nairobi in 1977 drew further attention to the issue but

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[1] The discounted present value of a stream of future returns is calculated as $PV = Y_1/(1+r) + Y_2/(1+r)^2 + ... = \sum_t Y_t/(1+r)^t$, where Y_t represents net returns in period t and r represents the farmer's discount rate.

failed to generate a sustained response. Discussions at the 1992 Earth Summit in Rio de Janeiro resulted in the eventual creation of the United Nations Convention to Combat Desertification (UNCCD) in 1994. Recognizing “the complex interactions among physical, biological, political, social, cultural and economic factors” that drive desertification and undermine productivity, UNCCD members committed themselves to sharing financial resources and coordinating strategies to combat desertification and eradicate poverty. The United States signed the UNCCD in 1994 and ratified it in 2000 (joining over 100 other countries). The UNCCD entered into force for the United States in February 2001.

At the 1996 World Food Summit in Rome, the United States joined 185 other countries in pledging to reduce the number of hungry people worldwide by half (from more than 800 million) by 2015. Sustainable management and use of land and other natural resources was recognized as a critical component of efforts to reach this goal. Key elements of the U.S. Action Plan (1999), developed in response to the World Food Summit, include developing and implementing environmentally sensitive agricultural and land-use policies to ensure domestic and international food systems that are sustainable, profitable, and equitable. Today, researchers and policymakers acknowledge that progress will have to accelerate if Summit goals are to be achieved (IFPRI, 2002).

To the extent that resource quality and land degradation affect both domestic food production and incomes, they also shape demand for commercial food imports and food aid. Improved understanding of the links between resource quality and productivity may enhance projections (such as those made by ERS) of future trade patterns and food aid needs and consequent demand for U.S. agricultural commodities. For example, the International Food Policy Research Institute (IFPRI) estimates that 60 percent of the developing world’s net cereal imports in 2020 are projected to come from the United States (Pinstrup-Andersen et al., 1999).

New contributions in data and analysis

These issues have been of concern for decades, but data and methodological constraints have limited analysis of the interactions between resources and food security, leaving latitude for widely varying claims and widely differing beliefs about the urgency of policy response. Recent improvements in data and methods allow a new look at these interactions at a variety of scales. For example, existing data on soil properties and new data on climatic characteristics can now be overlaid with high-resolution satellite data on land cover to create spatially referenced indicators of cropland quality. These new indicators can be used to refine our understanding of the factors that influence agricultural productivity differences across countries.

The same data can be used to generate spatially referenced estimates of soil erosion rates, which can be linked with site-specific information on erosion’s impacts on crop yields to estimate potential productivity losses to erosion over time. At the farm scale, new analyses of land quality, farmer characteristics, and management practices offer improved insights into the choices that farmers make, and thus the extent to which the potential impacts of land degradation are likely to be realized in practice. Estimated losses can, in turn, be incorporated in simulations of agricultural production and trade to evaluate their impacts on food security at national, regional, and global scales.

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.

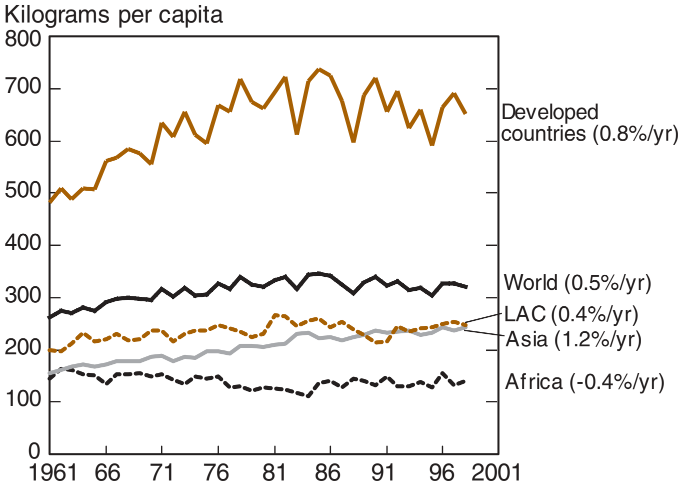
Based on projected changes in population, income, and urbanization, FAO and IFPRI project that global demand for cereals will increase by 1.2-1.3 percent per year over the next two to three decades, while demand for meat is projected to increase slightly faster. Growth rates for both food categories 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.

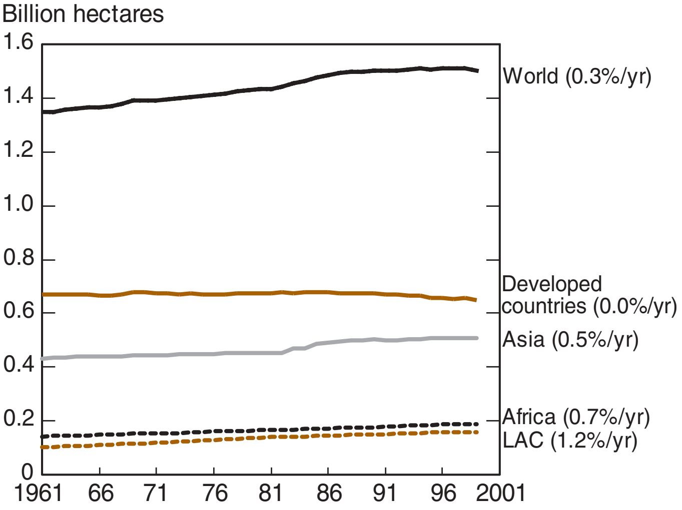
Analyses that attempt to incorporate these costs also indicate that sufficient food can be produced for the foreseeable future but with considerably less excess capacity. As a result of changes in demand and related changes in the extent and intensity of agricultural production, IFPRI projects that world 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.

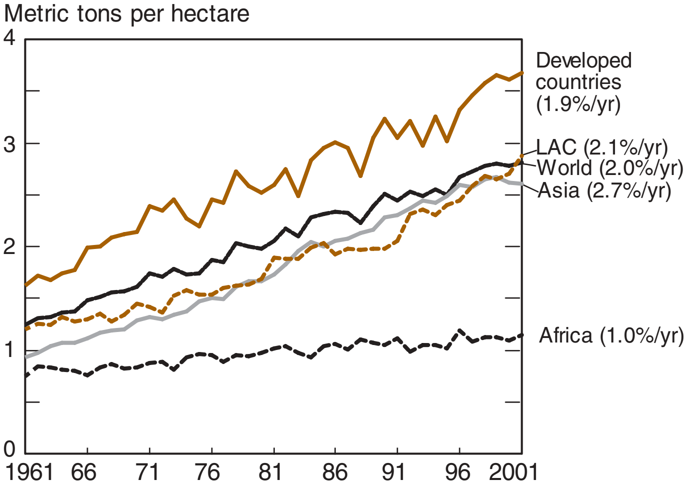
For these reasons, most analysts predict that cropland area will expand only slightly over the next several decades. FAO projects that arable (i.e., cropped) land in the developing countries will increase by about 120 million hectares (0.3 percent per year) by 2030, most of it in Sub-Saharan Africa and 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).

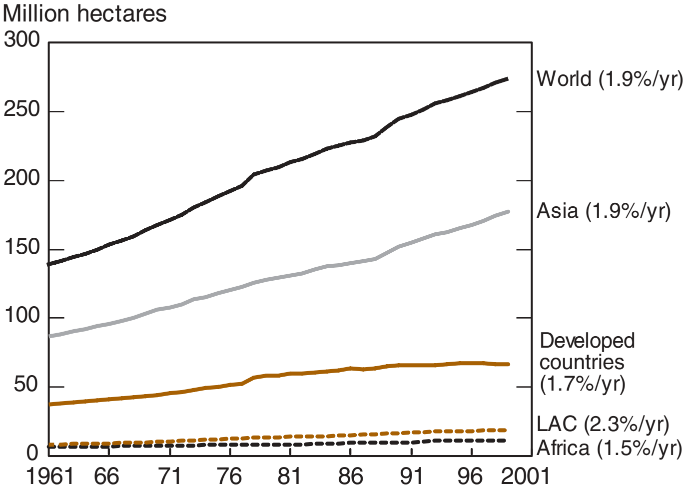
Among developing regions, per hectare fertilizer consumption increased most rapidly in land-scarce Asia (at 7.5 percent annually, to about 130 kilograms in 1998) and most slowly in Africa (at 3.7 percent annually, to just 19 kilograms in 1998—application rates in Sub-Saharan Africa are just half the 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.

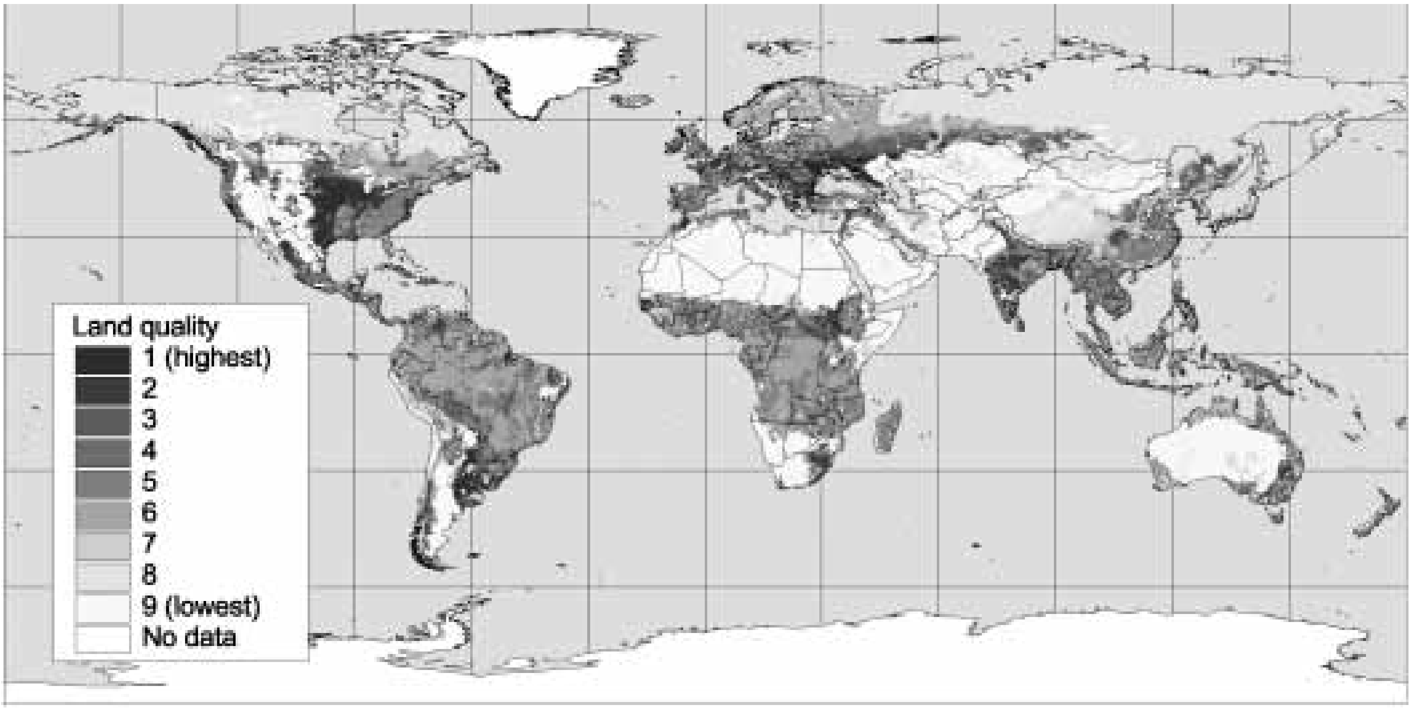
Such results raise questions about the cost of overcoming constraints to expanded (or intensified) agricultural production. To address such questions, Eswaran et al. (various) prioritized these soil stresses in terms of severity and the expenditure needed to make land suitable for sustainable crop production 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 km^2	*% 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).

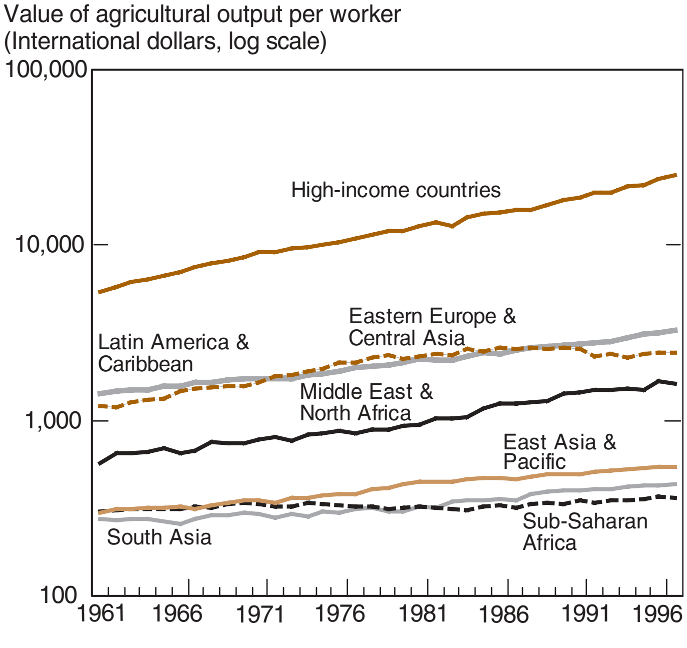
On the whole, these studies suggest that land degradation to date has had significant impacts on the productivity or quality of cropland in some areas, but not in others. Impacts are sensitive to location-specific biophysical and economic factors and, thus, remain unclear at regional and global scales. 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.

3. Land Quality and Agricultural Productivity

Agricultural productivity is a measure of the amount of agricultural output produced for a given amount of inputs. Agricultural productivity can be defined and measured in a variety of ways, including partial measures, such as the amount of a single output per unit of a single input (e.g., tons of wheat per hectare of land), or in terms of an index of multiple outputs divided by an index of multiple inputs (e.g., the value of all farm outputs divided by the value of all farm inputs). Different measures of agricultural productivity may be of interest in addressing different questions. Land productivity measures, for example, help determine the amount of land needed to meet future world food needs—and thus the potential level of pressure on land currently providing other environmental services. Labor productivity measures help determine the incomes and welfare of people employed in agriculture (including the majority of rural people in developing countries).

Agricultural labor productivity has grown in most regions over the past four decades, but significant differences exist across regions, both in levels and in rates of growth (fig. 3.1). Productivity in Sub-Saharan Africa is low and nearly unchanged since 1961, for example, while productivity in the high-income countries has grown steadily from a much higher base.

Figure 3.1—Agricultural labor productivity by region, 1961-1997



Source: ERS, based on data from FAO.

To what extent are such patterns influenced by differences in land quality? Determining the precise nature of land quality's role has been difficult because of severe data limitations. Recent advances in spatially referenced data on land quality and in the computer technology used to analyze such data have improved our ability to determine land quality's effect on agricultural productivity. Continued efforts to account more precisely for all aspects of resource quality differences are important, because analyses that do not correctly specify these differences may incorrectly attribute observed differences in productivity to other factors.

Factors that can influence agricultural productivity levels and growth rates are typically studied using either a production-function approach or an index-number approach. In a production-function approach, differences in output or productivity across spatial units (e.g., farms or countries) and/or time are explained by differences in the levels of inputs, both conventional (e.g., land, labor, tractors, livestock, and fertilizer) and nonconventional (e.g., land quality, physical infrastructure, research, and government policies). This approach usually uses partial productivity measures, such as land productivity (e.g., crop yields per unit of land) or labor productivity (e.g., output per worker).

Despite their value in addressing specific questions, land and labor productivity are both incomplete indicators of agricultural productivity because they measure the productivity of only a single factor of production and may well move in opposite directions. (For example, an individual farmer who increases the land area of his or her farm without hiring additional labor might well generate an increase in total output. Because labor is unchanged, this would imply an increase in labor productivity. If output increased less (proportionately) than the amount of land farmed, however, land productivity would decline.)

To address this problem, the index-number approach to studying productivity estimates total factor productivity (TFP), which measures levels and changes in agricultural output relative to changes in an aggregated index of multiple inputs. If price data are available, a price-weighted index of output is divided by a price-weighted index of conventional inputs to construct TFP indexes. If price data are unavailable, data envelopment analysis (DEA)—a nonparametric programming approach that uses data on physical inputs and outputs—can be used to construct other TFP measures, differences or changes of which may then be explained by differences or changes in the levels of nonconventional inputs (including land quality).

The following sections describe recent research using each of these approaches, taking advantage of progressive developments in spatially referenced data to derive improved estimates of land quality's effect on agricultural productivity.

Previous production-function analyses

Studies using the production-function approach to compare agricultural productivity across countries date back several decades. Kawagoe et al. (1985) analyzed data from 43 countries for 1960, 1970, and 1980, using five conventional inputs (land, labor, tractors, livestock, and fertilizer) and two education variables to adjust for differences in labor quality. To adjust for differences in land quality, they also experimented with the share of each country's land that was irrigated and the ratio of cropland to pastureland but dropped these variables when they produced coefficients that were negative or insignificant—"probably because the data were too crude to capture the effect of land quality differences" (p. 116). Lau and Yotopoulos (1988) used the same data as Kawagoe, Hayami, and Ruttan, included first differences to account for fixed country-specific effects, and showed that results varied with functional form.

In their study of 18 developing countries, Fulginiti and Perrin (1993) experimented with a measure of potential dry matter production drawn from Buringh et al. (1979) and concluded that it was "a very poor measure of aggregate land quality" (p. 479). (Mundlak et al. (1997) reached a similar conclusion.) By contrast, Fulginiti and Perrin found an alternative land quality index developed by Willis Peterson to be significant and positively associated with agricultural output. Peterson's (unpublished, 1987) land quality index has been used frequently (see also Frisvold and Ingram (1995) and Lusigi and Thirtle (1997)) as an indicator of country-level land quality because it is one of the few such measures available to researchers on a global scale. This index is based on the share of a country's agricultural land that is not irrigated, the share of its cropland that is irrigated, and its longrun average annual precipitation, weighted by coefficients derived from a cross-sectional analysis of land prices in the United States. Concerns about the relevance of such coefficients for international comparisons and recent improvements in the availability of spatially referenced land and climate data have motivated efforts to develop better measures of land quality.

Craig et al. (1997) analyzed 98 countries over six time periods (covering 1961-90), and included as indicators of land quality three variables similar to those underlying the Peterson index: the percentage of each country's agricultural land in annual or permanent crops, the percentage of cropland that is not irrigated, and long-term average rainfall for the country as a whole. They found output per worker to be significantly associated with all three measures of land quality. An additional measure of land quality, agro-ecological zone (based on climate and length of growing period), was not found to be a significant determinant of agricultural productivity.

Most recently, Chan-Kang et al. (1999) extended the Craig et al. analysis for 36 African countries with annual data for 1961-96. To account for differences in land quality, Chan-Kang et al. included among their explanatory variables the share of agricultural land in annual or permanent crops, the share of agricultural land that is irrigated, and an improved GIS-based measure of annual (as opposed to longrun average) rainfall based on a 2.5-degree grid. The first of their three land quality variables was consistently positive and significantly associated with agricultural output per worker; the others became insignificant when cumulative R&D expenditures (also insignificant) were included. Only recently have indicators of the quality of soils been explicitly incorporated in econometric analyses of agricultural productivity.

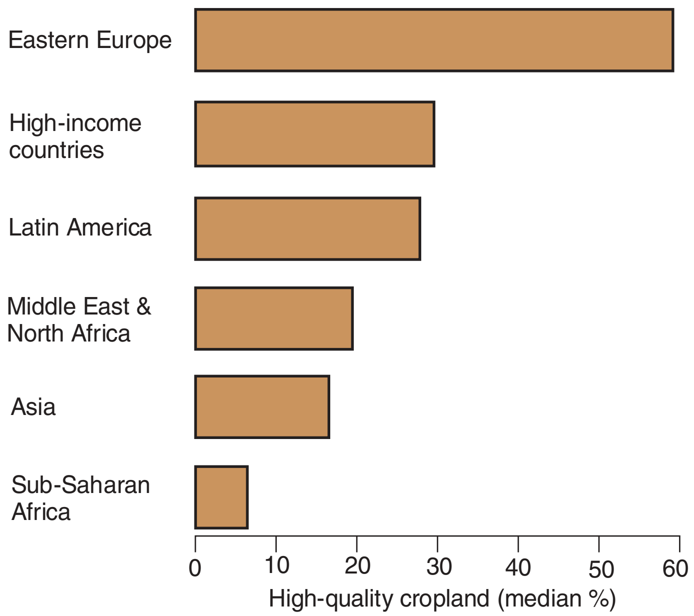
New land quality indicators

Indicators of land quality used in previous studies, such as the percentage of agricultural land that is classified as arable land or permanent cropland and the percentage of arable land or permanent cropland that is not irrigated, are available from the Food and Agriculture Organization of the United Nations (FAO). While frequently used, either directly or indirectly (via the Peterson index), these measures may reflect economic and other influences in addition to purely biophysical quality differences. To better isolate and control for the effects of differences between countries in inherent land quality, recent analyses used spatially referenced soil and climate data in combination with new high-resolution land-cover data to develop a new measure: the share of each country's cropland that is not subject to major soil or climate constraints on agricultural production.

This measure is based on measures of land quality described earlier: FAO's Digital Soil Map of the World and associated soil characteristics (e.g., slope, depth, and salinity), combined by Eswaran et al. with spatially referenced longrun average temperature and precipitation data to establish nine land quality classes distinguished by their suitability for agricultural production (see fig. 2.5). Wiebe et al. (2000) then overlaid these land quality classes with political boundaries and global land-cover data generated from satellite imagery with a resolution of 1 kilometer (U.S. Geological Survey) (fig. 3.2). (Note that earlier and higher resolution land-cover data are available (e.g., from Landsat imagery) but have not been systematically classified at a global scale and/or made publicly available.) They focused on cropland identified according to the International Geosphere-Biosphere Programme land-cover classification scheme—similar to the scheme used in the recent assessment of agro-ecosystems by IFPRI and the World Resources Institute (Wood et al., 2000).

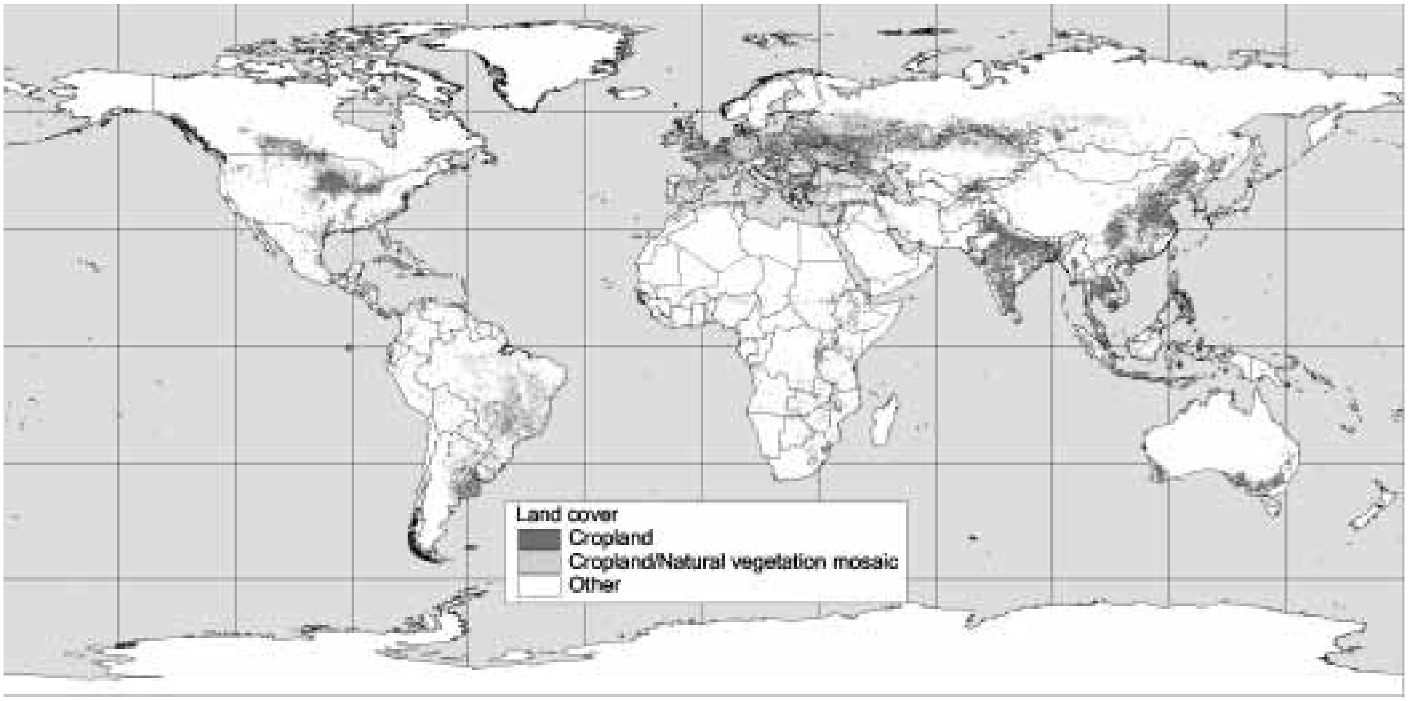
The result is a continuous variable based on the share of each country's cropland that is found in the three best quality classes. This share ranged from 0 (for Niger and 13 other countries) to 0.91 (for Bulgaria). Regional medians are highest in Eastern Europe (nearly 0.6) and lowest in Sub-Saharan Africa (about 0.06) (fig. 3.3). Countries where the share exceeds the median for all 110 countries (0.20) are identified as having good soils and

Figure 3.3—Regional cropland quality



Source: ERS, based on data from the World Soil Resources Office, NRCS, USDA.

Figure 3.2—Global cropland cover



Source: ERS, based on USGS Global Land Cover Characteristics database.

climate; those with less than the median are identified as having poor soils and climate.

This static measure, based on cross-country differences in inherent soil and climate characteristics, supplements existing time-variant quality indicators, such as the percentage of agricultural land that is cropped (or irrigated) and annual rainfall. To better capture this last factor, which is critical to agricultural production on rainfed lands, we also developed a higher resolution measure of annual rainfall by aggregating and overlaying monthly precipitation data on a 0.5-degree grid (Climatic Research Unit, 1998) with national boundaries and cropland as described earlier. The result is a country-specific time-variant measure of rainfall on cropland (fig. 3.4).

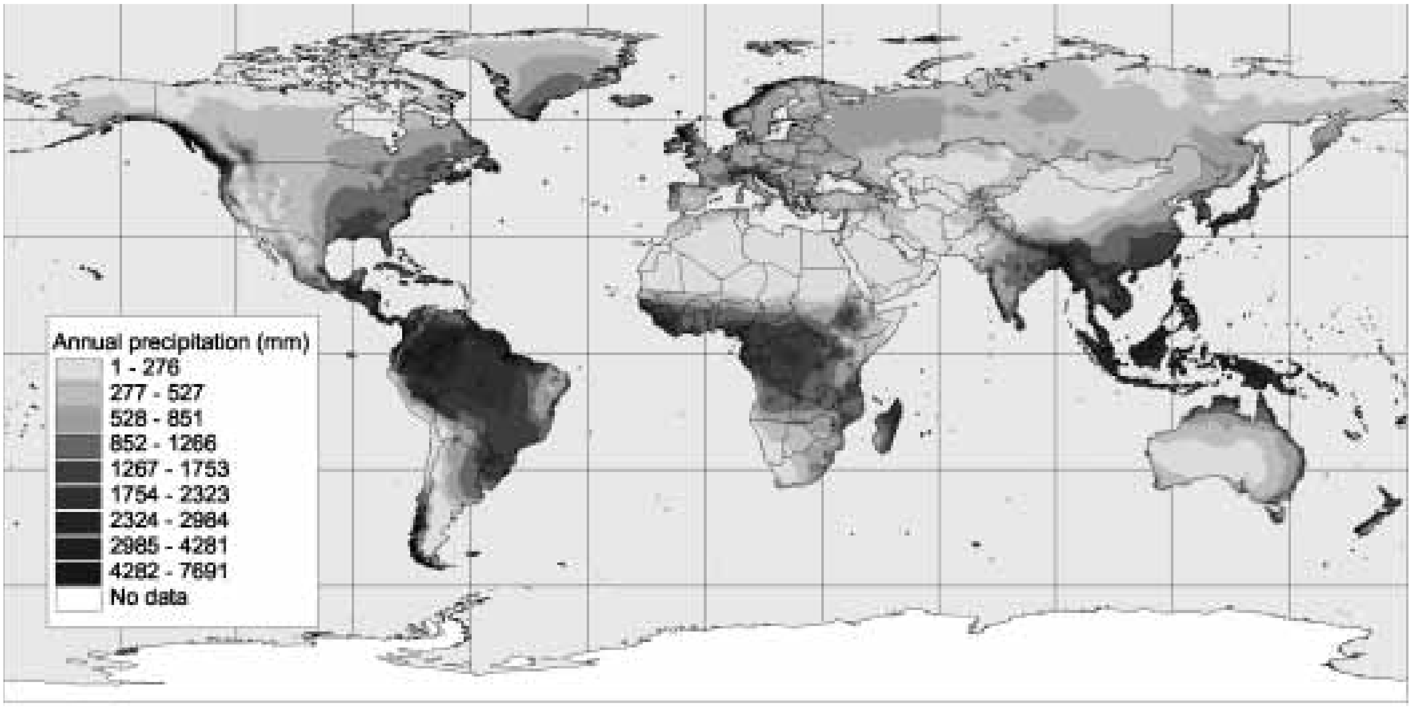
New econometric analyses

Wiebe et al. (2000) combined these new indicators of land quality with information on agricultural output and inputs (land, labor, fertilizer, livestock, and machinery) in an econometric analysis of agricultural productivity in 110 countries over the period 1961-97. (Countries are classified by World Bank (1999) income and geographic criteria, and include high-income countries as well as low- or middle-income countries in Asia, Sub-Saharan Africa, Eastern Europe, Latin America, and the Middle East/North Africa.) Data are taken from published and unpublished sources at FAO. Following earlier studies, Wiebe et al. focused on the productivity of agricultural labor. Based on the FAO data, agricultural labor productivity is thus measured in this study as output per worker, that is, the value of total agricultural production (expressed in international dollars, after deductions for feed and seed) divided by the total economically active population in agriculture.

The most basic of the factors that would be expected to influence agricultural productivity are the other conventional inputs used in previous studies. Land is measured as total agricultural land (i.e., the sum of arable land, permanent cropland, and permanent pasture). Livestock refers to the total number of livestock animals, aggregated by weights used by Hayami and Ruttan. Tractors refers to the total number of tractors used in agriculture. Fertilizer refers to the total quantity of fertilizer consumed in agriculture.

In addition to these conventional inputs and the new land quality indicators described earlier, several other factors are incorporated to control for differences in resource quality. Labor quality (represented by life expectancy

Figure 3.4—Average annual rainfall



Source: ERS, based on data from the Climatic Research Unit, University of East Anglia.

and literacy), infrastructure (road density and expenditures on agricultural research), and two additional measures of land quality (the share of agricultural land that is cropland and the share of cropland that is irrigated) are similar to variables used in previous studies. Finally, to capture the possible impact of differences in institutional quality and stability, building on recent work by Messer et al. (1998) and de Sousa et al. (1999), a new variable measured the occurrence of armed conflict. Using these variables, production functions were estimated for the full set of countries, for each region, and by land quality class within regions—in each case maintaining individual countries as observations (table 3.1).

Among the land quality variables, the coefficient on annual rainfall is significant in all regions and positive in most regions. The percentage of land arable or permanently cropped has a significant and positive effect on labor productivity for each region except Asia, where this percentage is consistently high across countries. Land expansion has historically been associated with increased output per worker in Asia, but growth in the agricultural labor force has not. This suggests that population density is closing the land frontier in Asia, and that further growth in agricultural output per worker will have to come from increased production on lands already cropped. Good soils and climate are associated with a 28-percent increase in output per worker relative to poor soils and climate in Sub-Saharan Africa, a 34-percent increase in Asia, and a 22-percent increase in the high-income countries.[2] In Latin America and the Caribbean, where most countries lie above the global median in terms of land quality, additional analysis indicates that only the best soils and climate are significantly associated with increased output per worker.

Results for the variables representing labor quality, institutional quality, and infrastructure also vary by region. Notably, the significant negative effect of armed conflict in the model for the full set of countries appears to be driven by the effects of conflict in Sub-Saharan Africa. Coefficients on the year dummies for that region (1995 omitted) are also unique in that they are negative and significant only for 1976-93, suggesting that agricultural output per worker had declined from earlier years, everything else being equal. Coefficients on year dummies for the other regions generally indicated level or rising trends in agricultural labor productivity over the entire period.

Table 3.1—Factors affecting agricultural productivity, by region

Variable	Sub-Saharan Africa	Latin America & Caribbean	Asia	High-income countries
Intercept	-3.03***	-0.45	-1.64	-11.65***
Conventional inputs:				
Land	0.17***	0.10***	0.54***	0.12***
Labor	-0.08***	0.00	-0.04***	0.04***
Livestock	0.19***	0.55***	0.43***	0.53***
Tractors	0.03***	0.06***	-0.07***	-0.05***
Fertilizer	-0.01**	0.00	0.21***	0.35***
Land quality:				
Annual rainfall	0.13***	0.10***	0.24***	-0.18***
Percent arable or permanently cropped	0.17***	0.47***	0.01	0.04**
Percent not irrigated	-0.94***	-0.38***	-0.38***	-0.48***
Good soils and climate	0.25***	-0.18***	0.29***	0.20***
Labor quality:				
Life expectancy	0.98***	-0.70***	-0.36	2.09***
Adult illiteracy	0.20***	-0.56***	-0.30***	0.04***
Institutional quality:				
Armed conflict	-0.08**	0.07***	0.04**	-0.04
Infrastructure:				
Road density	0.07***	-0.08***	-0.12***	0.23***
R^2	0.67	0.97	0.97	0.99
Countries	37	16	10	17
Years	1961-95	1961-94	1961-94	1961-95

Note: *** indicates significance at the 1-percent level and ** indicates significance at the 5-percent level.
All models include year dummies.
Source: Wiebe et al. (2000).

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[2] These percentage changes are derived from, but not equivalent to, the coefficients on the dummy variable for good soils and climate in table 3.1.

Estimates of the effect of good soils and climate can be used to shift measured productivity levels up or down to adjust for differences in the quality of an individual country's soils and climate. Because most countries in the high-income group, in Latin America and the Caribbean, and in Eastern Europe and Central Asia lie above the global median in terms of land quality, and most countries in Sub-Saharan Africa lie below the global median, such shifts would narrow the distance between the regional trends depicted in figure 3.1, while leaving their slopes unchanged. (The median for Asia is equivalent to the global median.)

Regional median values for the land quality index were presented in figure 3.3. To further explore the potential impact of land quality differences on the coefficients for other conventional and nonconventional inputs, the countries in each region were divided into two groups. Those with land quality indexes above the relevant regional median were analyzed separately from those with land quality below the regional median. The results reveal important differences by land quality class that are broadly consistent across geographic regions (table 3.2).

In both Sub-Saharan Africa and the high-income countries, for example, the coefficient on land is significant for countries with good soils and climate but not for those with poor soils and climate. This is perhaps not surprising but confirms that agricultural land area per se is a poor indicator of the contribution of land to agricultural production. The coefficients on labor in the two regions suggest constant or weakly increasing returns to scale in countries with good land and decreasing returns to scale in countries with poor land. The corresponding output elasticities with respect to labor are positive except in Sub-Saharan African countries with poor soils and climate. Whereas Frisvold and Ingram (1995) found labor to be the principal source of growth in land productivity for Sub-Saharan Africa as a whole over the period 1973-85, this suggests that subsequent population growth has brought Sub-Saharan African agriculture close to the effective land frontier, at least in countries characterized by poor land and low levels of fertilizer and irrigation.

Fertilizer is positively associated with output per worker in both regions regardless of the quality of soils and climate, although elasticities are larger in countries with poor land. The marginal product of fertilizer is of the same order of magnitude in Sub-Saharan Africa and the high-income countries, although slightly smaller in Sub-Saharan Africa, perhaps due to limits on other inputs, such as water or fertilizer-responsive crop varieties.

Annual rainfall significantly affects productivity for countries with good land in both regions but not for countries with poor land. Coefficients on the share of agricultural land that is arable or permanently cropped are highest in Sub-Saharan African countries with poor land, and significant and positive everywhere except high-income countries with poor land. Labor productivity is sensitive to the share of cropland that is not irrigated in all four cases presented, with the magnitude of the impact being highest in Sub-Saharan African countries with poor land.

Results for other resource quality indicators are mixed. Neither life expectancy nor adult illiteracy are significant in countries with poor land in either region. In Sub-Saharan Africa, coefficients on both indicators are significant with the expected signs in countries with good land. In high-income countries with good land, curiously, illiteracy is positive and significant statistically—but probably not economically, as the range in illiteracy among high-income countries is relatively small. Armed conflict is significant and negatively associated with output per worker in each case, and more strongly so in countries with poor land. (No occurrences were reported in high-income countries with good land.) Road density is positively associated with output per worker in Sub-Saharan African countries that have good land but not in those with poor land. In high-income countries with poor land, road density is negatively associated with labor productivity.

Overall, the results indicate that improved indicators of resource quality contribute significantly to observed international differences in agricultural labor productivity, above and beyond the effect of conventional inputs and resource-quality indicators that were used in earlier studies. Better soils and climate are associated with levels of agricultural output per worker that are 20-30 percent higher in most regions, everything else being equal. Further improvements in the accuracy of estimates are expected from continued refinement and experimentation with alternative spatially derived land quality indicators and with alternative measures of agricultural productivity.

Improved indicators of land quality also enhance our understanding of the effects of other conventional and nonconventional factors on productivity. Results suggest a land quality-related hierarchy of constraints limiting the productivity of agricultural labor. In countries poorly endowed with soils and climate, basic inputs such as fertilizer, water (in the form of irrigation), and institutional stability are more important than in countries that are relatively well endowed with good soils and climate. Factors such as labor quality, road density, and mechanization appear less constraining for poorly endowed countries at present than for countries with better soils and climate. These results are particularly clear in Sub-Saharan Africa but hold true with some variations in high-income countries and other regions as well.

Given that the spatial distribution of good soils and climate favors regions already characterized by higher and faster growing agricultural labor productivity, special effort will be required if regional disparities in productivity are to be prevented from widening over time. On a more positive note, however, these findings also suggest that substantial gains in productivity can be realized in regions with poor soils and climate, both directly and indirectly, from additional investment in the protection and enhancement of resource quality, especially through increased use of fertilizer and irrigation and reduction in armed conflict.

Decisions about inputs (as well as output) are influenced by land quality and other factors, even while input and output levels help determine changes in land quality (Lipper and Osgood, 2001). Recent studies have sought to incorporate such simultaneity in various ways. Lindert (2000) reports on careful analysis of crop production and land degradation in China and Indonesia, in which output and land quality are simultaneously determined, given inputs. Hopkins et al. (2001) use a longrun simulation model to demonstrate the errors that may result when output, inputs, and land quality are not simultaneously determined. More work is needed in this area, but data requirements for a fully simultaneous system are high.

As an intermediate step, Masters and Wiebe (2000) experiment with various simultaneous-equation systems that make labor, fertilizer, and R&D endogenous (along with output). They also add an additional indicator of resource quality (the occurrence of seasonal frost). Seasonal frost is potentially important for productivity from an agronomic perspective because of its beneficial role with respect to soil organic matter (by slowing biotic activity that breaks down organic matter into its mineral components), soil structure (through cycles of freezing and thawing), spring water release (by preserving winter

Table 3.2—Factors affecting agricultural productivity, by region and land quality class

	Sub-Saharan Africa		High-income countries	
Variable	Countries with good soils and climate	Countries with poor soils and climate	Countries with good soils and climate	Countries with poor soils and climate
Intercept	-7.97***	16.36***	-0.56	-0.69
Conventional inputs:				
Land	0.63***	0.17	0.29**	0.11
Labor	0.20*	-0.67***	0.13	-0.26**
Livestock	0.35***	0.28***	0.32***	0.19***
Tractors	0.02**	-0.01	0.22***	0.07***
Fertilizer	+0.00**	0.01***	0.12***	0.17***
Land quality:				
Annual rainfall	0.18***	0.06	0.06**	0.00
Percent arable or permanently cropped	0.16***	0.74***	0.28***	0.11
Percent not irrigated	-0.65***	-3.44***	-0.85***	-0.38***
Good soils and climate (omitted)	--	--	--	--
Labor quality:				
Life expectancy	1.00***	-0.09	-0.06	0.66
Adult illiteracy	-0.35***	0.09	0.22***	-0.07
Institutional quality:				
Armed conflict	-0.05***	-0.18***	--	-0.05**
Infrastructural quality:				
Road density	0.04***	0.00	0.01	-0.12***
R^2	0.97	0.94	0.99	0.99
Countries	19	18	9	8
Years	1961-94	1961-95	1961-95	1961-95

Note: *** indicates significance at the 1-percent level level, ** indicates significance at the 5-percent level, and * indicates significance at the 10-percent level.
All models include country dummies and year dummies.
Source: ERS analysis.

precipitation until the growing season), and by killing or enforcing dormancy on pests, parasites and disease vectors in a regular seasonal cycle. Earlier work sought to control for such effects by using latitude as a proxy, but improvements in data allow construction of a frost index similar to that developed for land quality (i.e., the percentage of a country's land that receives more than 5 days of ground frost each winter, following a frost-free summer).

Results indicate that soils and frost are both significant in determining labor productivity. In a (three-stage least-squares) framework that allows for simultaneous determination of output and selected inputs, the frost-frequency advantage enjoyed by high-income countries raises their agricultural output per hectare an average of 6.5 percent relative to low- and middle-income countries in general, and 8.5 percent relative to Sub-Saharan Africa. The land quality advantage held by high-income-countries raises their agricultural output per hectare an average of 2.7 percent relative to low- and middle-income countries and 5.1 percent relative to Sub-Saharan Africa. These impacts are significant but smaller than those estimated by Wiebe et al. The difference may be due partly to the fact that land quality exerts an indirect effect on productivity through its effect on labor, fertilizer, and R&D expenditures in the Masters and Wiebe analysis. It might also be the case that including both frost frequency and the land quality indicator reduces the effect of the latter indicator because the land quality indicator incorporates characteristics associated with frost (especially long-term average temperature).

In a series of related studies, Sachs (2001) and McArthur and Sachs (2001) argue that biophysical conditions—and not just institutional factors—critically influence productivity and economic development. Their analyses focus on the ways in which biophysical factors affect the economy in general through their effects on transportation costs, health, and labor quality (as well as agricultural productivity).

Total factor productivity analysis

Ball et al. (2001) employ a different approach to productivity analysis. They compare levels and changes in TFP for the United States and nine European countries (Germany, France, Italy, the Netherlands, Belgium, the United Kingdom, Ireland, Denmark, and Greece) for the period 1973-93. They use price and value data to construct indices of aggregated agricultural output, intermediate inputs (goods that are used in production during the calendar year, such as feed and seed), capital, labor, and land.

Land was adjusted for differences in quality by estimating a hedonic econometric model of land prices as a function of inherent soil properties and other variables. Proximity to urban areas was included as an attribute of land hypothesized to be associated with higher returns to agricultural production. Information on 14 soil properties was drawn from the NRCS database described earlier. Continuous moisture deficits, acidity, the absence of major soil constraints to agricultural production, irrigation, and urban proximity were among the most significant of the land quality characteristics tested.

Quality-adjusted land prices were then used to construct the land input index. Results indicate, for example, that the unadjusted price of a hectare of agricultural land in France is 17 times that of a hectare in the United States. Adjusting for quality reduces the difference to 12 times. A lower quality adjusted land price implies a higher land input quantity and, thus, a lower partial productivity for agricultural land (and TFP) in France than would otherwise be the case.

The United States had the highest amount of quality-adjusted land input, roughly 10 times that of the next-highest country in the study (France), and the highest ratio of land to labor. TFP estimates (relative to the United States in 1990) ranged from 1.36 for the Netherlands to 0.68 for Ireland. Eight of the nine European countries (all but Belgium) increased levels of land input relative to the United States over the period 1973-93. The range of TFP levels narrowed over the period, from 0.76-1.70 in 1973 to 0.71-1.39 in 1993. Differences in relative levels of productivity were much smaller than differences in relative output; the authors conclude that differences in levels of output were more closely associated with differences in the quantities of capital, labor, land, and intermediate inputs than with differences in TFP. The authors also determine that quality characteristics are fully "embodied" in the price index used to construct the intermediate input index, but no similar analysis of the success of the land quality adjustment is presented.

Data envelopment analysis

Agricultural productivity can also be investigated through the technical efficiency with which inputs are converted into outputs. Technical efficiency is typically compared across producers (e.g., countries) relative to a common technology frontier that represents maximum technical efficiency. However, differences in productive capacity (e.g., due to land quality) may limit the ability of a producer to achieve technical efficiency relative to this common frontier. A country must take its soils and climate as factors that, at least in the short term, are given and uncontrollable, although they contribute greatly to total agricultural output.

Wiebe et al. econometrically analyzed a land-quality index that measured the share of a country's cropland that was of high quality, and Ball et al. relied primarily on underlying soil characteristics in their analysis of TFP. Malcolm and Soule (2001) recently incorporated a similar measure of land quality, representing the average quality of each country's cropland, in an alternative approach, data envelopment analysis (DEA).

DEA first identifies the set of efficient producers—those who use the lowest level of inputs to produce any given level of output. These producers can be thought of as being located along the production frontier (fig. 1.4). Producers that require higher input levels to produce a given level of output are inefficient relative to this frontier. Given inferior land quality, however, it may be impossible for some producers to reach this frontier. Instead, it may be appropriate to define a separate frontier for producers with poor land quality. By comparing a particular producer's efficiency relative to these two frontiers, it is possible to estimate the contribution of land quality differences to technical inefficiency.

Countries with higher land quality do tend to define the technically efficient frontier for all countries (Malcolm and Soule, forthcoming). In other words, the efficient frontier for countries with lower land quality lies (everywhere) below the efficient frontier for countries with higher land quality (and thus for all countries). This suggests that efficiency and productivity analyses that do not account for differences in land quality will thus overestimate the potential for productivity gains in countries with poor land.

4. Land Degradation and Agricultural Productivity

Agricultural productivity is affected by differences between countries in measures of average land quality (fig. 1.4). Results suggest that agricultural productivity would also be affected by changes in land quality within a given area over time (fig. 1.5). Testing this hypothesis has been difficult, however, because of the scarcity of data—both on changes in land quality over time and on the impacts that those changes have on productivity. In the absence of data on these and other factors affecting productivity, a wide range of estimates have been offered regarding the magnitude of losses in agricultural productivity at various scales.

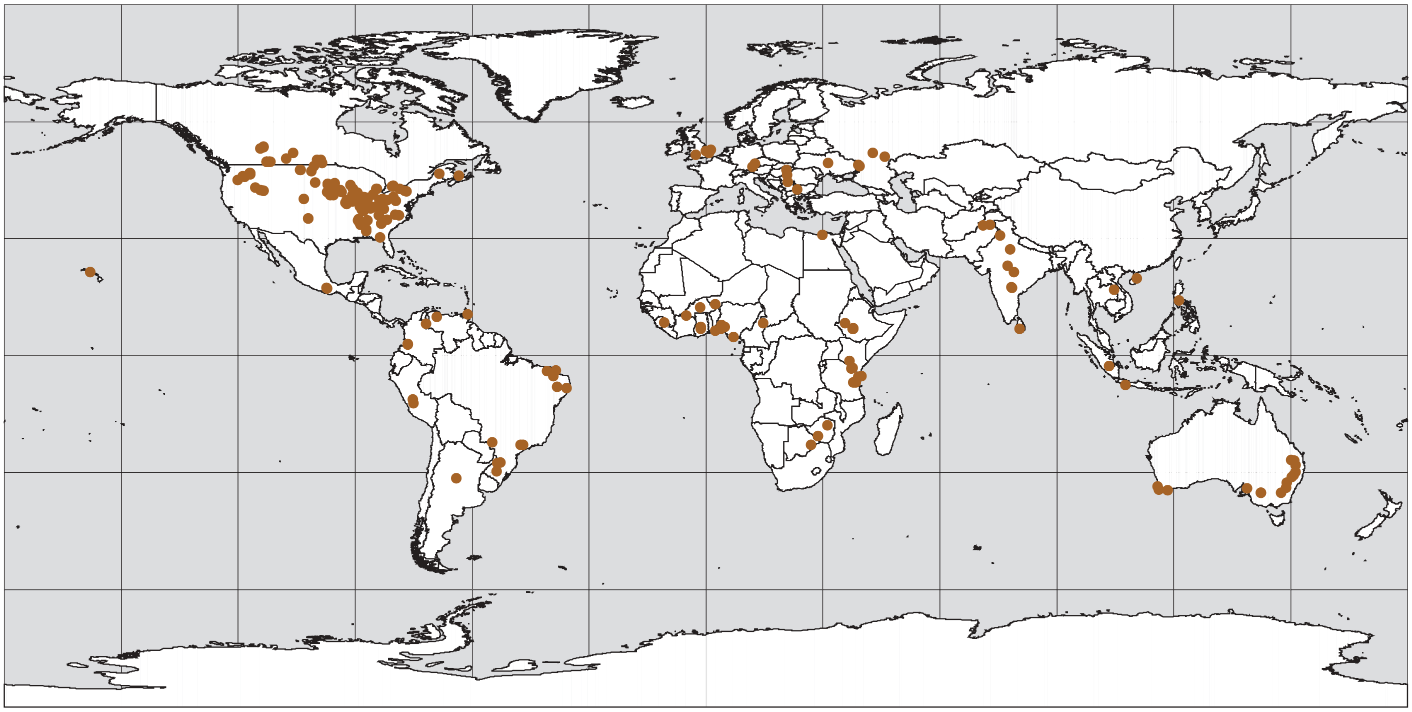
These studies, however, were based on models that were not described by their authors and therefore cannot be evaluated (e.g., Pimentel et al., 1995), data from a single country (e.g., Alt et al., 1989; Crosson, 1986; and Pierce et al., 1983), or inference from global opinion-based assessments of land degradation (e.g., Crosson, 1995a, 1995b). Since erosion and its impacts on productivity are extremely site-specific processes, dependent on environmental characteristics, management practices, and thus economic factors, site-specific data are costly to collect and global data are nonexistent. To overcome at least some of these limitations, den Biggelaar et al. (2001, forthcoming a and b) recently analyzed plot-level data from around the world on potential crop yield losses to soil erosion, using information on soil and climate characteristics to control at least partially for site-specific differences.

Evidence from plot-level studies

An extensive search of online databases and library catalogues identified 179 published plot-level studies from around the world that report changes in crop yields as a result of erosion. These studies contain a total of 328 records, each corresponding to a unique combination of crop, soil, and experimental method. These records represent a total of 38 crops on 9 soil orders in 37 countries (fig. 4.1).

The distribution of published research on soil erosion and crop yields is highly skewed with respect to the

Figure 4.1—Plot-level study sites



Source: ERS, based on data from den Biggelaar et al. (forthcoming a).

scope of agricultural production and land degradation (table 4.1). Of the 328 records identified, 197 (60 percent) represent experiments conducted in North America (the United States or Canada), but only 14 (5 percent) represent experiments conducted in Asia, which contains over a third of the world's cropland and degraded cropland, nearly half of the world's cereal production, and over three-quarters of the world's agricultural labor force. North American shares of each of these indicators are less than one-fifth. Africa and Oceania are well represented in proportional terms, at least at the aggregate level, while Europe and Latin America are under-represented with respect to most of the selected indicators. Even within regions, records tend to be highly concentrated, often in areas that are relatively productive but not necessarily particularly sensitive to erosion.

In the absence of long-term time-series data recording yield changes as erosion actually occurred on study plots, the studies used several generally accepted methods (Lal et al., 1998) to estimate yield effects of topsoil loss associated with erosion. About 35 percent of records compared yields on differentially eroded plots on a given soil. Another 29 percent involved mechanical removal or addition of topsoil, while 22 percent involved measurement of actual topsoil depth. Other studies compared yields across management practices associated with differential rates of erosion (e.g., conservation tillage and contour plowing); these studies are excluded from further consideration to avoid confusing the effects of changing practices with the effects of erosion per se. Records including multiple levels of an input (e.g., fertilizer) within a single management practice are retained, resulting in a total of 484 experiments for the 38 crops.

Crops represented in the plot-level studies include pasture and fodder crops, vegetables, and other high-value crops (such as tea), but the majority involved grains, pulses, and root crops. Den Biggelaar et al. analyzed six crops—maize, wheat, soybeans, sorghum, millet, and potatoes—that together accounted for three-quarters of the experiments conducted.

Mean yields and yield losses per ton of soil erosion were calculated across soils for each crop and region (table 4.2). Note that yield losses may accelerate, remain constant, or decelerate as soil erodes, depending on soil type and other factors (as in the hypothetical relationship depicted earlier in figure 1.4). Evidence suggests that accelerating losses are characteristic of many temperate soils, while decelerating losses are characteristic of many tropical soils (Lal, 1998a). Recognizing that yield losses cannot accelerate or remain constant indefinitely, and lacking sufficient data to estimate precise functional forms for each crop, soil, and region, a constant percentage change in yields is assumed, corresponding to the case where absolute yield losses decelerate as soil erodes. While this would certainly be an oversimplification over the long term, it should not introduce unreasonable bias for incremental losses of soil and yields over the shorter term.

In most cases, mean yield losses range between 0.01 percent and 0.04 percent per ton of soil loss. Percentage declines are generally lowest in North America and Europe, due in part to the fact that most experiments in those two regions were conducted on alfisols and mollisols, which are relatively abundant in temperate regions.[3] (Losses tended to be higher on oxisols, ultisols, and vertisols, which are relatively abundant in other regions, and where many studies in the other regions were done.) Lower percentage losses in North America and Europe are also due in part to higher mean yields in those regions due to higher levels of inputs (such as fertilizer). In one case (potatoes in North America), percentage losses were substantially greater, and in another case (soybeans in Asia), the mean yield on eroded plots was actually higher than the mean yield on uneroded plots. Two of the three North American potato experiments reported soil losses in tons rather than centimeters, as in the experiments for other crops and regions; it is possible that these yield loss estimates are biased due to different assumptions regarding soil bulk density. (We assumed a bulk density of 1.5 tons per cubic meter for all soils and regions.) A single experiment drove the average increase in Asian soybean yields; if data from that experiment were excluded, average yields for Asian soybeans would have declined 0.01 percent per ton of soil erosion.

Boardman (1998) cautions against uncritical extrapolation from plot-level data, describing the example of studies reporting a European-average erosion rate based ulti-

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[3] **Alfisols** are soils with neutral pH and high in bases that form under forest or savanna vegetation in climates with seasonal moisture deficits, and predominate in the corn-growing areas of North America and northern Europe (Soil Conservation Society of America, 1982; Soil Survey Staff, 1998; Lal, 2003). **Oxisols** are highly weathered and leached mineral soils with low pH and low base concentration that predominate in the humid tropics of South America and Central Africa. **Ultisols** are less weathered than oxisols, but with low pH and low base concentration such that permanent cultivation is not possible without fertilization, and predominate in the southeastern United States and Southeast Asia. **Mollisols** are soils characterized by decomposition and accumulation of large amounts of organic matter, and predominate in the wheat-growing areas of North America, the former Soviet Union, and temperate South America. **Vertisols** are dark, nutrient-poor soils of the semiarid and arid regions of the tropics and subtropics; they have a high clay content and swell when wet and crack when dry, and predominate in parts of South Asia and the Sudan.

mately on data from 12 small test plots outside Brussels. The studies described by Boardman overlook the site-specific variation in characteristics of the sample (test plots) relative to the population (of all cropland in Europe). Yet limited data on site-specific characteristics are precisely what make careful extrapolation so difficult. The present analysis runs similar risks, not only in terms of extrapolating from plot-level data on yield losses per unit of soil loss (as described earlier) but also in generating the estimated erosion rates that are necessary

Table 4.1—Geographic distribution of plot-level studies relative to selected agricultural indicators

Region	Plot-level studies	Cropland (1999)	Degraded cropland (1990)	Agricultural population (1999)	Cereal production (2000)
	# of records	*Million hectares*	*Million hectares*	*Million people*	*Million tons*
World	328	1,491	562	2,575	2,049
Africa	52	202	121	431	112
Asia	14	544	206	1,957	987
Europe	17	308	72	65	384
Latin America	28	156	92	110	139
North America	197	225	63	7	395
Oceania	20	53	8	6	31
			% of world total		
Africa	16	14	22	17	5
Asia	4	36	37	76	48
Europe	5	21	13	3	19
Latin America	9	10	16	4	7
North America	60	15	11	<1	19
Oceania	6	4	1	<1	2

Note: "Degraded" refers to cropland that is classified in the GLASOD survey (Oldeman et al., 1991) as lightly, moderately, strongly, or extremely degraded due to biological, chemical, and physical degradation. Erosion accounts for 84 percent of total degraded area, and water-induced erosion accounts for 67 percent of total erosion in the GLASOD survey.
Sources: FAOSTAT (11Jul2001), Scherr (1999), den Biggelaar et al. (forthcoming a).

Table 4.2—Mean loss in annual yield per ton of soil erosion

Region	Crop	Experiments	Mean yield	Mean yield loss per ton of soil erosion	
		Number	*Tons per hectare*	*Kg per hectare*	*% of mean yield*
Africa	Maize	42	2.6	0.9	0.03
Asia	Maize	4	1.7	0.7	0.04
	Millet	2	0.3	0.1	0.03
	Soybeans	4	0.9	-0.5	-0.01
	Wheat	4	3.0	0.7	0.02
Australia	Potatoes	2	54.1	3.6	0.01
	Wheat	16	1.2	0.5	0.04
Europe	Millet	2	0.3	0.1	0.02
	Potatoes	2	11.4	0.6	0.00
	Soybeans	1	0.6	0.1	0.02
	Wheat	8	3.5	0.2	0.00
Latin America	Maize	15	2.9	1.4	0.05
	Potatoes	1	20.2	0.7	0.00
	Soybeans	4	2.1	0.6	0.03
	Wheat	1	2.1	0.4	0.02
North America	Maize	131	6.2	0.6	0.01
	Potatoes	3	30.5	127.0	0.42
	Sorghum	17	4.2	0.1	0.00
	Soybeans	43	2.1	0.3	0.01
	Wheat	64	2.6	0.4	0.01

Note: Some studies report multiple experiments.
Source: den Biggelaar et al. (forthcoming a).

to estimate annual yield losses (as described in the following sections). Recognizing these risks, this analysis attempts to control at least partially for such variation by incorporating spatial data on soil and climate characteristics and crop production areas.

Extrapolation using GIS data on land cover and erosion vulnerability

Estimating annual erosion-induced yield losses requires information on the rate at which soil is being lost to erosion. Such information is scarce, because accurate data are limited to a very few locations where long-term experiments have been conducted. Wider inference from more broadly available measures (such as soil type and climate patterns) is limited by the dependence of erosion on highly location-specific factors, such as slope, vegetative cover, precipitation intensity, and land management practices. Despite these limitations, broad inferences provide an approximation of the erosion rates needed to translate relative yield losses per ton of soil loss to annual yield losses due to erosion.

To estimate erosion rates by crop, soil order, and region, den Biggelaar et al. began with the digital map of soil orders compiled by Eswaran et al. (1997) based originally on FAO's Digital Soil Map of the World. Combining associated information on inherent soil properties (including soil depth and soil moisture regimes) with climate data, Eswaran et al. (2001) constructed a spatially referenced scale of vulnerability to water-induced erosion. (Note that water erosion accounts for 67 percent of GLASOD's global eroded area, and 56 percent of the 1997 NRI's estimate of soil erosion in the United States—with wind erosion accounting for the remainder.) Each of the five classes of this scale (depositional, low, medium, high, and very high) corresponds to a range of predicted annual erosion rates, with midpoints of 0.0, 9.3, 14.3, 17.2, and 25.8 tons per hectare, respectively.

To link these erosion rates with yield losses by crop, it was necessary to estimate spatially referenced crop production areas. (Actual crop production areas are reported annually at the national level by FAO, but these are not spatially referenced or identified with respect to soil type.) Potential crop production areas were identified for each crop based on crop-growth requirements and spatially referenced data on climate and soil characteristics.

Estimated erosion rates were then overlaid with soil orders and potential crop production areas to generate weighted-average annual erosion rate estimates for each crop area, soil order, and region (table 4.3). Estimated erosion rates vary widely by crop production area, soil,

Table 4.3—Estimated potential erosion rates by region, crop, and soil order

Region	Crop	Alfisols	Inceptisols	Mollisols	Ultisols	Mean
		Tons per hectare per year				
Africa	Maize	14.1	18.8	16.6	12.0	13.7
Asia	Maize	12.6	18.9	13.7	15.1	15.1
	Millet	14.1	11.4	17.2	14.5	14.5
	Soybeans	12.2	13.5	12.5	16.8	14.9
	Wheat	11.0	18.4	13.3	15.3	14.3
Australia	Potatoes	12.1	22.4	15.6	7.0	12.5
	Wheat	12.3	22.6	15.7	14.0	15.1
Europe	Potatoes	10.7	18.1	10.6	0.7	8.9
	Millet	13.6	11.0	14.3	12.1	10.8
	Soybeans	12.3	10.6	12.0	16.7	11.5
	Wheat	5.4	19.2	10.6	8.1	9.1
Latin America	Maize	14.4	19.2	14.3	13.1	14.0
	Potatoes	10.3	19.9	14.5	14.3	12.4
	Soybeans	14.4	14.1	14.4	15.7	13.8
	Wheat	11.0	21.3	14.3	15.4	13.2
North America	Maize	11.4	24.0	13.9	16.7	15.0
	Potatoes	11.1	11.6	13.3	15.0	8.7
	Sorghum	13.5	14.0	12.9	14.3	13.1
	Soybeans	10.7	14.5	14.5	16.8	14.3
	Wheat	10.7	14.3	13.2	15.0	12.1

Note: Mean erosion rates are calculated across all soil orders, including those not reported here.
Source: Eswaran et al. (various).

and region but range in most cases between 12 and 15 tons per hectare per year (corresponding to approximately 0.8-1.0 mm per year). Estimates tend to be highest on inceptisols, in some cases above 20 tons per hectare per year, because these soils are highly susceptible to erosion, particularly in sloping areas with intense rainfall and low water-infiltration capacity. Estimated rates for North America are typically higher than the average rate reported in the 1997 NRI for all U.S. cropland (10.3 metric tons per hectare), perhaps because the NRI seeks to account (however imperfectly) for the management practices actually chosen by farmers.

Annual losses in yields and production

Annual yield loss rates are estimated by multiplying the percentage yield loss per ton of soil loss (for each crop and region, averaged across soil types) by the estimated annual erosion rate for each crop, soil order, and region. These loss rates are then combined with estimates of total production to generate estimates of total production lost to water-induced erosion.[4]

Not surprisingly, given variation in relative yield losses per ton of soil loss and variation in estimated erosion rates, annual yield losses vary widely (table 4.4). Maize yield losses range from an average of 0.15 percent per year in North America (due to a combination of low relative yield losses and moderate erosion rates in major production areas) to 0.94 percent per year in Latin America (due to higher relative yield losses and higher erosion rates in many areas). Yield losses are generally lower for sorghum and millet, ranging from 0.06 percent for sorghum in North America (where percentage yield losses are near zero on all soils) to 0.51 percent for millet in Asia. Annual wheat yield losses are below 0.30 percent, except in Australia, where they average 0.67 percent.

Annual potato yield losses were 0.01 percent in Latin America and 0.12 percent in Australia, driven in each case by low relative yield losses. Mean relative yield losses from the three records in North America are much higher, generating annual yield loss estimates of 3.98 percent despite moderate erosion rates. Average soybean yields increased with erosion in Asia, driven by the results of a single study on vertisols; soybean yield losses elsewhere are relatively uniform, averaging between 0.22 and 0.33 percent annually.

To summarize erosion-induced yield losses across crops at regional and global levels, losses are weighted by total production levels (FAO, 2000) and 2000/01 commodity prices (USDA, 2001). (Prices per ton were $72.83 for maize, $72.75 for millet, $180.04 for soybeans, $93.96 for wheat, $129.00 for potatoes, and $64.96 for sorghum.) Results are presented as regional subtotals in table 4.4. Average annual losses in the value of production of the crops studied are lowest in Europe, at 0.04 percent, where higher loss rates in millet and soybeans are offset by lower rates on more economically important potatoes and wheat. Average annual loss rates are highest in Australia (0.61 percent) due to high relative yield losses in wheat. Losses in Africa, Latin America, and North America range from 0.45 to 0.49 percent per year. (North American losses would fall to 0.17 percent if potatoes were excluded.) Losses in Asia average 0.24 percent per year, with higher loss rates for maize and millet offset by smaller losses for wheat and gains for soybeans.

Finally, aggregating across regions for each commodity generates estimated annual losses in the global value of crop production that range from 0.06 percent for sorghum and 0.08 percent for soybeans to 0.60 percent for potatoes. Intermediate loss rates are found for wheat (0.20 percent), maize (0.42 percent) and millet (0.48 percent). Aggregating across regions and crops generates a global average annual erosion-induced loss of 0.30 percent in the value of crop production.[5]

Lessons from plot-level studies

These results need to be interpreted with caution. First, estimates of erosion and yield response are highly sensitive to site-specific environmental and economic characteristics, which are not fully addressed by the spatial

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[4] Total production was derived by multiplying estimated crop production areas by estimated yields for each crop, soil order, and region. Estimated potential production areas exceeded actual production areas reported by FAO for 1998-2000 for each crop and continent (FAO, 2000), because they were based only on biophysical potential, regardless of economic criteria, and many areas are capable of growing a variety of crops. Potential production areas were scaled to actual totals by overlaying them with 1-kilometer-resolution satellite data (USGS, 2000) on the location of cropland and then scaling them up or down to match harvested areas reported by FAO. In most regions and for most crops, production is concentrated on alfisols, mollisols, ultisols, and inceptisols, which represent an estimated 86 percent of the total acreage reported by FAO for these crops. Estimated crop yields were similarly scaled to FAO-reported yields for each crop and region.

[5] Estimated annual losses are based on the sum of regional production totals calculated from our estimates of production areas and yields, and represent 23 percent, 49 percent, 60 percent, 89 percent, 97 percent, and 100 percent of the average annual world production reported by FAO for 1998-2000 for sorghum, millet, potatoes, maize, wheat, and soybeans, respectively (FAO, 2000). The remaining shares of those crops are produced in regions that were excluded from our estimates because we found no erosion-productivity studies for those crops in those particular regions.

controls in the present research. Second, these estimates are indicative of the *potential* scale of yield losses to erosion; actual losses will be smaller to the extent that farmers mitigate the impacts of erosion through changes in input levels and/or management practices. In terms of figure 1.5, potential losses correspond conceptually to the difference in yields over time between case (a) and case (d), while actual losses are represented by the difference between case (a) and whichever degradation rate is actually chosen or accepted by farmers. (This issue will be explored in the next section.) Third, these estimates represent impacts only for the selected crops in regions where relevant plot-level studies were found. If proportionate impacts were assumed to occur on the selected crops in other regions, the estimated total value of losses for these crops would rise from $439 million to more than $500 million. Furthermore, the six selected crops represent only a fraction of the total value of global crop production; if impacts on other crops occur in proportion to their value, estimated losses would rise about fourfold, to $2 billion. Fourth, these estimates represent impacts only of water-induced erosion; NRI and GLASOD data on the relative extent of wind erosion suggest that adjusting for similar impacts from wind-

Table 4.4—Estimated value of potential annual erosion-induced production losses by crop and continent

Region	Crop	Total production[1]	Production loss	Value of total production[2]	Value of production loss[2]	Production loss
		Thousand tons per year		*Million $ per year*		*% per year*
Africa	Maize	41,198	202	3,000	15	0.49
	Subtotal	--	--	3,000	15	0.49
Asia	Maize	162,289	961	11,820	70	0.59
	Millet	12,693	64	923	5	0.51
	Soybeans	23,493	-254	4,230	-46	-1.08
	Wheat	254,338	740	23,898	69	0.29
	Subtotal	--	--	40,870	98	0.24
Australia	Potatoes	1,872	2	241	<1	0.12
	Wheat	22,739	152	2,137	14	0.67
	Subtotal	--	--	2,378	15	0.61
Europe	Millet	1,060	2	77	<1	0.23
	Potatoes	136,832	51	17,651	7	0.04
	Soybeans	2,3134	5	417	1	0.22
	Wheat	181,517	74	17,055	7	0.04
	Subtotal	--	--	35,200	15	0.04
Latin America	Maize	74,608	704	5,434	51	0.94
	Potatoes	16,281	2	2,100	<1	0.01
	Soybeans	55,426	184	9,979	33	0.33
	Wheat	21,720	58	2,041	5	0.27
	Subtotal	--	--	19,554	90	0.46
North America	Maize	259,122	399	18,872	29	0.15
	Potatoes	25,903	1,031	3,341	133	3.98
	Sorghum	13,811	8	897	1	0.06
	Soybeans	77,879	191	14,021	34	0.24
	Wheat	90,360	96	8,490	9	0.11
	Subtotal	--	--	45,622	206	0.45
Total[3]	Maize	537,217	2,266	39,126	165	0.42
	Potatoes	180,888	1,086	23,335	140	0.60
	Millet	13,752	67	1,000	5	0.48
	Sorghum	13,811	8	897	1	0.06
	Soybeans	159,110	126	28,646	23	0.08
	Wheat	570,675	1,120	53,621	105	0.20
	Total	--	--	146,625	439	0.30

[1] Production data from FAO (2000).

[2] Prices based on projected 2000/01 crop prices from USDA (2001).

[3] Totals fall short of global total production of these crops because they exclude crop-region combinations for which no plot-level studies were found (e.g., wheat in Africa).

Source: den Biggelaar et al. (forthcoming b).

induced erosion would raise estimated losses by an additional 50 percent, to $3 billion, and still further for other forms of soil degradation. (This figure represents about 0.4 percent of the total value of global crop production in the mid-1990s (Wood et al., 2000).) Fifth, these estimates exclude offsite impacts of soil erosion, both on productivity (e.g., via deposition of fertile sediments downstream or via wider economic impacts on income, growth, and food security) and on environmental quality. Evidence suggests that these impacts may be substantially larger than onsite effects.

Cautions notwithstanding, these results have important implications for the ongoing debate on erosion and its impacts on productivity. First, they are consistent with the lower range of previous estimates, similar in percentage terms to that of Crosson, and much lower in both relative and absolute terms than the Pimentel et al. figure ($27 billion per year for the United States alone). This does not mean that erosion-induced yield losses are unimportant—just that they have historically been masked by growth in yields (which has averaged over 2 percent per year in recent decades for the world as a whole) due to improvements in technology and increases in input use. Such increases may become more difficult to sustain in the future, with projections that yield growth will slow to about 1 percent per year over the next few decades.

Second, these results indicate areas where high erosion rates and/or high relative yield losses per ton of soil loss generate potential annual yield losses well in excess of global or regional averages. Of special concern is the wide disparity in experimental research relative to the potential severity of erosion impacts, particularly the scarcity of studies in developing regions where yields are especially sensitive to erosion and farmers are especially sensitive to losses in income. (Information on farmer responses to erosion and other forms of degradation is also relatively scarce in developing regions.) Erosion impact studies are relatively scarce for all crops in Asia and for crops other than maize in Africa and Latin America. For maize, yield losses (in percentage terms) are three to five times as high in the developing regions as they are in North America.

Third, these results suggest the importance of additional spatially referenced research on erosion, yield impacts, and, especially, farmer responses, to better understand how potential impacts on yields may translate into actual impacts on agricultural productivity.

Finally, these results indicate that, at least at global and regional scales, potential yield losses are generally small enough that private incentives to reduce erosion may be weak. This strengthens the case for policy measures to address erosion's other (and perhaps more significant) effects: offsite impacts, both economic and in terms of sedimentation's effect on water quality, flooding, irrigation costs, and environmental quality.

As noted, these are potential impacts assuming no changes in other inputs, but we know that farmers will in general have an incentive to respond in ways that reduce or avoid such impacts. In fact, Crosson suggests the small actual productivity losses he estimates indicate that private incentives are strong enough to mitigate potential losses that could conceivably be somewhat larger. Private incentives are indeed critical to actual outcomes. But private incentives are sensitive to economic factors as well as biophysical conditions, and data on economic factors are as scarce as data on biophysical conditions. We examine private incentives next.

5. Farmer Responses to Land Degradation

Our analysis of erosion-induced crop yield losses in the absence of farmer response provided an example of the underlying biophysical relationship between levels of (or changes in) productivity and levels of (or changes in) land quality, given a particular practice and fixed input levels. Such analyses help determine the potential impact of differences or changes in land quality if production practices and input levels remain fixed. But practices and input levels are not, in general, fixed across producers or over time. Actual interactions between land quality and productivity are shaped by technical, physical, and biological processes, many of which are complex, highly interdependent, and dynamic. Impacts of land degradation also depend critically on farmers' choices, which change over time in response to (and in anticipation of) changing economic and environmental conditions.

Farmers' incentives and choices

A variety of activities may be considered conservation practices because they maintain or improve soil fertility or reduce soil erosion and runoff of nutrients and pesticides. These activities include residue management practices (e.g., conservation tillage), soil-conserving crop rotations, nutrient and pest management practices, and land improvements (e.g., installation of grassed waterways). These practices differ from one another and from conventional management practices in the expected magnitude and timing of their costs and returns to the farmer. Some practices, such as conservation tillage, may be profitable in the short term due to reduced labor and machinery costs (Rahm and Huffman, 1984). Others may become profitable only over the medium term (e.g., contour farming, stripcropping, and grassed waterways) or the long term (e.g., terracing) as they control erosion and maintain or enhance soil fertility and thus improve productivity and land values.[6] Because of the relative availability and quality of appropriate data, the United States offers a useful case in which to examine farmers' choices regarding conservation practices.

Soil fertility management and erosion control in a dynamic context

To understand farmers' decisions about practices that affect land quality and productivity, it is necessary to take a longrun perspective. One such approach is to examine farmers' choices using a dynamic economic analysis. For simplicity, some previous simulation studies of degradation and productivity assumed that current practices continued into the future and generated a range of estimated erosion-induced productivity losses. Pierce et al. (1984) estimated productivity losses of 1.8-7.8 percent over 100 years, while Alt et al. (1989) estimated losses of 3.5 percent over 100 years. Improved models (e.g., Burt, 1981 and Van Kooten et al., 1990) allow for both farmer response to resource conditions and resource-quality change in response to management practices in a single-dimension (topsoil depth) framework.

Hopkins et al. (2001) extend Burt and Van Kooten et al. in several ways. First, they allow farmers to consider economic incentives under all resource states, rather than just the steady state. They also analyze a two-dimensional definition of soil degradation rather than just a single dimension—thereby incorporating both irreversible soil erosion and reversible nutrient depletion. Finally, they determine how optimal levels of two practices—fertilizer application and residue management—vary with the two dimensions of soil degradation.

The Hopkins et al. model chooses levels of fertilizer application (F) and residue management (R) to maximize the expected present value of net returns over time from corn production, recognizing that yields (Y), soil nutrient condition (N), and topsoil depth (D) are determined jointly. Yields are determined jointly in any period by the interaction of fertilizer, soil nutrient condition, and topsoil depth, based on specifications derived from earlier research (Johnson and Shepherd 1978; Schumacher et al., 1994). Soil nutrient stocks may be built up or drawn down relative to initial levels (at least for potassium and phosphorus), depending on removal in harvested crops, fertilizer application, and changes in topsoil depth. Topsoil depth in any given period depends on soil depth in the previous period and on the level of residue management (in conjunction with the inherent erosion potential of the soil based on physical soil properties, landscape position, and climate condition). Costs of residue management are assumed to increase exponentially in

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[6] Some practices, such as grassed waterways, may not directly prevent erosion from occurring on the cultivated portion of a field, but by slowing runoff and preventing the formation of gullies near waterways, they still help sustain productivity onsite.

residue levels, to represent the additional complexity of management required, based on data from Rausch and Sohngen (1997). The farmer's problem is thus to plan the optimal path of fertilizer application levels and residue management levels (for each period t, present and future) given that

$$\begin{aligned} Y_t &= f(F_t, N_t, D_t) \\ N_t+1 &= g(N_t, F_t, Y_t, D_{t+1}, D_t) \\ D_t+1 &= h(D_t, R_{t+1}) \end{aligned}$$

By planning an optimal management path, the farmer is, in effect, choosing the optimal path of soil degradation over time. Optimal choices of fertilizers and residue management vary with initial levels of soil depth and soil nutrients and change at different rates with changes in these variables. These optimal choices vary with soil depth and nutrients, depending on soil type and other characteristics. For some soils and soil properties, for example, yields will decline at an accelerating rate with reductions in topsoil depth. On other soils, yields will change at a constant or decelerating rate. (Alternatively, as depicted in figure 1.4, each of these three patterns may be exhibited at different levels of erosion on a single soil type.) These differences in soil quality imply differences in optimal choices.

Hopkins et al. apply this method to data on nine soils from the north-central United States, drawn from Schumacher et al. (1994). Some of the nine soils exhibit yield losses that accelerate as soil erodes (characteristic of the upper part of the production function in figure 1.4). Other soils exhibit constant yield losses as soil erodes. A final group of soils exhibit yield responses that decelerate with erosion (characteristic of the lower part of the production function in figure 1.4).

Characteristics of the nine soils are presented in table 5.1, along with the optimal residue management levels and annual costs of soil degradation estimated for each soil. In general, differences in optimal management across soils exceed differences in optimal management over time. Optimal levels of residue management vary by only a few percentage points across soil depth within any one soil, for example, but vary by a factor of two or more across soils. A similar pattern is associated with optimal soil nutrient levels. It is also the case that decisions regarding optimal fertilizer application and residue management are more sensitive to soil nutrient levels than to topsoil depth.

Table 5.1 also shows the annual loss in the asset value of the soil by farmers who make optimal choices about management practices. An incremental inch of topsoil loss can be costly, particularly for the last inch of topsoil lost within the profile. (Note that this does not represent the last inch of topsoil on the field but rather the last inch lost in the experiments conducted by Schumacher et al. (1994).) Because these soils typically erode at rates well below an inch per year (even under minimal residue conditions), however, annual losses are less than a dollar per acre per year for most soils. Relative to cropland values,

Table 5.1—Benchmark soils in the north-central United States

Soil	State	Soil loss	Yield loss	Optimal residue management			Annual cost of soil degradation			
				First inch	Middle inch	Last inch	First inch	Middle inch	Last inch	Last inch
		Inch/year	*Percent*	*Percent*			*$/acre*			*Percent*
Accelerating yield losses:										
Beadle	SD	0.09	11	18	19	21	0.12	0.27	0.49	0.10
Grantsburg	IL	0.12	16	20	22	25	0.12	0.36	0.78	0.03
Marlette	MI	0.05	25	17	17	19	0.22	0.75	2.34	0.14
Rozetta	IL	0.35	6	31	33	35	0.68	1.27	2.15	0.09
Constant yield losses:										
Clarence	IL	0.30	32	38	38	38	3.88	3.87	3.85	0.16
Ves	MN	0.12	11	19	19	19	0.10	0.10	0.10	0.01
Decelerating yield losses:										
Dubuque	WI	0.46	7	31	31	29	0.48	0.50	0.10	0.01
Egan	SD	0.12	5	19	24	20	0.11	0.79	0.13	0.03
Sharpsburg	NE	0.01	4	27	27	27	0.01	0.01	0.01	0.00

Notes: Soil loss was estimated by Schumacher et al. (1994) using an EPIC simulation under zero residue. Yield loss is the cumulative loss associated with a change to a severely eroded condition (more than 75 percent loss of the "A" soil horizon) from a slightly eroded (less than 25 percent) or moderately eroded (25-75 percent) condition. Cropland values in 1999 were $491 per acre in South Dakota, $2,370 in Illinois, $1,300 in Wisconsin, $1,670 in Michigan, $1,080 in Nebraska, and $1,280 in Minnesota.
Sources: Schumacher et al. (1994), Hopkins et al. (2001), NASS (2001).

these dollar losses correspond to percentage losses ranging from 0.00 percent per year (for the Sharpsburg soil in Nebraska) to 0.16 percent per year (for the Clarence soil in Illinois) for the last inch of soil eroded (final column). Percentage losses for first and middle inches of soil would be correspondingly lower for the soils characterized by accelerating yield losses and higher for some of the soils characterized by decelerating yield losses. In terms of figure 1.5, these losses correspond to the difference between case (a) and the optimal level of degradation chosen by farmers.

For comparison, figures 5.1, 5.2, and 5.3 depict optimal residue management, fertilizer application, and land values for stylized examples that exhibit each of the three basic yield regimes considered (that exhibit accelerating, constant, and decelerating erosion-induced yield losses, respectively), assuming a hypothetical 20-percent yield loss associated with a change from a slightly or moderately eroded condition to a severely eroded one. The three stylized cases help depict how optimal practices and outcomes vary with soil type (and thus yield regime) and soil condition (i.e., soil depth and soil nutrient status).

Figure 5.1 depicts optimal levels of residue management as they vary with soil depth and soil nutrients for the three stylized soil types. In each case, optimal residue levels increase (at a decreasing rate) with soil nutrient levels but vary only slightly with soil depth, indicating that the benefits of residue management derive primarily from protecting soil nutrient stocks rather than slowing the rate of soil loss.

Optimal fertilizer application levels for the three cases are depicted in figure 5.2. In each case, it is optimal to apply fertilizer at relatively high rates to build up nutrient stocks when they are low and to apply no fertilizer and draw nutrient levels down when they are high. The optimal fertilizer surfaces are linear in the soil nutrient dimension because fertilizer is freely substitutable for soil nutrients.

Under optimal management practices, the three cases generate land values that vary with initial soil properties as depicted in figure 5.3. (The surfaces represent returns less the cost of practices that vary with soil depth and nutrient status, rather than land values per se.) The shapes of the surfaces reflect the shape of the underlying relationships between yields and soil properties. In each case, optimal values rise at a constant rate with respect to soil nutrient levels. By contrast, as soil depth falls, optimal values fall at increasing, constant, or decreasing rates, depending on the soil type.

Figure 1.6 showed hypothetical net returns to alternative practices. The farmer's choice of optimal practice or the optimal level of multiple practices, such as fertilizer application and residue management, depends on the farmer's time horizon. Suboptimal choices will reduce net returns to the farmer. Using the dynamic model in this section, it is possible to estimate the gains from optimal behavior (i.e., the magnitude of optimal productivity losses relative to those estimated with suboptimal/short-sighted response, or with no response to changing resource conditions over time). Figure 5.4 depicts streams of returns (net of the costs of fertilizer and residue management) to three alternative strategies for corn production on the Rozetta soil in Illinois over 50 years.

The first strategy simply applies fertilizer to maximize current-year returns but does not update these practices over time in response to changing conditions; returns (net of fertilizer and residue management costs) start at about $340 per acre, fall sharply to about $260 per acre as soil nutrients are depleted, and then decline more gradually after a new soil-nutrient steady state is reached with returns about 30 percent below initial levels. The second strategy does update fertilizer applications so as to optimize soil nutrients over time; initial returns are slightly lower than in the first strategy, reflecting higher fertilizer application, but decline only gradually to about $280 per acre (8 percent below initial levels) after 50 years. The third strategy manages both soil nutrients and soil depth optimally; returns decline by 5 percent to $300 per acre after 50 years.

These strategies provide an empirical example of the choices described with reference to land tenure and the length of planning horizons in figure 1.6. For a farmer with a planning horizon of only a few years, it would clearly be optimal to deplete soil nutrient levels and disregard residue management, as in the first strategy. Over a longer planning horizon, on the other hand, the ranking of the first and third strategies is reversed. Over the 50-year period, the discounted present value of net returns increases by about 15 percent as a result of switching from myopic practices to those that are optimal over the long term, most of which is accounted for by soil nutrient management.[7]

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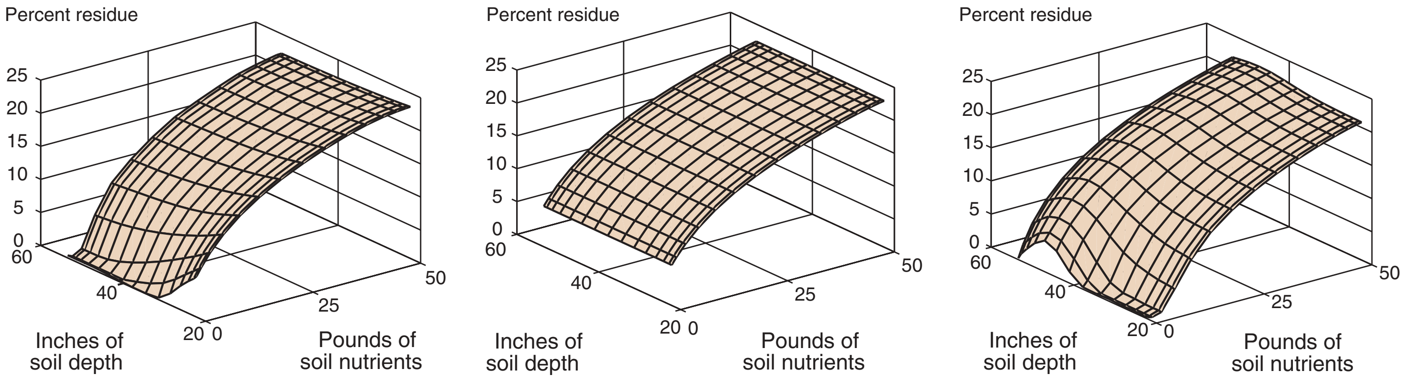
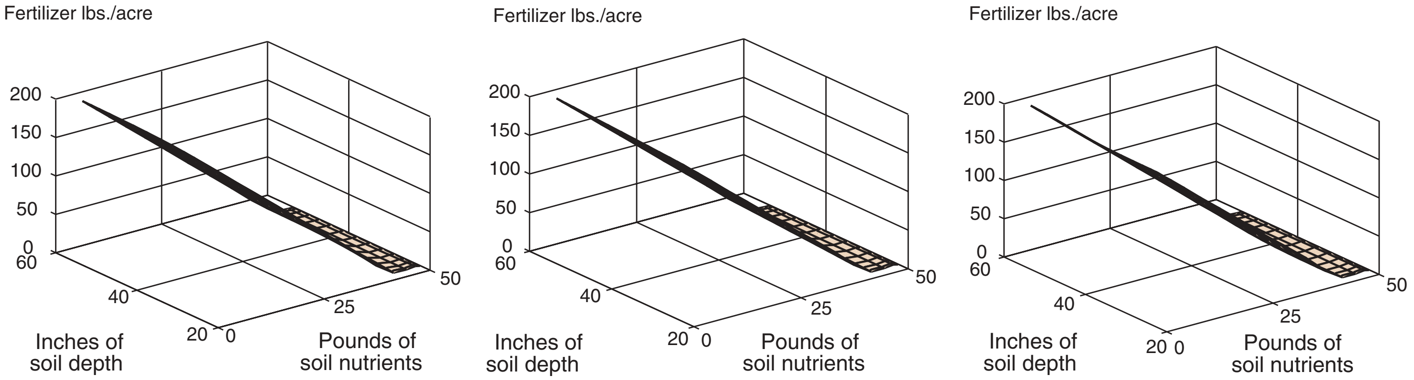
[7] Simulations over time periods exceeding a single generation are typically motivated by assumptions that farmers care about the welfare of their heirs, or that farmers care about land values over a shorter period of time but that those land values reflect the present discounted value of net returns farther into the future.

Figure 5.1—Optimal residue management levels



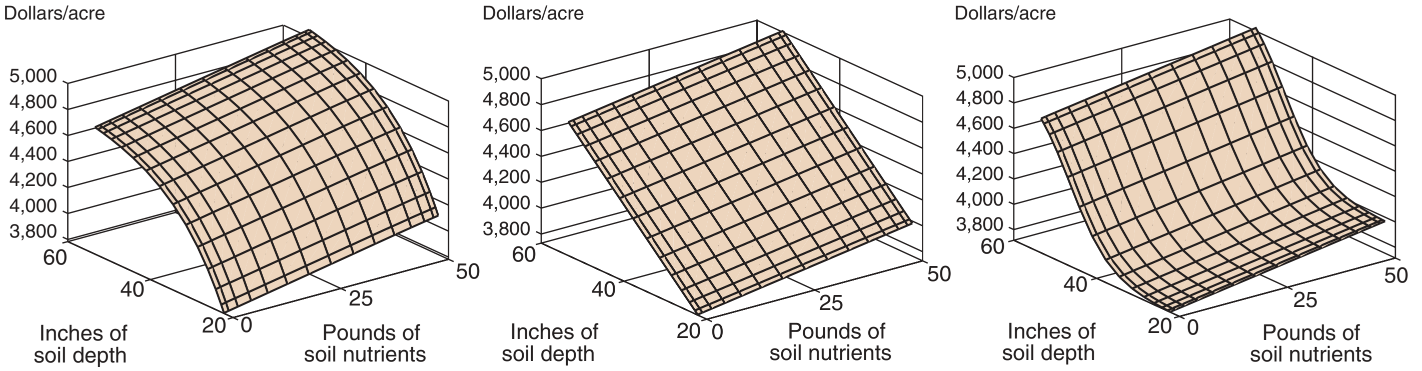
Source: Hopkins et al. (2001).

Figure 5.2—Optimal fertilizer application levels



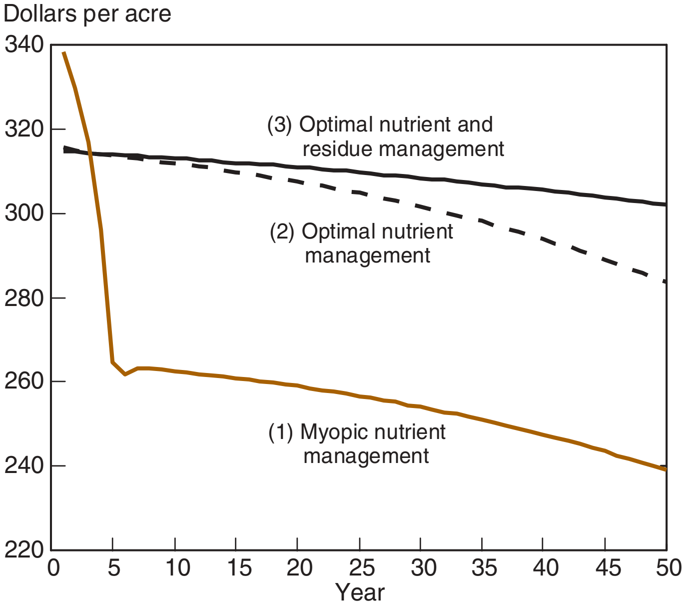
Source: Hopkins et al. (2001).

Figure 5.3—Relative land values under optimal management



Source: Hopkins et al. (2001).

Figure 5.4—Returns to alternative strategies



Source: ERS analysis.

Given the importance of long-term considerations in making management decisions in the present, it is critical to incorporate such considerations in understanding the conservation choices actually made by farmers. It is reasonable to expect that such considerations might manifest themselves in different decisions made by farm operators with different time horizons (e.g., farmers who operate land under differing forms of tenure).

Land tenure and the adoption of conservation practices in the United States

Conventional wisdom has long held that owners of a resource will take better care of that resource than users without a long-term interest in the resource. Economists have formalized this hypothesis in models in which a decisionmaker with a short time horizon was shown to have less incentive to invest in practices that provide benefits over the long term.

Previous research on this question has provided inconclusive or contradictory results, however, because it has not adequately addressed two important dimensions of the relationship between tenure and conservation. First, tenure's impact may depend on the timing and magnitude of the costs and returns generated by the conservation practice under study. For example, conservation tillage may increase short-term profits due to cost savings (e.g., on labor and fuel), but it may take several years to generate positive net returns to "medium-term practices," such as contour farming, stripcropping, or grassed waterways. Tenure's role in adoption is likely to vary with these differences.

Second, different lease arrangements may also influence renters' conservation decisions. For example, share-renters may have an additional incentive, relative to cash-renters, to adopt conservation practices that increase use of inputs for which they bear only a share of the cost. Furthermore, landlords tend to participate more actively in the management of farms rented under share leases (Rogers, 1991). This arrangement could induce share-renters to behave more like owner-operators than cash-renters. Failure to consider such distinctions would obscure tenure's true effect on the adoption of conservation practices.

Recent research by Soule et al. (2000) and Soule and Tegene (forthcoming) explores these two dimensions both conceptually and empirically, using data on corn and soybean production from USDA's Agricultural Resource Management Survey (ARMS). ARMS data provide a valuable opportunity (with farm, land, farmer, and practice data in a single large sample) to conduct an econometric analysis of tenure and other factors affecting the adoption of conservation practices.

Soule et al. begin with a model in which farmers choose a production practice to maximize the present value of current net returns plus terminal land value (at the end of the first period), where terminal land value is itself a function of expected future net returns. Different production/conservation practices, such as conventional tillage versus conservation tillage, generate different streams of costs and returns over time. Farmers who own their land are confident of realizing future returns to investments in conservation today (either through higher yields in future periods or through higher asset value if they sell their land). Renters are less likely to realize future benefits unless they operate the land under a long-term lease.

To capture this difference in expectations, Soule et al. weight terminal land value by a tenure-security parameter γ, which takes on the value 1 for owner-operators and

Table 5.2—Distinguishing tenure classes

Tenure class	Renter's output share (α)	Renter's input share (β)	Tenure security (γ)
Owner-operator	1	1	1
Cash-renter	1	1	<1
Share-renter	<1	<1	<1

Source: Soule et al. (2000).

less than 1 for renters. Soule et al. further distinguish renters according to the terms of their lease (i.e., whether they pay a cash rent and keep the entire crop or share the crop, and possibly input costs as well, in lieu of a rental payment). To capture this distinction, output is weighted by a share parameter α while inputs are weighted by a share parameter β (both of which are less than 1 for share-renters, and equal to 1 otherwise) (table 5.2).

The farmer's problem is thus to choose production practices that maximize present and future net returns as expressed by

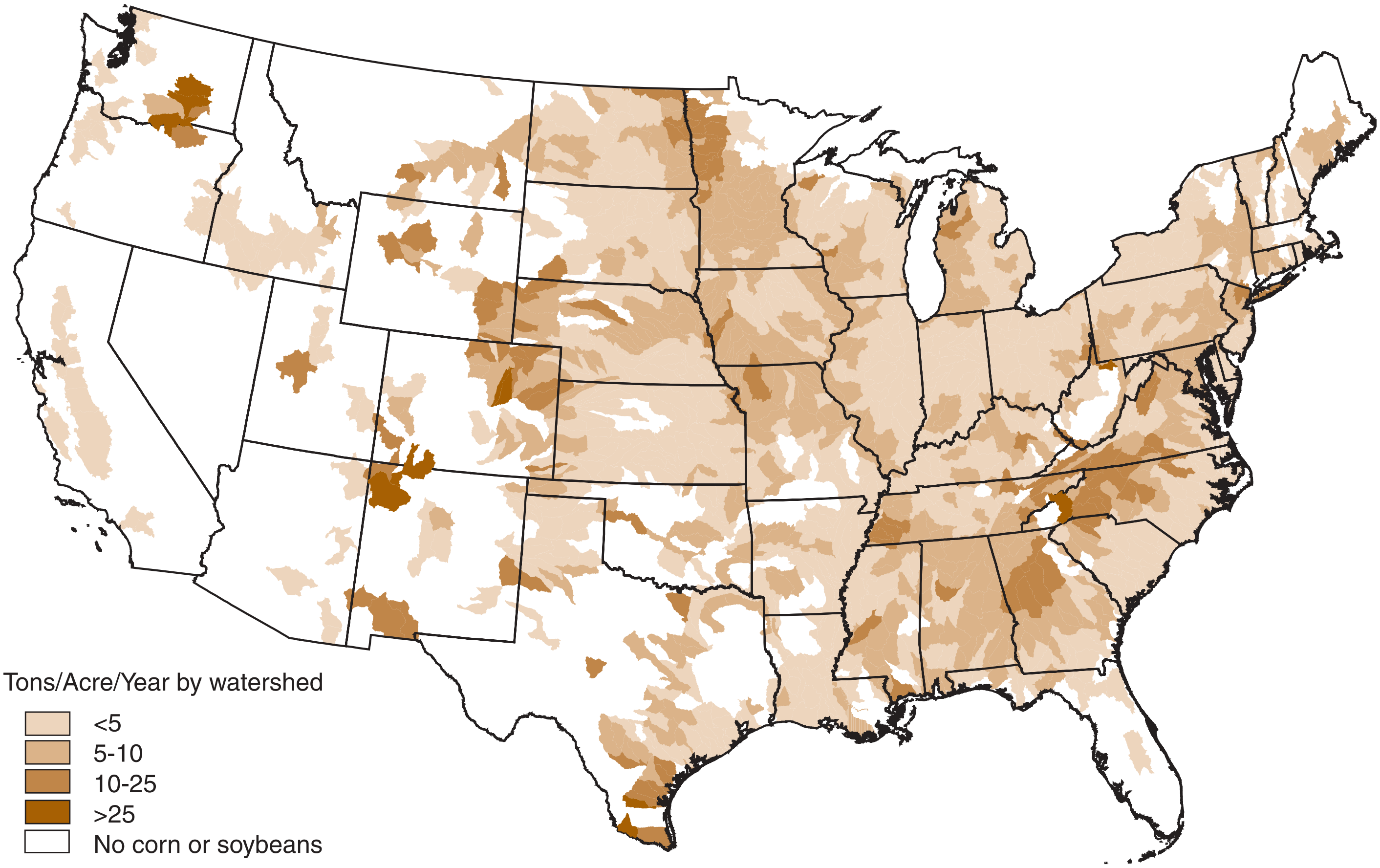
$$(\alpha \times \text{output value}) - (\beta \times \text{input costs}) + (\gamma \times \text{terminal land value})$$

If a practice, such as conservation tillage, reduces labor and/or fuel costs sufficiently to be profitable in the short run (as well as in the long run), little difference in incentive to adopt would be expected between owner-operators and renters. Within the category of renters, however, share-renters may find it especially profitable if the practice saves on inputs (such as labor and fuel) that are commonly supplied by share-renters (for whom $\beta < 1$).

Renters may have less incentive to adopt a practice such as contour farming or terracing, however, if it requires upfront costs that are not recovered until some time in the future because the value of the renter's objective function would be reduced by the parameter γ. In the case of share-renters, this reduced incentive might be offset by the increased participation of landowners in share-rented farm operations.

Data used to test these hypotheses were obtained primarily from ARMS, with information on 941 U.S. corn producers in 1996 and 1,417 U.S. soybean producers in 1997 (fig. 5.5). Variables included farm characteristics (e.g., farm size, field tenure, erodibility, location, climate, urban proximity, and program participation), farmer characteristics (e.g., age and education), and choice of practices (e.g., conservation tillage, contour farming, and grassed waterways).

Figure 5.5—Erosion on U.S. cropland in corn and soybeans



Source: ERS, based on data from the 1997 National Resources Inventory.

Table 5.3—Probability of adopting a conservation practice, relative to owner-operators

Tenure class	Conservation tillage		Medium-term practices	
	Corn	Soybeans	Corn	Soybeans
All renters	same	same	less likely	same
Cash-renters	less likely	same	less likely	same
Share-renters	same	less likely	less likely	same

Source: Soule et al. (2000); Soule and Tegene (forthcoming).

These data were analyzed econometrically to examine the effects of tenure on decisions by corn and soybean producers to adopt conservation tillage and "medium-term practices" (namely, contour farming, strip cropping, or grassed waterways) that offer benefits only in the future. (Data limitations prevented analysis of longer-term practices, including investment in conservation structures, such as terraces.)

Results indicate that land tenure is an important factor in farmers' decisions to adopt conservation practices, in ways that may not be revealed in conventional analyses (table 5.3). Specifically, conventional models that do not distinguish between types of renters fail to recognize the different incentives faced by cash-renters and share-renters (at least in corn production). Among corn producers, cash-renters are less likely than owner-operators to use conservation tillage, although share-renters behave much like owner-operators in adopting conservation tillage. Both share-renters and cash-renters are less likely than owner-operators to adopt at least one of the medium-term practices. Among soybean producers, the results do not follow the prediction so closely, but cash- and share-renters do seem to have different incentives for adopting conservation tillage, if not the medium-term practices.

Among other factors that help explain adoption of conservation practices, only designation of highly erodible land is consistently significant across crops and practices. This finding may reflect a combination of factors, namely, that such land is identified as needing conservation measures more urgently and that conservation measures on such land are a requirement if farmers wish to receive certain government program payments. Larger farms were significantly more likely to adopt conservation tillage (on both crops) but not medium-term practices. Younger farmers were significantly more likely to adopt both types of conservation practices in corn production but not in soybean production.

Econometric analysis shows that tenure is an important factor in the adoption of some conservation practices—at least those for which benefits to the farmer outweigh costs only over the longer term—underscoring the importance of a long-term perspective in assessing likely paths of farmer response to realized or anticipated changes in land quality. Given the extent of leasing in the United States (40 percent of all farmland, and 50 percent in the Corn Belt), and the fact that a majority of landlords are neither engaged in nor retired from farming (suggesting that most are not actively involved in farm decisionmaking), it is important to keep tenure in mind when considering policies to encourage adoption of conservation practices. Gaps in the analysis also reinforce the need for better data on tenure (e.g., lease conditions and duration) to improve our understanding of farmers' choices, especially regarding investment in long-term conservation practices (such as terracing).

Adoption of conservation practices in other countries

The foregoing analysis focused on conservation choices in a setting in which property rights are well defined, incomes are relatively high and secure, markets for commodities and inputs (including credit) function well, and information on alternative management practices and their economic and environmental consequences is relatively widely available.

By contrast, less-developed countries are generally characterized by property rights that are less well-defined (at least in formal terms), incomes that are lower and more variable, imperfect markets, and incomplete information on alternative management practices. These factors can shorten time horizons, raise discount rates, and otherwise limit investment in practices to reduce or reverse land degradation. Shiferaw and Holden (1999) argue that such factors drive low levels of conservation-related activities—and subsequent dismantling of poorly conceived conservation structures built under food-for-work programs—in Ethiopia's highlands.

Some observers (e.g., Pagiola) note, however, that informal property rights may well offer considerable tenure security in some cases, and that poverty could conceivably increase a household's incentive to conserve its land over the long term—particularly if that is its only productive asset apart from its labor power. Building on previous research on soil conservation in Kenya (Tiffen et al., 1994), Pagiola (1996) found that terraces were widespread in Machakos District even in the absence of public incentives or extension efforts. Site-specific land characteristics are critical—adoption of terraces was found to be profitable only on slopes of about 15 percent or more. Output prices and proximity to markets in Nairobi are also influential factors that may limit generalization from the Machakos experience. Despite concerns about severe land degradation in El Salvador, Pagiola (1998) found that ignorance, tenure insecurity, and lack of credit are not significant constraints on the adoption of conservation practices, while data were insufficient to draw firm conclusions about the influence of poverty. Pagiola found that a third of surveyed fields (and over half of steep fields) had some form of conservation in place, mostly minimum tillage and crop residue cover, but that terracing was unlikely to be cost effective in most cases. Templeton and Scherr (1999) reviewed more than 70 empirical studies from around the world and find that incentives to invest in the maintenance and improvement of land, and thus land productivity, tend to increase as the value of land rises relative to the cost of labor. In Burkina Faso, Kazianga and Masters (forthcoming) found that stronger property rights (even in the absence of formal tenure) were positively associated with investment in soil and water conservation.

The particulars of land, property rights, markets, wealth, and information will vary from farm to farm and from one period to the next, and optimal choices about agricultural production and conservation will vary accordingly. In general, however, conservation choices in less-developed countries are driven by the same principles as those that drive conservation choices in the United States and other more developed countries: farmers' perceptions of what is best for them and their families over the short and long term.

6. Land Degradation and Food Security

This report defines food security in terms of secure and sustainable access to sufficient food for active and healthy lives, whether access derives from production or exchange. Most studies of the effects of land degradation focus on selected measures of productivity, but land degradation may also affect food security, through its impacts on food production as well as on incomes and food prices. Citing studies in Africa, Asia, and Latin America, Scherr (1999b) notes that poor farmers tend to rely disproportionately on annual crops cultivated on marginal lands, often with insecure tenure—characteristics associated with a higher vulnerability to both land degradation and food insecurity. The potential impact of land degradation on food security at a global scale is difficult to quantify, given limited data and complex interlinkages, but preliminary findings are provided by recent efforts using global simulation models of agricultural production and trade.

Baseline estimates from ERS and IFPRI models

Several institutions have developed models of global food production and trade, but these have rarely been used to explore the impacts of land degradation. IFPRI's IMPACT model is a partial-equilibrium simulation model that determines supply, demand, and prices in a competitive market for 16 crop and livestock commodities in 36 countries and regions as functions of specified initial conditions (Rosegrant et al., 2001). Demand is specified as a function of prices, income, and population, while supply depends on prices and technology through their impacts on crop area and yields. Baseline projections indicate that global cereal demand and supply will increase at about 1.3 percent per year through 2020, while prices continue their long-term decline (although at a slower pace than in the past). Food security is indicated in the IMPACT model by the number of malnourished children, which is projected to decline by 21 percent to 132 million by 2020 (but increase 34 percent in Sub-Saharan Africa).[8]

Similarly, the ERS food security assessment (FSA) model is a partial-equilibrium simulation model used to project food availability and access in over 60 developing countries in five regions (North Africa, Sub-Saharan Africa, Asia, Latin America, and the New Independent States of the former Soviet Union) (Shapouri and Rosen, various years). Each country model includes three commodity groups: grains, root crops, and other crops. Production is determined by a system of area and yield response functions, where area is a function of crop yields, prices, and exogenous polices, and yields are a function of inputs (namely labor, fertilizer, capital, and technology). Commercial imports are modeled as a function of domestic prices, world commodity prices, and foreign exchange availability.

Food security is assessed in the ERS model by measuring the size of and trends in several alternative food gaps. The *status quo gap* measures the additional amount of food needed, beyond domestic production and commercial imports, to support 1997-99 levels of per capita consumption for each country. The *nutritional gap* is the gap between available food and food needed to meet the minimum daily caloric intake requirements estimated by FAO (FAO, 2000). (National average requirements vary but fall in the range of 2,000-2,310 kilocalories per person per day when allowing for moderate activity. Note that these requirements are significantly higher than consumption levels needed to meet the weight-for-age threshold that IFPRI's model uses to define child malnutrition, so results from the two models are not directly comparable.) The status quo and nutritional gaps do not account for access to food by individuals and households within a country, however, so ERS also projects food consumption by different income groups based on income distribution data for each country. The *distribution gap* measures the amount of food needed to raise the food consumption of each income quintile to the nutritional standard. Finally, based on the distribution gap and the projected population, ERS projects the number of people who cannot meet their nutritional requirements.

Over the past four decades, growth in agricultural production at a global scale has come predominantly from increases in yields, and this pattern is projected to continue in the future (FAO, 2000). These trends, subject to regional variation, are apparent in historic data and incorporated in baseline projections (table 6.1).

In the baseline analysis (assuming that recent conditions, trends, and policies continue), food gaps of each type are projected to grow during the next decade (table 6.2). The total status quo food gap for the 67 countries (needed to

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[8] Malnutrition is indicated in the IMPACT model by weight-for-age at least two standard deviations below the median, using U.S. National Center for Health Statistics/World Health Organization standards (Rosegrant et al., 2001).

Table 6.1—Growth in area, yield, and production, selected developing countries

Region (No. of countries)	Area cultivated	Historic change, 1980-99			Baseline projection, 2000-10		
		Area	Yield	Production	Area	Yield	Production
	% of potential	*% per year*					
North Africa (4)	76	0.5	3.0	3.5	1.7	0.3	1.9
Sub-Saharan Africa (37)	21	2.2	0.4	2.6	1.2	1.3	2.5
Asia (10)	67	0.1	2.4	2.5	0.1	1.6	1.7
Latin America & Caribbean (11)	18	0.7	0.4	1.1	0.6	1.1	1.7
New Independent States (5)	52	na	na	na	0.7	1.0	1.8
All (67)	32	0.6	1.8	2.4	0.5	1.3	1.8

Notes: Sub-Saharan Africa figures exclude Nigeria. "All" excludes New Independent States for 1980-99. "na" = not available.
Sources: FAO (2000), ERS database.

Table 6.2—Food security in 2000 and 2010 (baseline scenario)

Region	Status quo gap 2000	Status quo gap 2010	Nutritional gap 2000	Nutritional gap 2010	Distribution gap 2000	Distribution gap 2010	Hungry people 2000	Hungry people 2010
	Million metric tons						*Millions*	
North Africa	0.4	0.8	1.6	0.9	2.0	1.1	48	31
Sub-Saharan Africa	3.3	8.3	11.0	16.5	15.3	22.5	344	435
Asia	2.6	3.2	2.9	3.5	5.5	5.3	307	177
Latin America & Caribbean	0.3	0.5	0.7	0.9	1.9	1.8	62	47
New Independent States	0.4	0.0	0.8	0.3	0.4	0.4	13	6
Total	7.0	12.7	17.1	22.1	25.0	31.0	774	694

Source: Shapouri and Rosen (2000).

maintain per capita consumption at the 1997-99 base level) is estimated at 7.0 million tons for 2000 and 12.7 million tons in 2010. The total nutritional gap is projected to increase from 17.1 million tons in 2000 to 22.0 million tons in 2010, while the total distributional gap is projected to increase from 25.0 million tons in 2000 to 31.0 million tons in 2010. In each case, the largest share of the gap is accounted for by Sub-Saharan Africa, followed by Asia.

Based on the distribution gaps, ERS estimated the number of people (in each income quintile) whose consumption would fall short of the minimum nutritional requirement in each country. While food gaps are projected to grow in magnitude, the number of people failing to meet the nutritional target is projected to decline by 2010, both in total and for all regions except Sub-Saharan Africa. This means that nutritional disparity among and within countries will intensify more than food deficits will spread. In other words, the hunger problem will get more severe in the most vulnerable countries and/or among the lower income groups in those countries, even while the total number of hungry people declines. For the 67 countries, the number of people failing to meet the nutritional target is projected to decline from 774 million in 2000 to 694 million by 2010. About 44 percent of the projected total for 2000 are in Sub-Saharan Africa, with another 40 percent in Asia; by 2010 the Sub-Saharan African share will rise to 63 percent, while that of Asia will fall to 26 percent.

Alternative scenarios

Over the past four decades, growth in agricultural production at a global scale has come predominantly from increases in yields, and this pattern is projected to continue (FAO, 2000). In many low-income countries, however—particularly in Sub-Saharan Africa—yields have stagnated in recent years and most increases in agricultural output have stemmed from area expansion (table 6.1). While additional land is still available to be brought into food production, in most countries it is marginal land with lower productivity, more uncertain rainfall, and potentially greater vulnerability to degradation, implying lower and more variable crop yields. Moreover, continued conversion of range and forestland to cropland involves increasingly high economic and environmental costs, and area growth cannot be sustained indefinitely. In South Asia, for example, over 80 percent of potentially arable land is already cultivated (FAO, 2000).

These trends imply that for most food-insecure countries, constraints on land area and quality will play an increasingly important role in determining food security in the future. The baseline model projects trends in area and yields, implicitly reflecting actual historic losses due to soil erosion and other forms of land degradation. To explore the possible impacts of land degradation on food security, we compared the baseline results with two alternative scenarios: (1) reduced losses in cropped area, and (2) reduced losses in crop yields.

Reduced area losses to land degradation

Arable land in Asia, Africa, and Latin America has expanded by about 5 million hectares per year over the past four decades and now accounts for about half of the world's total arable land (FAO, 2000). Data on land degradation at a global scale are scarce, but recent estimates suggest that 5-6 million hectares of arable land worldwide are irreversibly lost each year as a result of soil erosion, salinization, and other degradation processes (Scherr, 1999b). If that degradation occurs in rough proportion to total arable area, then roughly half (about 2-3 million hectares per year) could be assumed to occur in developing regions. The gross increase in arable area in developing regions would then be about 7-8 million hectares per year, or 2-3 million hectares per year faster than the net rate apparent in simple historic trends. Our first alternative scenario explores the impacts of these irreversible losses in arable land by considering what might have happened in the absence of such losses. Accordingly, area expansion is assumed to be half again as rapid as the rate used in the baseline model for each country (table 6.3).

Results of the first alternative scenario are presented in table 6.4. (Note that food security impacts are felt through changes in production and commercial imports but not through changes in income.) Reduced area losses have the greatest impact on food gaps in Sub-Saharan Africa, where low levels of commercial imports mean consumption is heavily dependent on domestic production, which in turn has been based over the past two decades primarily on expansion in cultivated area. Status quo, nutritional, and distribution food gaps projected for 2010 in Sub-Saharan Africa decrease to 5.0, 12.0, and 17.8 million tons respectively (down 40, 27, and 21 percent relative to baseline projections). Reduced area losses have smaller impacts on food gaps in Latin America, despite the historic importance of area growth, because of the region's greater reliance on commercial imports. Impacts on food gaps are small in other regions as well, due to the combined effects of lower dependence on area growth as a source of increased domestic production and greater reliance on commercial imports as a source of consumption. For the 67 countries studied, status quo, nutritional, and distribution gaps projected for 2010 decrease by 28 percent, 22 percent, and 16 percent, respectively, relative to the baseline.

Table 6.3—Growth in area, yield, and production, selected developing countries, 2000-10

Region	Scenario 1 (reduced area losses)			Scenario 2 (reduced yield losses)		
	Area	Yield	Production	Area	Yield	Production
	% per year					
North Africa	2.5	0.3	2.8	1.7	0.4	2.2
Sub-Saharan Africa	1.8	1.2	3.0	1.2	1.4	2.6
Asia	0.1	1.6	1.7	0.1	1.7	1.7
Latin America & Caribbean	0.9	1.0	2.0	0.7	1.2	1.9
New Independent States	1.1	0.9	2.0	0.8	1.0	1.7
All	0.8	1.2	2.0	0.5	1.4	1.9

Note: Sub-Saharan Africa figures exclude Nigeria.
Source: ERS analysis.

Table 6.4—Food security in 2010 (Scenario 1: reduced area losses)

Region	Status quo gap	Nutritional gap	Distribution gap	Hungry people
	Million metric tons			*Millions*
North Africa	0.6	0.8	1.0	31
Sub-Saharan Africa	5.0	12.0	17.8	400
Asia	3.2	3.4	5.2	146
Latin America & Caribbean	0.4	0.8	1.6	42
New Independent States	0.0	0.3	0.3	7
Total	9.2	17.2	26.0	626

Source: ERS analysis.

Under the baseline assumptions, the number of people whose consumption falls short of the nutritional target in 2010 was projected to be 694 million for the 67 countries, or 22 percent of their total population. Under the reduced-area-loss scenario, the projected number of people with nutritionally inadequate diets in 2010 falls 10 percent to 626 million, or 20 percent of the projected population of those countries.

Put differently, for the 67 countries as a group, projected food gaps are 38, 28, and 19 percent higher in the baseline than they are in the reduced-area-loss scenario (for status quo, nutritional, and distribution gaps, respectively) as a result of irreversible losses in cropland due to land degradation. As a result, the number of people with inadequate diets is projected to be 11 percent higher in the baseline than in the reduced-area-loss scenario. Most of the difference is accounted for by Sub-Saharan Africa.

Reduced yield losses to land degradation

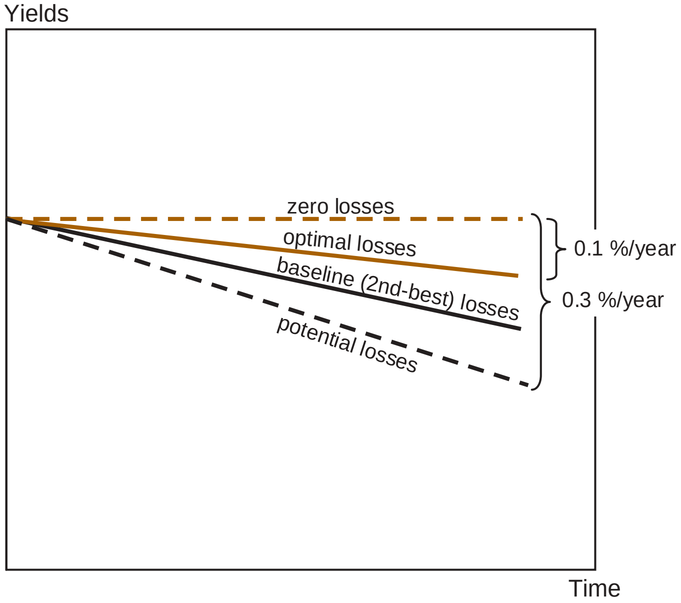
Given the importance of yield growth as a source of production growth in most regions, and the regionally varied impacts of land degradation on productivity, it is of interest to consider how food security might be affected by land degradation over time, even if cropland is not lost irreversibly to degradation. Agronomic studies suggest that soil erosion reduces crop yields by an average of 0.3 percent per year if all other factors are held constant. Economic analysis indicates that actual losses are smaller (although magnitudes remain unclear) because farmers have incentives to adjust their practices to reduce soil erosion.

As noted earlier, the baseline model implicitly reflects historical farming practices and rates of soil erosion and other forms of land degradation in low-income developing countries. If erosion continues at historical rates and other factors are held constant, yields will follow the baseline trajectory (fig. 6.1). Reducing erosion would raise yields relative to the baseline. If erosion rates increase in the future, yields would fall relative to the baseline. We assume that farmers in low-income developing countries have adjusted their practices to reduce soil erosion to a certain extent but not to the full extent that would be optimal under secure tenure and well-functioning markets as studied by Hopkins et al. (2001). Lacking more precise data, we assume that the baseline thus reflects second-best strategies that are midway between maximum potential losses (with no farmer response) and optimal losses under well-functioning markets.

To explore the impacts of soil erosion on crop yields, our second alternative scenario restores area growth to baseline levels and increases yield growth rates for each country by a portion (one-third) of the potential annual erosion-induced yield losses estimated for each region and presented in table 4.4 (i.e., 0.49 percent for Africa, 0.24 percent for Asia, 0.46 percent for Latin America, and using the global average annual loss of 0.30 percent for the New Independent States). This corresponds to an assumption that baseline yield growth rates are 0.1 percent lower, on average, than they would be if economic and environmental conditions in low-income developing countries allowed optimal choices closer to those found by Hopkins et al. (2001) for the United States (table 6.3).

Results of the second alternative scenario are presented in table 6.5. As was the case for reduced area losses, impacts of reduced yield losses are greatest for Sub-Saharan Africa, where food gaps for 2010 fall 9-18 percent (distribution and status quo gaps, respectively) relative to the baseline. In the other regions, due to a combination of faster baseline yield growth, smaller losses to erosion, and/or greater reliance on commercial imports, the food security impacts of reduced yield losses are generally smaller. For all 67 countries studied, distribution and nutritional gaps projected for 2010 decrease by an average of 7-10 percent, respectively, while status quo gaps decrease by an average of 13 percent. The number of people with nutritionally inadequate diets under the reduced-yield-loss scenario falls 5 percent from the baseline analysis to 657 million, or 21 percent of the total projected population of the 67 countries in 2010.

Figure 6.1—Yields at different rates of land degradation



Source: ERS.

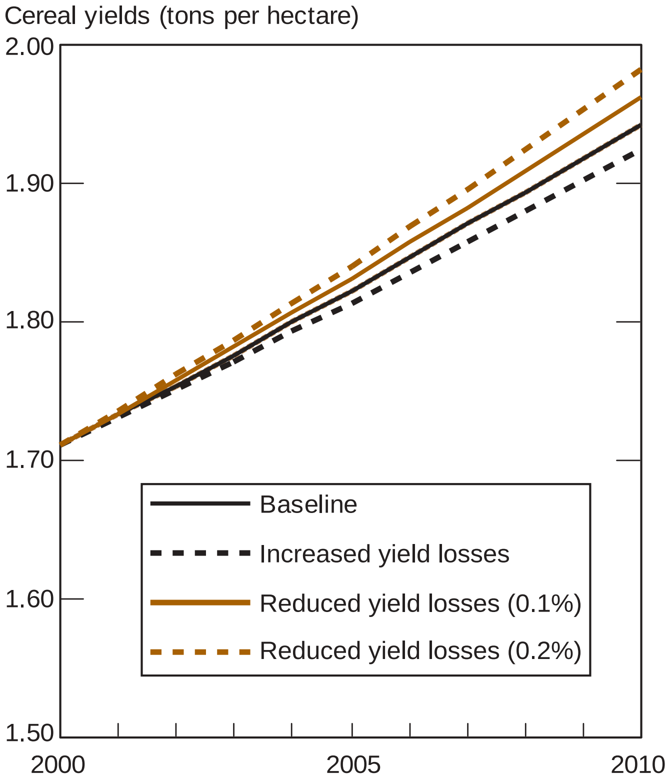
In other words, for the 67 countries as a group, projected food gaps in 2010 are 15, 11, and 8 percent higher in the baseline than in the reduced-yield-loss scenario (for status quo, nutritional, and distribution gaps, respectively) as a result of crop yield losses due to soil erosion. Thus, the projected number of people with inadequate diets is 6 percent higher in the baseline than in the reduced-yield-loss scenario.

In an earlier analysis using IFPRI's IMPACT model, Agcaoili et al. (1995) simulated the effects of a hypothetical 10-percent decline in productivity due to land degradation in developing countries through 2020, along with additional degradation-induced limits on yields and area growth in Pakistan and China. Their analysis suggested that adverse effects on global food supplies would be sufficient to reverse the decline in world food prices projected in IFPRI's baseline, but that effects on nutritional status would be modest at the global level, due to the potential for substitution from other producing areas (Scherr and Yadav, 1996). Impacts on supply could be much greater in areas where degradation is most severe, however, and child malnutrition in developing countries was projected to increase by about 4 percent relative to baseline numbers as a result. (Recall that IFPRI defined child malnutrition with respect to a standard different than that used by ERS to define nutritional and distribution gaps.)

All of these projections are subject to a considerable margin of error due to limitations in data on land degradation and its impacts on productivity over time, as well as to the inherent limitations of existing models (including assumptions about changes in area and yield). For example, the reduced-area-loss scenario projected that a total of 626 million people in the 67 countries studied would have nutritionally inadequate diets if area losses to irreversible degradation were eliminated. If area losses were doubled instead, the projected number of hungry people would rise to 1.0 billion. Similarly, the reduced-yield-loss scenario projected that 657 million people would be hungry if yield losses to soil erosion were reduced by an average of 0.1 percentage points. If yield losses to erosion were reduced by an average of 0.2 percentage points instead, the projected total number of hungry people would fall to 627 million (fig. 6.2 and 6.3). Such improvements would contribute to meeting the 1996 World Food Summit objective of halving the number of undernourished people in the developing world by 2015 but would not be sufficient to meet this objective.

If yield losses to erosion increased by an average of 0.1 percentage points, the number of hungry people would rise to 980 million. Asia was the region most sensitive to changes in both area and yield growth rates.

Figure 6.2—Cereal yields in low-income developing countries under alternative yield-loss scenarios



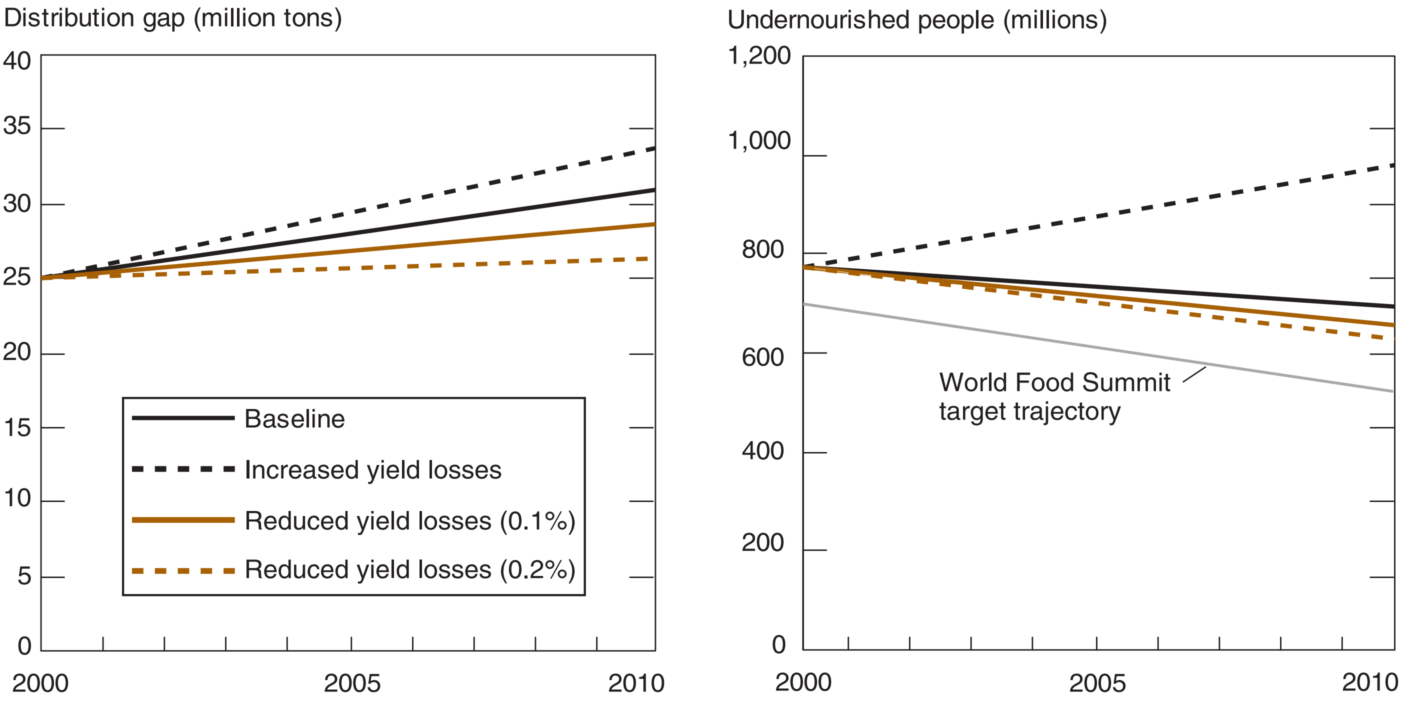
Source: ERS analysis.

Table 6.5—Food security in 2010 (Scenario 2: reduced yield losses)

Region	Status quo gap	Nutritional gap	Distribution gap	Hungry people
		Million metric tons		*Millions*
North Africa	0.7	0.9	1.1	31
Sub-Saharan Africa	6.8	14.5	20.5	428
Asia	3.1	3.4	5.1	146
Latin America & Caribbean	0.4	0.9	1.7	44
New Independent States	0.0	0.3	0.3	7
Total	11.0	19.9	28.7	657

Source: ERS analysis.

Figure 6.3—Food security in low-income developing countries under alternative yield-loss scenarios



Source: ERS analysis.

Implications and extensions

Data remain insufficient to accurately assess the probability of these alternative outcomes, but results nevertheless suggest the potential to "buy" improvements in food security through investments in conservation. Improved understanding of farmers' choices with regard to production and conservation practices is essential to increase our understanding of the potential costs and benefits of this link. It is also important to note that these projected food security impacts occur through reduced production (and thus availability), but reduced productivity also affects food security by reducing the income (and thus access to food) of individuals and households that depend on agriculture for their livelihoods. (The ERS model recognizes differences in income levels but does not currently permit endogenous changes in income resulting from changes in agricultural productivity.)

Future analyses will be able to take advantage of improved information on interactions between resources and food security. For example, IFPRI has recently extended its IMPACT model to incorporate data on water supply and use at the river-basin scale (Rosegrant et al., 2002), while ERS is upgrading its land and water resource database. Additional insights may be derived through analysis using static or dynamic global computable general equilibrium models that have been developed at ERS (and which incorporate interactions with nonagricultural sectors of the economy).

7. Challenges for Research and Policy

This report describes how new data and analyses have been used to re-examine an old question: how differences and changes in land quality affect agricultural productivity and food security. As rising populations and incomes increase pressure on land and other resources worldwide, agricultural productivity becomes increasingly important for continued improvement in food supplies and food security. Agronomic studies and conventional wisdom have long recognized that land quality affects agricultural productivity, but it has been difficult to disentangle land quality's effects from those of other factors, such as changes in input use. Advances in spatially referenced data and GIS techniques offer progress in understanding land quality's role in shaping patterns of agricultural productivity.

First, econometric analysis using new data on soils and climate, and controlling for the affects of agricultural inputs and other measures of resource quality, confirms that differences in land quality contribute to significant differences in agricultural productivity between countries. Some of these differences can be mitigated (e.g., by increasing fertilizer use to reduce or reverse soil nutrient depletion in Sub-Saharan Africa), but others may not be reversible at reasonable economic or environmental cost.

Second, land degradation appears to generate productivity losses that are relatively small on a global scale (although their relative importance may increase if productivity growth continues to slow). New estimates of productivity losses are consistent with the lower range of previous estimates. For example, potential yield losses to erosion estimated in the soil science literature average 0.3 percent per year across regions and crops. These estimates focus on biophysical relationships in the absence of behavioral response; actual yield losses will be lower to the extent that farmers act to avoid or reduce these losses.

Third, farmers' responses to land degradation affect how potential impacts on yields may translate into actual impacts on agricultural productivity. Econometric and simulation analyses show how differences in land tenure and other factors that affect farmers' planning horizons combine with differences in land quality to influence decisions about practices that reduce erosion and nutrient depletion. Results indicate that actual yield losses under optimal practices will typically be lower than potential losses estimated in agronomic studies (and are generally less than 0.1 percent per year in the north-central United States).

These findings do not imply that degradation-induced yield losses are unimportant—just that they have historically been masked by growth in yields (which has averaged over 2 percent per year in recent decades for the world as a whole) due to improvements in technology and increases in input use. Degradation-induced yield losses may become more significant in relation to yield growth in the future, as yield growth rates are projected to fall below 1 percent per year over the next few decades. Land degradation's effects on productivity are also likely to be more severe in some regions and local areas, due to a combination of resource factors (terrain, soils, and precipitation) and economic factors (poverty, tenure insecurity, and lack of infrastructure).

Finally, land degradation's impacts on productivity may affect food security in some areas both through losses in aggregate production (and thus higher food prices for all consumers) and through losses in income for those who derive their livelihoods from agricultural land or agricultural labor. Model results suggest that the number of people with nutritionally inadequate diets in low-income developing countries would decline 5 percent if average annual yield losses to land degradation in those countries were reduced from 0.2 percent to 0.1 percent over the next decade. Such improvements would contribute to meeting the 1996 World Food Summit objective of halving the number of undernourished people in the developing world by 2015 but would not be sufficient to meet this objective.

These results suggest that when markets function well, private incentives to reduce land degradation are generally sufficient to address onfarm productivity losses. When markets function poorly (e.g., when property rights are insecure or credit is expensive or unavailable), private incentives to address productivity losses are diminished. In either case, private actions are unlikely to adequately address land degradation's other, and perhaps more significant, effects: offsite impacts on both economic performance and environmental quality. Priorities for further progress in understanding and addressing the links between resource quality, agricultural productivity, and food security include targeted improvements in data, analysis, technology development, and policy.

Improving spatially referenced data on resources and farm practices

Recent years have seen dramatic improvements in the availability of spatially referenced, high-resolution data on natural resources—particularly on land cover, weather, and other variables suited to remote sensing. Nevertheless, important gaps remain. With respect to land cover, for example, consistent classification with fine resolution at the global scale is currently available only for a single composite time period (1992-93) from the AVHRR data set. Considerable effort and judgment are required to transform raw data into classification schemes that strike a useful balance between specificity and generality. The costs associated with this process inhibit the development of usable time series on land cover at high spatial and temporal resolution, even though relevant raw data (e.g., LANDSAT and MODIS) are being collected.

Data also remain scarce on actual (not just characteristic) land quality and land degradation. Improved data on land cover, precipitation, and slope, combined with data on inherent soil properties, offer the prospect of improvements in estimation of some land degradation processes (such as soil erosion). Efforts to allocate production spatially represent significant progress toward accounting for differences in data on inputs and outputs and allow improved estimates of nutrient depletion. But critical data on management practices remain scarce at fine spatial and temporal scales, limiting the precision of such estimates.

Spatially referenced data are even harder to find on property rights, institutions, infrastructure, and other less-tangible variables that nevertheless exert potentially significant influence on agricultural productivity. The complexity and context specificity of such variables pose considerable obstacles to improvement in data collection.

Despite these limitations, there remains considerable potential for improvements in coordination of and access to existing data on land cover and land quality characteristics, including nondigitized subnational data available in some countries, through collaboration with IFPRI, FAO, and other interested parties.

Incorporating simultaneity in analysis of resources and farm practices

In addition to new data and improvements in access to existing data, there remains considerable scope for improvements in analysis of existing data. One key area that deserves closer attention is empirical incorporation of the relationships between inputs, outputs, and land quality in a fully simultaneous system. While the simplest production function historically represented output as a function of conventional inputs (i.e., quantities of land, labor, and capital inputs), in fact the production function is only one component of a complex system in which output, inputs, and land quality are simultaneously determined.

Progress has been made in extending the simplest production functions to include land quality characteristics. Initial efforts (e.g., Masters and Wiebe, 2000) have estimated extended production functions in a simultaneous system with equations expressing inputs as functions of outputs and land quality, but further work is needed in this area. Lindert (2000) has estimated extended production functions simultaneously with land quality characteristics as functions of outputs and inputs using existing data at the subnational level in China and Indonesia. Hopkins et al. (2001) combine all three relationships in their simulation analysis of the north-central United States. Nevertheless, data requirements for a fully simultaneous econometric analysis (including the need for time-series data on soil erosion, salinization, nutrient balances, and farmers' practices) remain prohibitive at larger scales.

Improving R&D to address the needs of resource-constrained farmers and areas

Resource quality differences generate significant differences in productivity between regions/countries. Resource degradation generates productivity losses over time that are relatively small at a global scale but potentially much larger in some areas. Given that two-thirds of the rural population in developing countries live in "marginal areas" (Scherr, forthcoming) and that resource degradation also generates significant offsite effects in terms of both environmental quality and food security, there is a role for public policy to support agricultural R&D directed at areas with high potential impacts (particularly relative to trends in productivity, and particularly in areas with already-poor and/or degrading lands).

Heisey and Renkow (forthcoming) note that areas that are less favored in agro-ecological terms have also been less favored historically in terms of R&D investment. Whether such areas should receive greater priority, however, remains the subject of debate. Some argue that R&D for less favored areas should be increased to reduce widening geographic disparities in incomes, while others argue that scarce R&D funds should be focused on favored areas where returns are highest. Fan and Hazell (1999) estimate returns to research in some less favored areas that may actually exceed returns in relatively favored areas, but Heisey and Renkow argue that this conclusion is diminished by the significant spillovers to less favored areas from R&D targeted at relatively favored environments. Such spillovers, which may reduce income disparities, occur both through the gradual adoption of new technologies (e.g., seed varieties developed for favored areas) in less favored areas and also through indirect effects via commodity markets (e.g., production increases in favored areas reducing food prices in less favored areas) and/or labor markets (e.g., via increased wages in favored areas spilling over to, and drawing labor from, less favored areas).

Heisey and Renkow also note the growing share of agricultural R&D expenditures directed at resource/environmental concerns rather than (or in addition to) traditional productivity-oriented objectives. Such a shift would seem to indicate an increasing emphasis on less favored areas. Given that such concerns are generally of less interest to private sources of R&D funding, this implies an increased role for public support of agricultural R&D.

Improving policy and institutions to do likewise

To the extent that land degradation generates adverse effects (whether economic or environmental) on individuals who are not parties to the decisions that result in land degradation in the first place, policy has a role to play in modifying incentives and decisions to mitigate adverse impacts. Examples of policy roles include removing distortions produced by inappropriate or ineffective tenure systems—keeping in mind that formal systems based on individual private property rights are neither necessary nor sufficient in this regard. Other examples of policy roles include improving physical and institutional infrastructure and/or offering reasonably priced credit to reduce excessive discount rates and encourage investment.

In addition to efforts to improve market performance in general, it may also be necessary in some circumstances to offer direct payments over time to enhance farmers' incentives to adopt conservation practices that provide social/offsite as well as private/onsite benefits. Such payments are well established in conservation programs (such as the Conservation Reserve Program) in the United States and in many other countries but require careful attention to the timing and magnitude of incentive payments to sustain incentives for conservation over time. Such approaches may also be warranted to achieve the broader agricultural, environmental, and food security-related objectives of the 1994 UN Convention to Combat Desertification, the 1996 World Food Summit, the 2002 World Summit on Sustainable Development, and other multilateral initiatives.

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