Resource Quality and Agricultural Productivity: A Multi-Country Comparison

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Selected Paper for presentation at the
Annual Meetings of the American Agricultural Economics Association
Tampa, Florida, 31 July 2000

27 July 2000

Abstract

This paper builds on earlier studies of agricultural productivity by incorporating spatially referenced soil and climate data combined with high-resolution land-cover data. Econometric analysis of these data, along with panel data on agricultural inputs and outputs from 110 countries for 1961-1997, quantifies the significant impact that differences in land quality have on agricultural productivity.

The comments of Stan Daberkow, Christof den Biggelaar, Ellen Messer, Jan Poulisse, Shahla Shapouri, and Abebeyehu Tegene on earlier versions are gratefully acknowledged. The views expressed here are those of the authors, and may not be attributed to these reviewers or to USDA.

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Introduction

Over the next two decades, trends in population, income, and urbanization are projected to raise world demand for cereals, roots, and tubers by about 40%, and for meat by about 60% (Pinstrup-Andersen, Pandya-Lorch, and Rosegrant 1999). Given land constraints in some areas and environmental concerns about agricultural land expansion in others, most of the increased production necessary to meet this demand will have to come from increased productivity on land already in agricultural production. Meanwhile, a recent assessment concludes that nearly 40 percent of the world's agricultural land is seriously degraded, undermining both present and future productive capacity (IFPRI 2000).

While economists have long recognized the importance of accounting for differences in the quality of land and other resources when studying productivity, these efforts have been limited by data constraints. This paper builds on earlier studies by incorporating new data on resource quality for 110 countries over the period 1961-1997, offering improved estimates of the contributions of various factors to agricultural productivity. Evidence of the impact of cross-sectional differences in inherent land quality also suggests the importance of improved understanding of the potential loss of productivity associated with changes in land quality over time.

Previous research

We are interested in differences in agricultural productivity levels and growth rates across countries in order to better understand factors that are particularly influential in generating or impeding productivity growth. Those factors are typically studied using either a production function approach or an index approach. In the first approach, differences in output or in land or labor productivity across countries and/or time are explained by differences in the levels of inputs, both conventional (land, labor, tractors, livestock, and fertilizer) and nonconventional (e.g. resource quality, physical infrastructure, research, and government policies). In the second, output is divided by conventional inputs to construct Tornqvist total factor productivity (TFP) indexes, or data envelopment analysis is used to construct Malmquist TFP indexes, differences in which are then explained by differences in the levels of nonconventional inputs.

Studies assessing the contributions of various inputs to agricultural productivity across countries date back several decades. Kawagoe, Hayami, and Ruttan (1985) used a Cobb-Douglas framework to analyze 43 countries for 1960, 1970, and 1980, with five conventional inputs plus two education variables. They found constant returns to scale in the less-developed countries, and increasing returns to scale in the developed countries. Lau and Yotopoulos (1988) used the same data, included first differences to account for fixed country-specific effects, and showed that results varied with functional form. Fulginiti and Perrin (1993) included Peterson's (1987) land quality index in their study of 18 developing countries, and found it to be significant and positively associated with agricultural output in a Cobb-Douglas framework.

Peterson's (1987) unpublished land quality index has been used frequently (see also Frisvold and Ingram 1995, and Lusigi and Thirtle 1997) as an indicator of country-level inherent land quality because it is one of the few such measures that is available to researchers. It is based on the share of a country's agricultural land that is nonirrigated, the share of its cropland that is irrigated, and the log of its long-run average annual precipitation, weighted by coefficients derived from a cross-sectional analysis of land prices in the U.S. 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 improved measures of land quality.

Craig, Pardey, and Roseboom (1997) analyzed 98 countries over six time periods, and included as indicators of land quality the percentage of land that is arable, the percentage of land that is not irrigated, and long-term average rainfall. Using a Cobb-Douglas model, they found output per worker to be significantly associated with land quality. Most recently, Chan-Kang et al. (1999) extended the Craig-Pardey-Roseboom analysis for 36 African countries for 1961-1996. To account for differences in land quality, Chan-Kang et al. included among their explanatory variables the share of agricultural land classified as arable or permanently cropped, the share of agricultural land that is irrigated, and an improved GIS-based measure of annual (as opposed to long-run average) rainfall derived from a 2.5-degree grid. The first of their three land quality variables was consistently positive and significant; the others became insignificant when cumulative R&D expenditures (also insignificant) were included.

Continued efforts to account more precisely for resource quality differences are important, since models that do not correctly specify the differences due to resource quality may incorrectly attribute observed differences in productivity to other factors. In this paper we take advantage of new spatial data on soils and climate and new high-resolution data on land cover to develop and analyze improved measures of land quality for 110 countries. These are described after a brief overview of the model.

Model

We follow the labor productivity model of Craig, Pardey, and Roseboom (1997). The model uses a Cobb-Douglas production function for countries i and time periods t, in which output $Y_i(t)$ is a function of k conventional inputs $X_{ij}^*(t)$, m infrastructure inputs $P_{ij}(t)$, and a temporal shift parameter $A(t)$:

$$Y_i(t) = A(t)\prod_{j=1}^{k} X_{ij}^{*}(t)^{\beta_j} \prod_{j=1}^{m} P_{ij}(t)^{\gamma_j} \ . \qquad (1)$$

The model accounts for measurement error in inputs by allowing effective inputs $X_{ij}^*(t)$ to differ from observed inputs $X_{ij}(t)$ as a function of time-variant quality shifters $Z_{ij}(t)$ and time-invariant measurement errors α_{ij}:

$$X_{ij}^{*}(t) = \alpha_{ij} Z_{ij}(t) X_{ij}(t) \ . \qquad (2)$$

Equations (1) and (2) are combined, and then output and the conventional inputs are divided by the observed number of workers in agriculture, $X_{i1}(t)$, to give:

$$\frac{Y_i(t)}{X_{i1}(t)} = A(t) X_{i1}(t)^{\delta} \prod_{j=2}^{k} \left[\frac{X_{ij}(t)}{X_{i1}(t)} \right]^{\beta_j} \prod_{j=1}^{k} \left[\alpha_{ij} Z_{ij}(t) \right]^{\beta_j} \prod_{j=1}^{m} P_{ij}(t)^{\gamma_j} \ , \tag{3}$$

$$where\ \delta = \sum_{j=1}^{k} \beta_j - 1 \ .$$

If constant returns to scale in the scaled inputs holds, $\delta = 0$. Otherwise, output per worker varies with the number of workers as expressed by the term $X_{i1}(t)^{\delta}$ in equation (3).

We estimate equation (3) in its logarithmic form and add an error term, $\varepsilon_{ij}(t)$, to represent random shocks to output per worker. Dummy variables for all years but one replace the $A(t)$ term to allow for country-invariant shifts in the production function over time. Dummy variables for all countries but one are included to account for unmeasured and time-invariant differences α_{ij} across countries, except when the time-invariant land quality measure is included.

Data

Data on output and conventional inputs for 110 countries are taken from published and unpublished sources at the Food and Agriculture Organization (FAO 1999). *Output* is the value of total agricultural production, measured as the sum of price-weighted quantities of all agricultural commodities, expressed in international dollars, after deductions for feed and seed. *Land* refers to total agricultural land, i.e. the sum of arable land, permanent cropland, and permanent pasture. *Labor* refers to the total economically active population in agriculture. *Livestock* refers to the total number of livestock animals, aggregated with weights used by Hayami and Ruttan (1985). *Tractors* refers to the total number of tractors used in agriculture.

Fertilizer refers to the total quantity of fertilizer consumed in agriculture. Questions regarding the reliability of these data are discussed elsewhere (e.g. Wiebe, Soule, and Schimmelpfennig 1998).

Variables used to capture the effects of differences in resource quality are taken from a variety of sources. Two measures of *land quality* – the percentage of agricultural land that is classified as arable land or permanent cropland, and the percentage of arable land or permanent cropland land that is not irrigated – are taken from FAO. While frequently used, either directly or via the Peterson index, these measures may reflect a variety of economic and other influences in addition to purely physical quality differences. In an effort to better isolate and control for the effects of differences between countries in land quality, we 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 limited by major soil or climate constraints to agricultural production.

This measure is based on FAO's Digital Soil Map of the World and associated soil characteristics (e.g. slope, depth, and salinity). Eswaran et al. (1997) combined these data with spatially referenced long-run average temperature and precipitation data to establish nine land quality classes in terms of their suitability for agricultural production. We then overlaid these land quality classes with political boundaries and newly-available global land-cover data generated from satellite imagery with a resolution of one kilometer (USGS/UNL/JRC, 1999). We focused on cropland identified according to the International Geosphere-Biosphere

Programme land cover classification scheme – the same scheme used in the recent assessment of land degradation by IFPRI and the World Resources Institute (IFPRI 2000). The result is a dummy variable based on the share of each country's cropland that is found in the three best quality classes. Countries where this share exceeds the median value for all 110 countries (20 percent) are identified as having good soils and 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 long-term average or annual rainfall. To better capture this last effect, 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 above. The result is a country-specific time-variant measure of rainfall on cropland.

Two measures of *labor quality* -- life expectancy and the rate of adult illiteracy -- are taken from the World Bank (1999). To capture the enabling environment in which agricultural decisions are made, a first proxy for *institutional quality* is that used by Chan-Kang et al. (1999), a three-part dummy variable (free, partly free, and not free) based on an indicator of political and civil rights developed by Freedom House (1999). We developed an alternative indicator of a more basic dimension of the quality of the institutional environment -- one that seeks to capture the disruptive effects of armed conflict, which Messer, Cohen, and D'Costa (1998) estimate has caused production losses of 4-5 percent in sub-Saharan Africa in recent years. We created a dummy variable based on data from Wallensteen and Sollenberg (1999), Singer and Small (1994), and Sivard (1993) to indicate the occurrence of armed conflict by country and year.

Finally, two measures of *infrastructure* -- road density (in kilometers per hectare of agricultural land) and agricultural research and development expenditures (in cumulative dollars since 1961) -- are taken from Canning (1998) and Pardey, Roseboom, and Anderson (1991) respectively.

Results

Results of four models are presented in table 1. Recall that in each case the dependent variable is the value of agricultural output per worker, conventional non-labor inputs are expressed in per-worker terms, and all variables except dummies are expressed in logarithmic form. Country and time dummies are estimated but not presented. The first model includes conventional inputs and selected indicators of resource quality used in previous studies. Coefficients on the conventional inputs are significant, have the expected signs, and are similar to coefficients found in a model for all 110 countries that excludes nonconventional variables (not reported). They are also broadly consistent with the coefficients reported in Craig, Pardey, and Roseboom (1997), although our labor coefficient is larger in absolute value. Given the model specification in equation (3) above, the negative coefficient on labor indicates decreasing returns to scale in the conventional inputs. Coefficients on the nonconventional variables are also significant and have the expected signs. Coefficients on the year dummies (omitting 1996) were all significant and negative, indicating productivity growth over time (everything else being equal). Coefficients on most of the country dummies (omitting Zimbabwe) were also significant.

The land quality indicators included in the first model reflect annual variation in several land characteristics, some of which (e.g. the percent of agricultural land that is arable, i.e. cultivated) may be influenced by economic factors (e.g. commodity prices or population density). To isolate strictly physical underlying characteristics, the second model adds a dummy variable for the inherent quality of cropland soils and climate. The coefficient is significant and positive, indicating that better inherent soil and climate characteristics are associated with increased agricultural output per worker, everything else being equal. Specifically, taking the inverse log of the coefficient on the dummy indicates that good soils and climate are associated with an increase of about 13 percent in output per worker relative to poor soils and climate.

The coefficient on fertilizer is no longer significant, but most other coefficients increase in marginal significance. The magnitude of the coefficient on land area does not change, but that of the coefficient on the share of land that is arable or permanently cropped doubles. This suggests that when the quality of cropland soil and climate is held constant, output per worker is less sensitive to changes in the total quantity of agricultural land than it is to changes in the share of agricultural land that is used for crops. The coefficient on labor falls in absolute value, indicating that returns to scale are still decreasing, but less sharply than when the quality of soil and climate is not held constant. Since the inherent quality of soil and climate is country-specific but time-invariant, the country dummies are omitted in this model. Coefficients on year dummies (omitting 1996) are significant and negative for 1961-1988.

Model 3 adds measures of institutional quality and infrastructure. A model including the democracy variable used by Chan-Kang et al. (1999) as a proxy for institutional quality (not reported) generated inconsistent results. Armed conflict, by contrast, is associated with a significant decline of about 7 percent in agricultural output per worker. The coefficient on road density is significant and positive. Coefficients on year dummies (omitting 1995) are significant and negative for 1961-1993.

Model 4 adds cumulative agricultural R&D expenditures, the coefficient on which is positive and significant. Armed conflict is significant only at the 10-percent level. Coefficients on the other variables are similar to those generated in the previous models, although comparability is limited by the reduced time period over which R&D data are available. In contrast to the previous models, coefficients on year dummies (omitting 1985) are significant and positive for 1961-1971.

Results for the full set of countries conceal interesting variations across regions. Table 2 presents the results of model 3 for sub-Saharan Africa, Latin America, Asia, and high-income countries. (Remaining countries are located in North Africa, the Middle East, Eastern Europe, or Central Asia.) For example, the coefficient on labor is significant and negative in sub-Saharan Africa and Asia, zero in Latin America, and significant and positive in the high-income countries, indicating decreasing, constant, and increasing returns to scale, respectively. The coefficient on fertilizer is significant and negative in sub-Saharan Africa, zero in Latin America, and positive and significant in Asia and the high-income countries. Further analysis (Wiebe et al. 2000) shows that fertilizer response in sub-Saharan Africa is significant and positive both in countries that have good soils and climate and in countries that do not, although the magnitude of the response is about twice as large in the latter countries.

Among the land quality variables, the coefficient on annual rainfall is significant and positive everywhere except the high-income countries. The coefficient on the percentage of land arable or permanently cropped is significant and positive everywhere except Asia, where this percentage is consistently high. Although land expansion has historically been associated with increased output per worker in Asia (as indicated by the magnitude of the coefficient on land itself), this suggests that population density is closing the frontier, and that further growth in agricultural output per worker will have to come from increased output on lands already under cultivation. Coefficients on the variable representing the inherent quality of soil and climate are significant and positive except in Latin America. In Latin America, where most countries lie above the global median in terms of land quality, additional analysis (not reported) indicates that only the best soils and climate are significantly associated with increased output per worker. 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.

Results for the variables representing labor quality, institutional quality, and infrastructure also vary by region. Notably, the significant negative coefficient on armed conflict in the equivalent model for the full set of countries (table 1, model 3) appears to be driven by the effects of conflict in sub-Saharan Africa. Coefficients on the year dummies for that region (not reported; 1995 omitted) are also unique in that they are negative and significant only for 1976-1993, suggesting that agricultural output per worker had declined from earlier years, everything else being equal. Coefficients on year dummies for the other regions generally indicate level or rising trends in agricultural labor productivity.

Conclusion

Our results indicate that improved indicators of resource quality contribute significantly to observed international differences in agricultural labor productivity, above and beyond the effect of indicators used in earlier studies. Better soils and climate are associated with increases of 20 percent or more in agricultural output per worker in most regions, everything else being equal. Improved estimates of land quality's effects on agricultural output per worker may also improve estimation of the effects of other conventional and nonconventional factors on productivity. Further improvements are expected from continued refinement and experimentation with alternative land quality indicators. Future analyses will include estimation of land quality's effect on land productivity and TFP.

Our findings with regard to the magnitude of the productivity differences associated with differences in the inherent quality of soil and climate, while inherently cross-sectional thus far, suggest the potential productivity impact of changes in land quality over time – for example via land degradation – while controlling for the effects of other physical and economic factors. The impact of such productivity changes on food security underscores the importance of improved understanding of differences in land quality across space and time.

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Table 1 – Results by model for all countries

Variable	Model 1	Model 2	Model 3	Model 4
Intercept	-3.36	-7.83	-8.02	-7.91
	(-8.72)	(-30.39)	(-25.56)	(-24.97)
Conventional inputs				
Land	0.27	0.25	0.30	0.21
	(9.48)	(24.15)	(23.58)	(13.10)
Labor	-0.33	-0.09	-0.06	-0.20
	(-11.98)	(-18.62)	(-11.28)	(-16.44)
Livestock	0.38	0.27	0.27	0.27
	(28.28)	(32.48)	(29.96)	(27.96)
Tractors	0.04	0.10	0.05	0.03
	(8.86)	(18.12)	(7.74)	(3.82)
Fertilizer	0.01	+0.00	0.01	-0.00
	(6.30)	(1.38)	(1.65)	(-0.48)
Land quality				
Annual rainfall	0.13	0.06	0.09	0.09
	(7.40)	(5.39)	(7.42)	(6.48)
Percent arable or permanently cropped	0.18	0.36	0.29	0.23
	(8.20)	(32.86)	(22.55)	(15.83)
Percent not irrigated	-0.13	-0.08	-0.09	-0.07
	(-6.85)	(-12.70)	(-12.41)	(-9.49)
Good soils and climate	--	0.12	0.12	0.09
		(8.22)	(7.69)	(5.49)
Labor quality				
Life expectancy	0.35	1.20	1.28	1.27
	(5.73)	(18.75)	(18.08)	(16.37)
Illiteracy	-0.15	-0.08	-0.07	-0.05
	(-10.68)	(-30.37)	(-21.88)	(-13.60)
Institutional quality				
Armed conflict	--	--	-0.07	-0.05
			(-2.82)	(-1.66)
Infrastructure				
Road density	--	--	0.09	0.06
			(11.63)	(6.96)
Agricultural R&D	--	--	--	0.16
				(12.76)
R^2	0.99	0.94	0.95	0.95
Countries	102	102	92	86
Years	1961-96	1961-96	1961-95	1961-85

Note: figures in parentheses are t-statistics (critical t = 1.96 at the 95% confidence level for two-tailed tests). Model 1 includes country dummies; all models include year dummies.

Table 2 – Results by region for model 3

Variable	**Sub-Saharan Africa**	**Latin America**	**Asia**	**High-Income Countries**
Intercept	-3.03	-0.45	-1.64	-11.65
	(-3.24)	(-0.66)	(-1.41)	(-7.13)
Conventional inputs				
Land	0.17	0.10	0.54	0.12
	(8.61)	(2.96)	(20.13)	(6.15)
Labor	-0.08	+0.00	-0.04	0.04
	(-10.43)	(0.70)	(-3.12)	(5.16)
Livestock	0.19	0.55	0.43	0.53
	(15.19)	(13.16)	(11.94)	(26.05)
Tractors	0.03	0.06	-0.07	-0.05
	(2.73)	(3.72)	(-4.56)	(-4.36)
Fertilizer	-0.01	+0.00	0.21	0.35
	(-2.20)	(0.34)	(13.02)	(15.56)
Land quality				
Annual rainfall	0.13	0.10	0.24	-0.18
	(5.87)	(2.52)	(5.76)	(-8.15)
Percent arable or permanently cropped	0.17	0.47	0.01	0.04
	(9.44)	(17.60)	(0.20)	(2.21)
Percent not irrigated	-0.94	-0.38	-0.38	-0.48
	(-6.95)	(-3.40)	(-6.72)	(-13.13)
Good soils and climate	0.25	-0.18	0.29	0.20
	(9.85)	(-7.78)	(7.14)	(12.13)
Labor quality				
Life expectancy	0.98	-0.70	-0.36	2.09
	(7.82)	(-4.65)	(-1.57)	(5.81)
Illiteracy	0.20	-0.56	-0.30	0.04
	(5.21)	(-14.96)	(-12.51)	(12.46)
Institutional quality				
Armed conflict	-0.08	0.07	0.04	-0.04
	(-2.73)	(3.09)	(2.37)	(-0.73)
Infrastructure				
Road density	0.07	-0.08	-0.12	0.23
	(7.63)	(-4.18)	(-5.98)	(16.29)
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: figures in parentheses are t-statistics (critical t = 1.96 at the 95% confidence level for two-tailed tests). All models include year dummies.