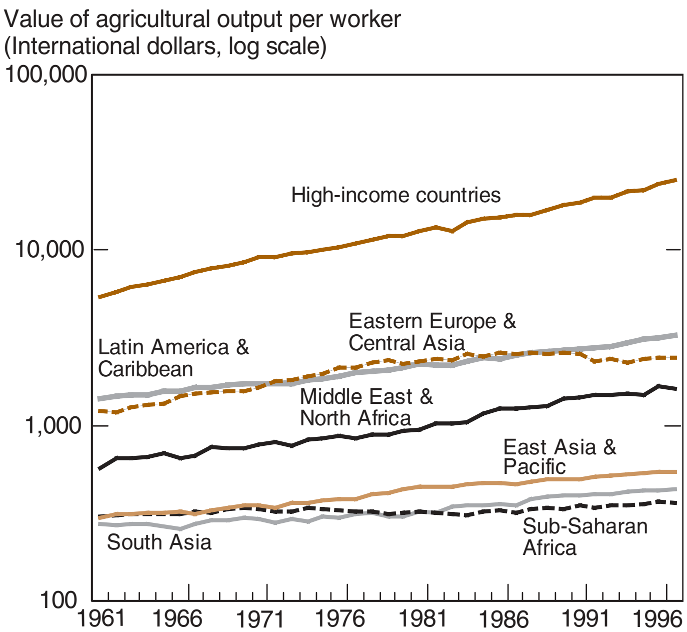
3. Land Quality and Agricultural Productivity

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.

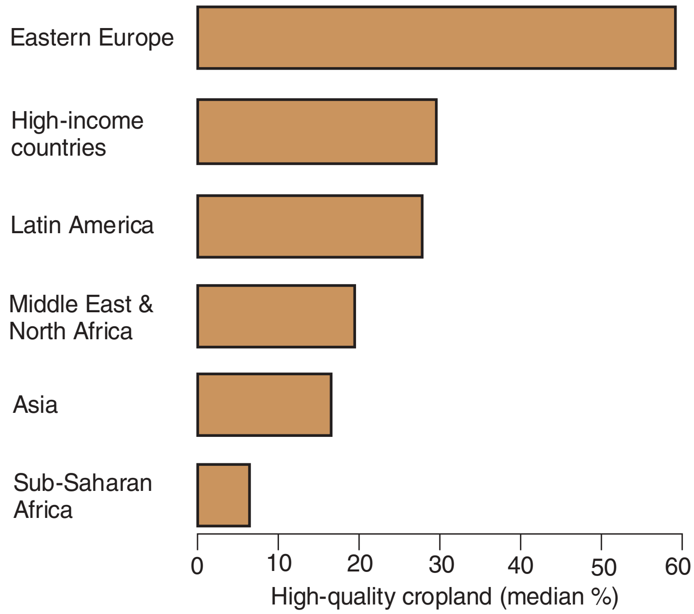
New land quality indicators

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).

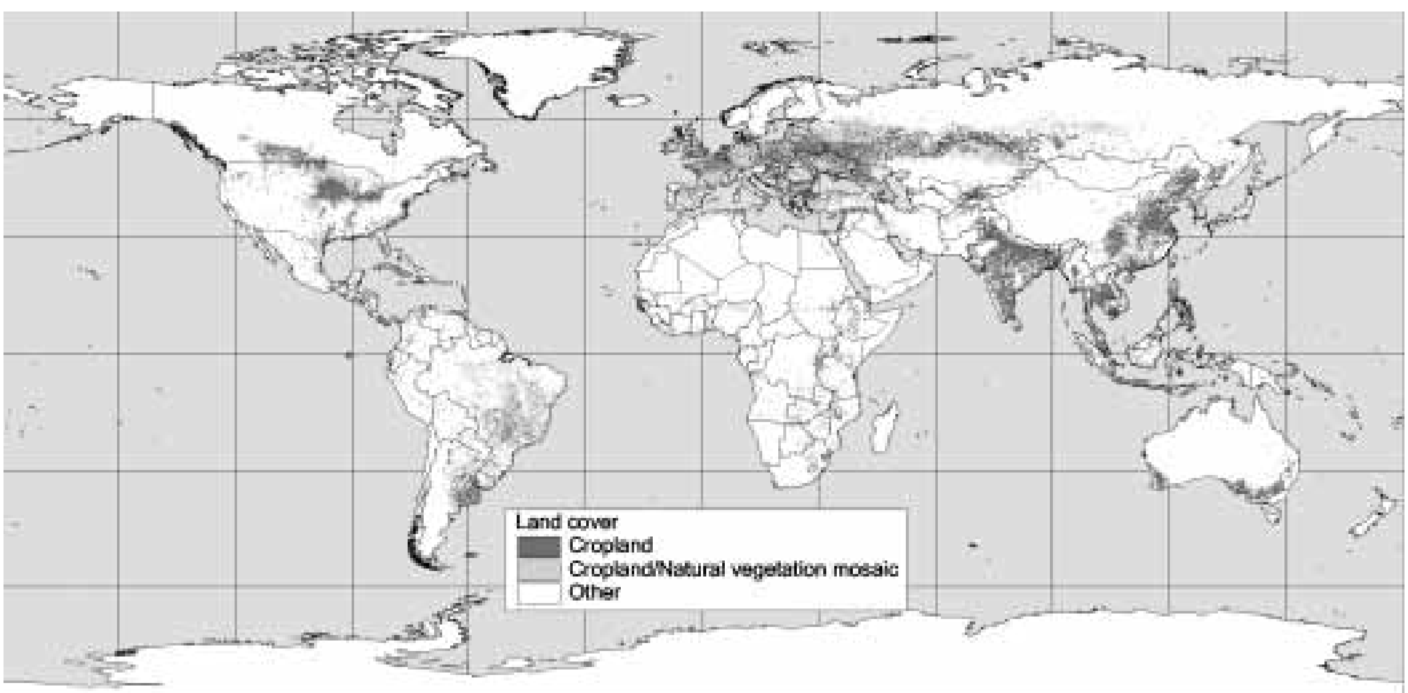
The result is a continuous variable based on the share of each country's cropland that is found in the three best quality classes. This share ranged from 0 (for Niger and 13 other countries) to 0.91 (for Bulgaria). Regional medians are highest in Eastern Europe (nearly 0.6) and lowest in Sub-Saharan 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).

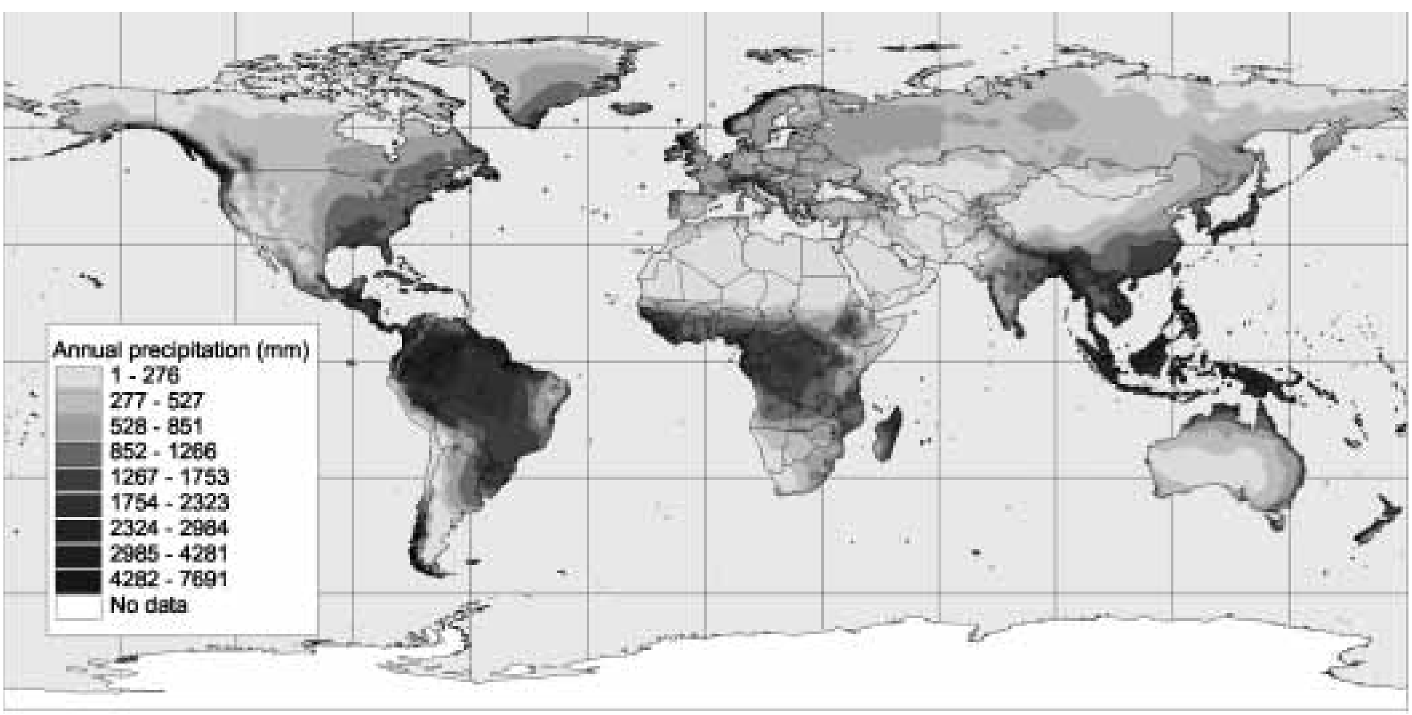
New econometric analyses

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.

[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.

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).

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.