Linking Land Quality, Agricultural Productivity, and Food Security

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1. Old Concerns and New Opportunities

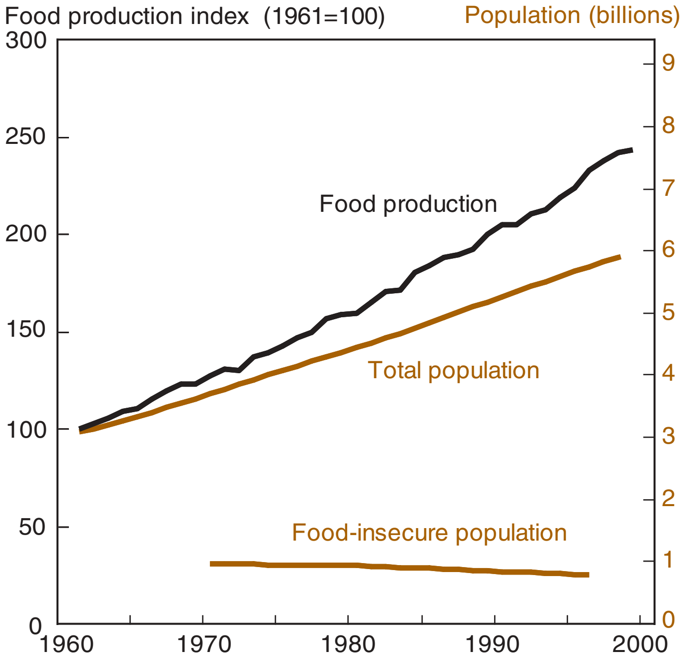
Two hundred years ago, citing limits on the extent and quality of agricultural land and concerns about population dating back to Plato and Aristotle, Thomas Malthus argued that population growth would inevitably outpace food production—unless checked by "moral restraint, vice, [or] misery" (Malthus, 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.

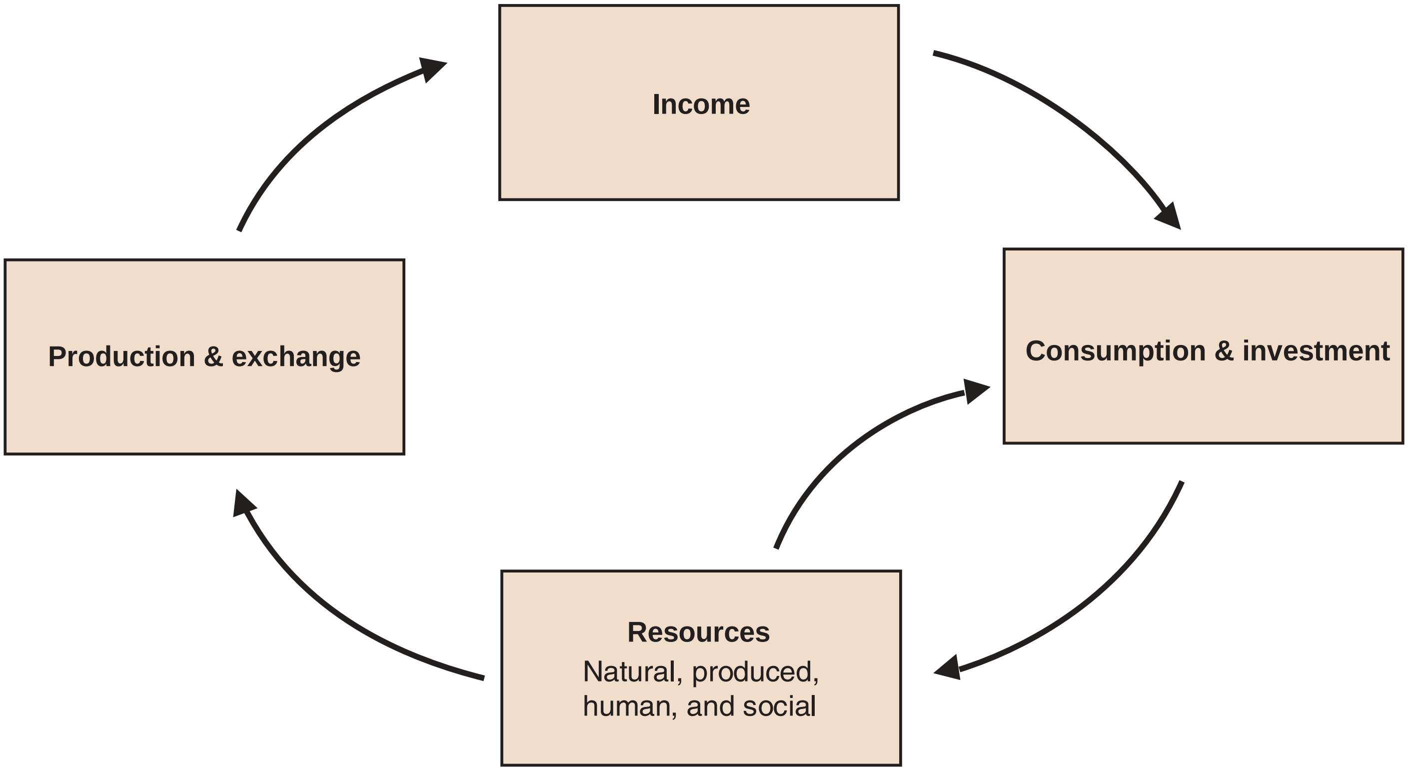
units), but data on biophysical characteristics, such as land quality or land degradation, may be available in only a few locations. Much may be known about selected sites, but little is generally known at the larger scales at which policy measures—if appropriate—become relevant.

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).

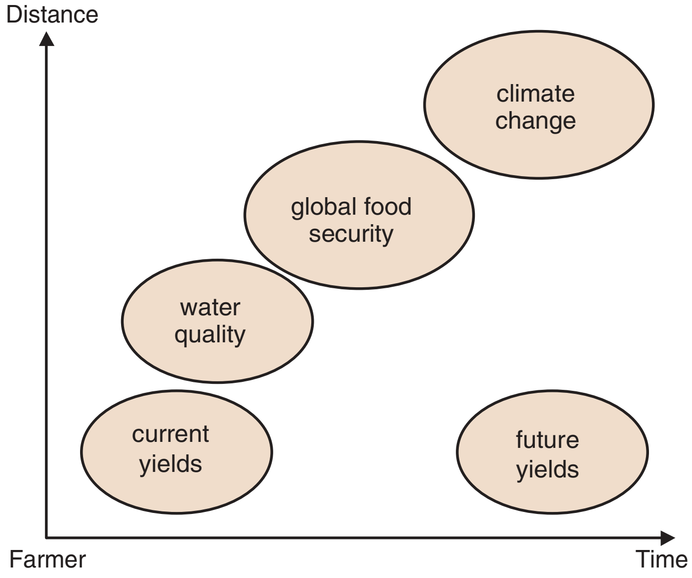
may affect the eroded location's ability to produce crops, while the deposition of eroded soil may affect the efficiency of measures to provide clean water, irrigation, flood control, and other services downstream.

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.

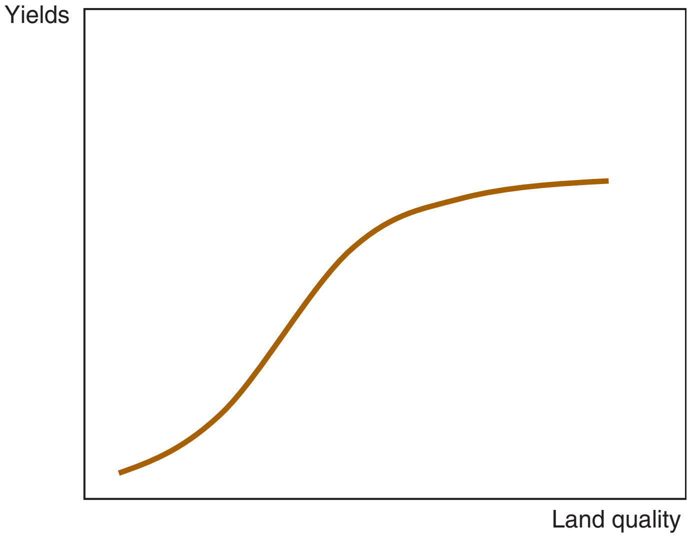
In general, farmers have little direct incentive to address offsite impacts of land degradation. By contrast, farmers have a direct incentive to address onsite productivity losses, particularly if productivity losses occur over a short period of time but also over the long run if property rights provide 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.

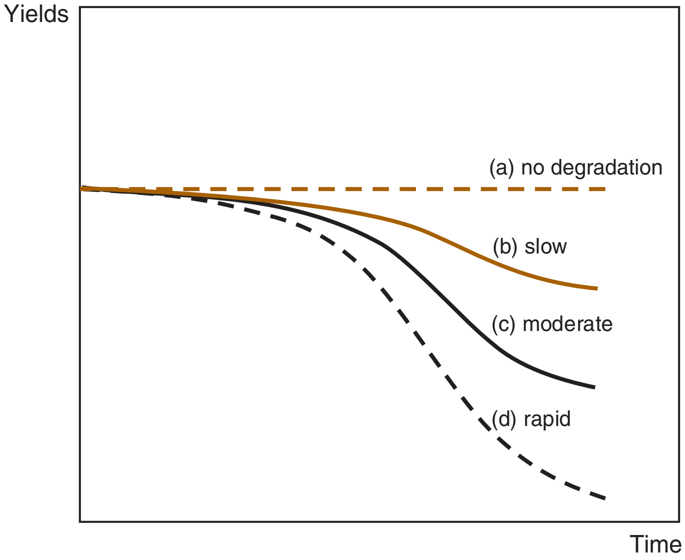
Figure 1.4 also implies that output will fall for a particular farmer if the quality of his or her land declines over time, everything else remaining equal. This proposition is more difficult to examine empirically, requiring not only data on output, land quality, and other inputs but also data on changes 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.)

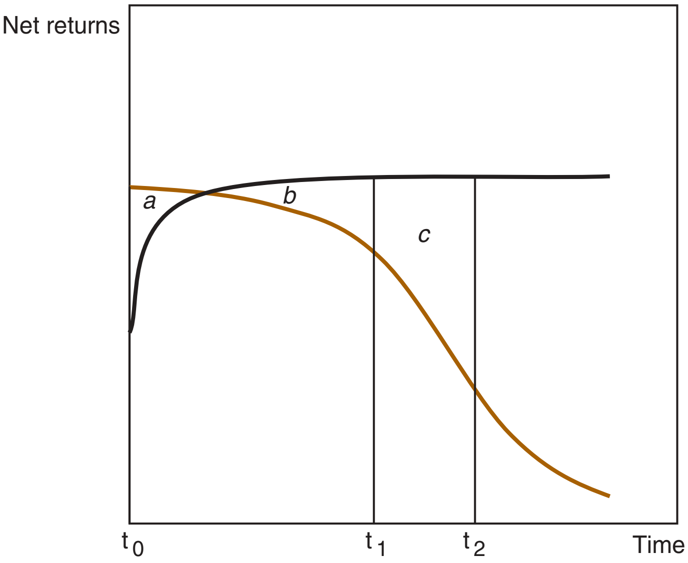
To understand how farmers make these choices, we need to move beyond yields and compare the level and timing of net returns to alternative practices over time, drawing on previous work by Pagiola (e.g., 1999a, 1992) and McConnell (1983). For example, consider two management practices with different streams 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.