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Cereal Crop Productivity in Developing Countries: Past Trends and Future Prospects

Prabhu L. Pingali and Paul W. Heisey

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Contents

Abstract

This paper synthesizes the evidence on cereal crop productivity in developing countries over the past 30 years and looks at future prospects for productivity growth. For more than three decades we have witnessed the phenomenal growth of cereal crop productivity in the developing world. Termed the Green Revolution, the initial phase of this growth resulted from an increase in land productivity and occurred in areas of growing land scarcity and/or areas with high land values. Significant investments in research and infrastructure development, especially irrigation, were the strategic components of this increased productivity. In the post-Green Revolution period, particularly in Asia, productivity growth has been sustained through increased input use and, more recently, through *more efficient* use of inputs. Lately, however, indicators show a decrease in the growth rate of productivity of two of the three primary cereals, rice and wheat. The first two sections of this paper present trends on cereal crop productivity in developing countries over the last three decades. Supporting evidence includes yield and other partial factor productivity trends and a summary of studies on total factor productivity. The third section speculates on the prospects for future growth.

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Introduction

For more than three decades (1965–present) we have witnessed the phenomenal growth of cereal crop productivity in the developing world: rice in Asia; wheat, globally in irrigated and favorable production environments; and maize in Mesoamerica and select locations in Africa and Asia. The extraordinary growth in cereal crop productivity, aptly termed the Green Revolution, resulted from an increase in land productivity and occurred in areas of growing land scarcity and/or areas with high land values. It was always associated with strong market infrastructure and supportive government policies. Significant investment in research and infrastructure development, especially irrigation, were the principal components of the strategy for improving cereal crop productivity during this era.

In the post-Green Revolution period, particularly in Asia, productivity growth has been sustained through increased input use and, more recently, through *more efficient* use of inputs. Lately, however, indicators show a decrease in the growth rate of productivity of two of the three primary cereals—rice and wheat—especially in the intensively cultivated lowlands of Asia. This reduction in productivity growth can be attributed to three key factors: 1) degradation of the land resource base due to intensive cultivation; 2) declining infrastructure and research investments; and 3) the increasing opportunity cost of labor. Future increases in food productivity growth will rely on substantial research investments aimed at shifting the yield frontier of rice and wheat, and improving the profitability of cereal crop production systems through more efficient use of inputs.

This paper synthesizes the evidence on cereal crop productivity in developing countries. Not unexpectedly, the vast majority of studies have measured productivity in terms of yield per hectare. A substantially smaller number of studies provide trends in other partial factor productivity (PFP) indicators, and a few provide total factor productivity (TFP) trends.[1] Fewer still decompose TFP growth to identify contributing factors, such as research, infrastructural investments, and agricultural policies. Although concerns may be expressed about data quality, aggregation procedures, or the methods used to measure productivity, comparisons across countries and continents do reveal some striking similarities in productivity trends.

The first two sections of this paper present trends on cereal crop productivity in developing countries over the last three decades. Supporting evidence includes yield and other PFP trends and a summary of studies on TFP. The third section speculates on the prospects for future growth.

1 Most of the literature refers to total factor productivity. We will tend to use the term "total factor" productivity even though in most empirical situations, some of the factors that produce agricultural output (e.g., environmental services) are not measured (Alston, Norton, and Pardey 1995).

Cereal Crop Productivity Performance and Sources of Growth

Increasing cereal crop productivity through the application of modern science to agriculture has been most successful in land-scarce economies, particularly in Asia. Partial and total factor productivity studies conducted in Asia attest to the contributions made by biological innovations to increasing food production and alleviating food scarcity. The returns to investments in agricultural research and irrigation infrastructure have been the highest in areas with acute land scarcities, but good market infrastructures. Rising land values caused by increasing land scarcity, and the rapid adoption of crop intensification technologies have been key factors contributing to productivity growth for rice and wheat in much of Asia.

The published literature for Latin America and Africa is much sparser and presents a more mixed record. At an individual country level, cereal yields have increased markedly in some Latin American and African countries, while demonstrating a more variable pattern in others. Given lower population densities than those found in Asia, the forces influencing intensification and productivity growth have been the level of prior investments in market infrastructure and the extent to which countries pursued an export-oriented trade policy. As demand for cereals became more elastic through improved access to domestic and export markets, the expansion of cereal output became profitable with the adoption of productivity-enhancing technologies. Cereal crop productivity growth in Argentina, Brazil, and South Africa can be traced to the explicit export orientation of their agricultural sectors.

In contrast, cereal crop output and productivity growth rates have been particularly low in sub-Saharan Africa over the last three decades. In many parts of the region, rapid population growth has outstripped more modest gains in food crop production. Relative land abundance (in comparison to Asia), poor market infrastructure, and inward-looking trade policies contributed to the modest performance of this region's cereal crop sector. Farmers there face an inelastic demand for basic cereals and have little incentive to invest in productivity-enhancing technologies.

Yield Growth in Rice, Wheat, and Maize

Output and yield growth rates remain the most commonly used indicators of productivity growth in developing country agriculture (Table 1). The aggregate rice output growth rate for Asia increased from 2.1% annually during 1955–65 to 2.9% annually during 1965–80, surpassing the annual population growth rate of 2.3%. Area expansion contributed to nearly one-third of Asian rice output growth in the 1960s and one-fifth in the 1970s. Rapid yield growth from 1965 to 1980 resulted primarily from the adoption of modern rice varieties. In the past decade, however, growth in aggregate rice output has declined to 1.5% per year. Rice yield growth in Asia also declined sharply in the 1980s from an annual rate of 2.8% in the preceding decade to 1.4% from 1986–present. Reasons for the slowdown in rice productivity growth in Asia are discussed in the following sections.

For all developing countries (excluding China and India, the two largest wheat producers) wheat yields grew at an average annual rate of more than 2% between 1956 and 1995. Wheat yields in China and India grew at a very rapid rate during much of this period, with yields in India rising particularly sharply during the initial Green Revolution period. Although these countries have recently experienced declining rates of growth in wheat yields, recent rates still exceed 2% per year or more according to the latest data. Wheat yields in South and East Asia, excluding China and India, grew at an annual average rate of 2.6% over the 1956–95 time period, displaying much the same pattern over time as India, but with a greater decrease in growth rates in recent years. Latin America lagged behind Asia with a yield growth rate of approximately 1.8% per year. In West Asia/North Africa and sub-Saharan Africa, rates of yield increase have tended to vary over time and to display a less consistent pattern than other regions.

Table 1. Annual rates of growth in yield for major cereals in developing countries

Region/Country	1956–95	1956–65	1966–75	1976–85	1986–95
Rice					
Total Asia	1.83	0.72	1.83	2.84	1.39
Southeast Asia	2.16	1.07	2.86	3.57	2.48
South Asia	1.49	0.01	1.93	2.89	2.48
China	2.70	1.29	1.45	4.89	1.39
India	2.02	1.41	2.25	2.79	3.00
Wheat					
All LDCs[a] less China, India	2.09	1.51	2.35	2.32	1.12
South, East, and Southeast Asia, less China, India	2.60	0.90	5.04	2.19	1.43
West Asia/North Africa	2.10	0.68	1.87	1.43	1.07
Latin America	1.80	3.54	1.90	4.58	1.59
Sub-Saharan Africa	2.44	2.79	3.56	-0.06	1.93
China	4.58	-0.70	4.66	7.32	2.08
India	3.45	2.33	4.59	3.58	2.58
Maize					
All LDCs less China, Brazil, Argentina, Chile, South Africa	1.65	1.75	1.01	3.00	2.05
South, East, and Southeast Asia, less China	1.70	1.23	1.43	2.96	2.26
West Asia/North Africa	2.75	3.74	1.85	2.52	2.28
Latin America less Brazil, Argentina, Chile	2.26	3.14	1.48	3.70	3.01
Sub-Saharan Africa less South Africa	1.04	0.41	1.93	-0.26	0.17
China	3.83	0.09	4.10	4.84	3.30
Brazil	1.68	0.68	1.47	2.62	4.29
Argentina	2.61	0.29	2.43	2.29	3.58
South Africa	1.81	1.08	4.67	-3.46	-2.27

[a] Less developed country (LDC).

Of the three major cereal crops, the global yield performance of maize was the worst during 1956–95, with particularly poor growth rates in sub-Saharan Africa (Table 1). Maize yields in developing countries, excluding the commercial producers (China, Brazil, Argentina, Chile, and South Africa, which plant a majority of their maize area to hybrids) grew at somewhat less than 2% annually during 1956–1995. Yield growth rates for maize do not display the patterns found in rice and wheat: the rates appear to fluctuate more randomly, particularly in sub-Saharan Africa, and some regions display rising yield growth towards the end of 1956–1995. The predominantly rainfed nature of maize production in sub-Saharan Africa and its subsistence orientation account for its low and fluctuating growth rates during the last three decades.

Changes in Partial Factor Productivity (PFP) of Land and Labor

Arnade (1994) provides estimates for land and labor productivities for countries in Asia, Africa, and Latin America. Cross country comparisons of land and labor productivities for the Asian rice economies are provided in Figure 1. Asian economies that started with low land and labor productivities in the 1950s and early 1960s are now on a trajectory toward high productivities. The movement toward achieving high land and labor productivities is conditioned by land scarcity and the level of economic development. Cross country comparisons of land and labor productivities for Latin America and Africa do not show a clear pattern.

Increases in land productivity have come from the intensification of agricultural production and the adoption of yield enhancing technologies, especially modern high-yielding varieties and fertilizers. The transition from low-yield, land-extensive cultivation systems to land intensive, double and triple crop systems is only profitable in societies where the land frontier is exhausted (Boserup 1965; Hayami and Ruttan 1985; Pingali and Binswanger 1987). Kikuchi and Hayami (1978) document the process of land augmentation as the

Labor productivity \ **Land productivity**	Low	Moderate	High
High			South Korea Malaysia Japan
Moderate	Thailand Myanmar	Indonesia Vietnam	China
Low	Bangladesh Cambodia Nepal Sri Lanka	India Pakistan Philippines	

Figure 1. Land and labor productivities in the Asian rice economies, 1985-87.
Source: Arnade (1994).

cultivation frontier closes for Japan, Taiwan, Korea, and the Philippines. Where population densities are low, the returns to intensification are high only if export markets are available and accessible (for example, the Central Plains of Thailand or parts of South America's Southern Cone). If these conditions are not present, labor and other costs associated with intensive agriculture are substantially higher than the incremental returns to intensification. This holds true even with the adoption of labor-saving technologies.

Much of South and Southeast Asia made the transition to land-intensive production systems in the 1950s and 1960s. East Asia made this transition earlier (Barker and Herdt 1985; Bray 1986). A cross-sectional comparison across Asian countries shows that the proportion of irrigated area, the percentage of area under high-yielding varieties (HYV) of cereal crops (especially rice and wheat), and fertilizer use is positively related to population densities (Pingali, Hossain, and Gerpacio 1997).

In other parts of the world, land augmentation technologies have also been developed and diffused, but on a far more dispersed basis. Looking at agroclimatic population densities (Higgins et al. 1982), one would expect this to occur more in regions such as the eastern African highlands or Latin American countries such as Mexico, Guatemala, El Salvador, and the Dominican Republic. Agroclimatic population densities are one example of an attempt to correct the measurement of the land variable to account for differences in land quality. Thus, for example, an apparently land abundant country like Niger has an extremely high agroclimatic population density because most of its land is of very poor quality.

The evidence relating population pressure to land augmentation outside of Asia is fragmentary and mixed. Block's (1993) study of sub-Saharan Africa shows that indeed, output growth in eastern Africa was the highest for all regions during 1963–1988. Likewise Thirtle, Hadley, and Townsend (1995) demonstrate high growth rates in agricultural sector total factor productivity (TFP) in densely populated Rwanda and Burundi. Beyond that, however, there are few apparent relations between agroclimatic population densities and regional TFP growth. This may be, in part, because African countries with widely differing population pressures are often grouped in the same geographical region. Another explanation could be that countries with very low land quality, such as many of those found in the Sahel, have comparatively high populations relative to available land when land quality is taken into account, while currently possessing fewer agricultural technology options (Sanders, Shapiro, and Ramaswamy 1996).

Rising labor productivity in Asia is associated with the increasing adoption of labor-saving technologies, both as a means of saving on higher labor requirements stemming from intensification and as a way of economizing on labor as its opportunity cost rises with economic growth. The movement from single crop cultivation systems to double- and triple-crop systems shifts out the demand for labor and also increases the need for timely completion of operations. Farm surveys conducted by the International Rice Research Institute (IRRI) in 30 rice growing villages across five Asian countries in 1970–71 indicate a shift in the demand for labor with modern variety adoption (Barker and Cordova 1978). The demand for both family and hired labor increased. A more recent comparison of labor requirements in the irrigated and rainfed rice production systems of six Asian countries indicates that adoption of modern varieties in favorable environments significantly increases labor use per hectare by raising labor requirements for crop care, harvesting, and threshing (David and Otsuka 1994).

Initially, the switch to modern varieties was profitable, even with higher labor requirements per hectare, because the labor requirements per ton of paddy were lower compared to that of traditional varieties (Barker and Cordova 1978). Over time, however, increased labor demand for peak-period operations led to a rise in real wages for these operations, even in densely populated, labor surplus countries such as India (Bardhan 1970; Lal 1976) and Indonesia (Naylor 1992). The rise in wages was further exacerbated by the concurrent growth in the rural non-farm sector and increasing employment opportunities in the urban sector, a trend previously identified in Japan and Korea and now being witnessed in Southeast Asia.

Widespread adoption of labor-saving mechanical and chemical technologies has alleviated the growing labor constraints, and contributed substantially to overall productivity growth (Sidhu and Byerlee 1992). The most notable confirmation of this hypothesis comes from the now developed country, Japan, where graphs plotting the log of land productivity against the log of labor productivity show almost no increases in land productivity, but substantial gains in labor productivity during the last 30 years (Hayami and Ruttan 1985; Craig, Pardey, and Roseboom 1997).

Changes in Input Use for Cereals

An assessment of overall growth in cereal crop productivity would require information on trends in productivity of other factors of production, such as fertilizers, and trends in crop specific TFP. The issue is one of identifying whether the rate of growth in output is greater than the rate of growth in inputs used. Though an increase in yields may be observed at the farm level, it may be coming at the cost of proportionately greater input use. While the evidence on positive output and yield growth is clear, the evidence on trends in other partial factor productivities (PFPs) is mixed both across countries and over time.

With rice, national data across Asia indicate that the rate of growth in yields has been substantially smaller than the rate of growth in fertilizer use over the past three decades (Pingali, Hossain, and Gerpacio 1997). Consider the following intensively cultivated rice bowls of Southeast Asia for 1980–1989: Central Luzon, Philippines; Central Plains, Thailand; and West Java, Indonesia. Farm panel data sets for each of these locations indicate that in the 1980s, the rate of growth in yields was lower than the rate of growth in input use (Pingali 1992). In Central Luzon, a 13% yield increase over a 10-year period was achieved with a 21% increase in fertilizer application (kg/ha), and a 34% increase in seed application (kg/ha). In the Central Plains, for the same period, yields increased by 6.5%, while fertilizer application rates (kg/ha) increased by 24% and pesticide application rates (kg/ha) by 53%. Similarly, for West Java, yields increased by 23%, while fertilizer use increased by 65%, and pesticide use increased by 69% (Pingali 1992).

In the case of wheat, factor use trends were assessed by Sidhu and Byerlee (1992) for the Indian Punjab, between 1972 and 1989, and by Kumar and Mruthyunjaya (1992) for five major Indian wheat producing states (Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, and Rajasthan) between 1971 and 1989. These states constitute 80% of India's wheat area and just under 90% of wheat production; three states (Punjab, Haryana, and Uttar Pradesh) form India's irrigated wheat heartland.[2]

Kumar and Mruthyunjaya (1992) found that in all the states studied, the "modern" inputs of fertilizer and machine power grew during 1979–1989 at even faster rates in the irrigated heartland. Pesticide use rose sharply from a limited base in Punjab and Haryana, while applications were negligible in the other states. Human labor fell in all states, particularly in Rajasthan and Madhya Pradesh, and animal labor fell precipitously in all states. Seed rates (kg/ha) rose in Punjab and Uttar Pradesh, rose slightly in Haryana, and showed no trend in the other states. Manure use in wheat production fell in all states except Madhya Pradesh. The trends in input use recorded by Kumar and Mruthyunjaya for Punjab are completely consistent with those reported by Sidhu and Byerlee (1992).

By the late 1980s, the most advanced "post-Green Revolution" areas of Asia, such as the Punjab of India and Central Luzon of the Philippines, had reached a point of sharply diminishing returns to further intensification and had entered a second "post-Green Revolution" phase characterized by the substitution of better knowledge and management skills for higher levels of input use (Byerlee and Pingali 1994). Productivity gains accrue to farmers from differences in the way inputs are used; that is, the timing and method of input use (Byerlee 1987; Pingali, Moya, and Velasco 1990). For instance, two farmers in the same location with the same soil types and irrigation access, using the same varieties and nitrogen levels, may have different yields because of differences in the timing and method of nitrogen application. Over time, farmer technical knowledge and management skill become the primary determinants of differences in productivity and profits between farmers.

Improved knowledge and skills help farmers improve the technical and allocative efficiency of input use. Varietal selection, fertilizer timing and placement, water use, and pesticide application are areas in which efficiency gains can lower unit costs of production. It should be recognized, however, that the adoption of knowledge-intensive technologies requires farmers to exchange reduced input levels for higher time commitments to management and supervision. Farmer incentives for adopting techniques that increase input efficiency depend upon the price of inputs relative to the opportunity cost of time.

We would predict that conventionally measured TFP indices, using standard methods, would show accelerating growth in TFP during the knowledge- and management-intensive phase. However, should the effects of greater labor demands (reflected in the increasing opportunity costs of time) be fully included, together with corrections to the labor input to account for human capital, the predicted results would be more ambiguous. At this point, accounting for the history of TFP measurement in developed countries would be useful.

2 Much of Rajasthan's wheat area is also irrigated, but growing conditions are somewhat harsher there.

For both South and Southeast Asia, the primary unexploited avenue for further productivity growth is enhancing input efficiency through knowledge-based technologies. The importance of using inputs more efficiently has been reinforced by recent evidence of significant problems in sustaining the quality of the resource base for intensive rice production systems in Asia (Pingali and Rosegrant 1993; Cassman and Pingali 1995). These sustainability problems are clearly reflected in the rapid decline in PFPs, especially for nitrogen fertilizer, and in the leveling off or decline in the growth of TFP. In other words, the yield gains achieved in the post-Green Revolution period are being maintained by increasingly higher levels of inputs to compensate for degradation of the lowland resource base (Byerlee and Siddiq 1994; Cassman and Pingali 1995).

Total Factor Productivity Growth in Developing Country Agriculture

Partial factor productivity measures do not provide a holistic picture of the long-term impact of technological change on cereal crop production systems. Is a partial productivity measure, such as yield increasing over time, attributable to a fundamental change in the production process, or are other inputs simply substituting for land? Total factor productivity trends over time are often used to assess net gains from technological change. Total factor productivity is calculated by dividing an output index by an input index. As a result, changes in output over time can be partitioned into changes resulting from increased input use and changes in TFP. A few studies (e.g. Fan 1991; Arnade 1992; Thirtle, Hadley, and Townsend 1995) further divide TFP into a technical progress component and an efficiency gain component. These simple decompositions will be the basis of most of our discussion.[3]

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3 Nonetheless, there are many complicating issues and alternative approaches to the analysis of TFP. These need to be remembered when considering the evidence on TFP presented below. The first issue is the relationship between TFP and the aggregate agricultural production function (Hayami and Ruttan 1985; Lau and Yotopoulos 1989; Trueblood 1991). If the underlying production function is not constant returns to scale, changes in aggregate output may be caused by scale effects and by changes in input levels, technical progress, and changes in efficiency (Capalbo 1988; Arnade 1992). Furthermore, it is almost always impossible to define and measure all of the inputs and outputs in the agricultural production process (Alston, Norton, and Pardey 1995).

Second, aggregation procedures and shifts in relative prices can be problematic for studies that make inter-country comparisons or analyses that compare the agricultural sector with other sectors in the same country. Two major approaches to output aggregation for international comparisons are the physical "wheat units" aggregation (Hayami and Ruttan 1985) and the method of first creating an index of real national-level output, then converting to a common currency using agricultural purchasing power parity (PPP)-based exchange rates (Pardey, Roseboom, and Craig 1992).

Quality differences and quality changes in outputs, and particularly in inputs, can cause both conceptual and measurement problems. One major issue is the endogeneity of land and labor quality to past investments in infrastructure and education. A related issue is whether input quality differences in a given period or over time are accounted for by price differentials (Craig, Pardey, and Roseboom 1997; Arnade 1994; and Binswanger, Khandker, and Rosenzweig 1993).

Finally, data limitations often hamper attempts to empiricize some of the more complex constructs pertaining to changes over time in agricultural output, input use, technical change, efficiency, and the like. This is a particular problem for developing countries.

Empirical Studies of Total Factor Productivity Growth in Developing Country Agriculture

There are few examples of crop-specific TFP measurement. The exceptions include Cassman and Pingali (1995), and Pardey et al. (1992) for rice; and Sidhu and Byerlee (1992), and Kumar and Mruthyunjaya (1992) for wheat. There are many TFP studies, however, that track productivity growth for the aggregate crops sector or the aggregate agricultural sector (Table 2). Total factor productivity estimates for aggregate crop output are widely available for Asia. Studies for Latin America and Africa, with a few exceptions, estimate TFP for the aggregate agricultural sector. Because a large part of observed technical change in developing country agriculture has affected cereal staples, in a broad sense these TFP estimates partially reflect technical change in cereal production.

Several observations emerge from Table 2 and from a comparison with TFP estimates for agriculture in developed countries. First, agricultural output growth in developing countries has been overwhelmingly positive and positively related to growth in TFP (Figure 2). On average, 40–45% of measured output growth in the studies reported in Table 2 results from growth in TFP. In contrast, recent growth rates in agricultural output in developed countries have been lower, on average, than those in developing countries; however, growth rates in agricultural TFP have been higher in the former than the latter. In many industrialized countries growth in TFP has accounted for all the growth in agricultural output in a simple accounting framework, as input use in agriculture has actually contracted (see, for example, Shane, Roe, and Gopinath 1998; Ball et al. 1997; Cox, Mullen, and Hu 1996; Narayanan 1996).

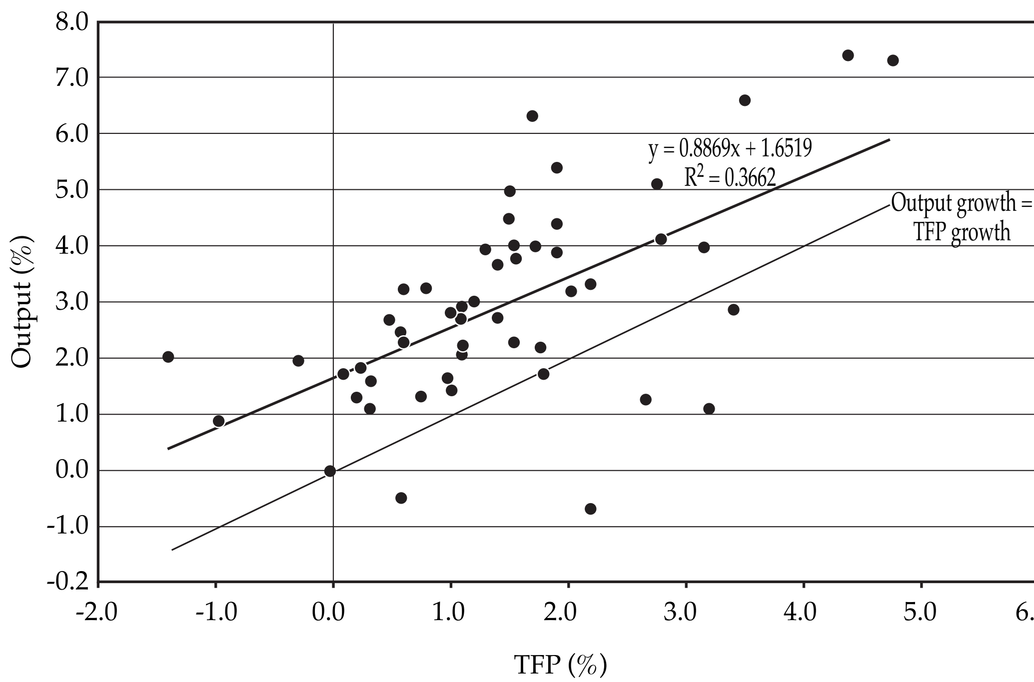

Figure 2. Contribution of TFP growth to output growth in developing country agriculture.
Source: Table 2.

Table 2. Evidence on productivity growth in developing country agriculture, all crops, 1950–1994

Country	Time period	Output growth	Input growth	TFP growth	Aggregation procedures	Indexing methods	Reference
		—Average annual rate—					
India	1950-60	3.9	2.0	1.9	Wheat units		V.D. Galgalikar, M.R. Alshi in APO (1987)
	1961-70	2.8	1.8	1.0			"
	1971-80	2.9	1.8	1.1	"		"
	1950-80	2.9	1.8	1.1	"		"
India	1956-67	2.2	1.1	1.1		Tornqvist-Theil TFP	Rosegrant and Evenson (1995)
	1967-76	2.7	1.3	1.4		"	"
	1976-86	2.1	1.0	1.1		"	"
India	1956-65			0.81		Tornqvist-Theil TFP	Rosegrant and Evenson (1993)
	1965-75			1.22		"	"
	1975-85			0.98		"	"
Pakistan	1950-55	1.8	1.6	0.22	Wheat units		S. Islam Ahmed in APO (1987)
	1955-60	2.3	1.8	0.60			
	1960-65	3.7	2.4	1.40			
	1965-70	5.1	2.3	2.78			
	1970-78	2.7	2.3	0.47			
	1978-83	4.0	2.4	1.58			
Pakistan	1956-65			1.65		Tornqvist-Theil TFP	Rosegrant and Evenson (1993)
	1965-75			1.86		"	"
	1975-85			-0.36		"	"
Philippines	1950-60	5.0	3.5	1.5			David et al. in APO (1987)
	1960-70	3.2	2.4	0.8			
	1970-80	6.3	4.6	1.7			
Thailand	1951-61	7.4	3.0	4.4	Wheat units		Boonkerd Budhaka APO, 1987
	1961-71	4.5	3.0	1.5			
	1971-81	5.4	3.5	1.9			
Bangladesh	1960-70			1.3		Tornqvist-Theil	Dey and Evenson (1991)
	1970-80			-0.09			
	1980-89			0.79			
Taiwan	1951-66	4.6	2.5	2.1	Constant prices 1965-67: base period	Laspeyres index (annual chain formula)	Yueh-eh Chen in APO (1987)
	1951-58	4.4	2.5	1.9			
	1958-62	2.7	1.6	1.1			
	1962-66	6.6	3.1	3.5			
	1966-75	1.5	0.4	1.1			
	1966-71	1.7	-0.1	1.8			
	1971-75	1.3	1.1	0.2			

cont'd.

Table 2. (continued)

Country		Time period	Output growth	Input growth	TFP growth	Aggregation procedures	Indexing methods	Reference
			—Average annual rate—					
Taiwan		1975-81	0.2	-2.5	2.7			
		1975-78	1.1	-2.1	3.2			
		1978-81	-0.7	-2.9	2.2			
		1951-81	2.7	0.8	1.9			
China	a)	1965-79			0.19		Production elasticities	Fan (1990)
		1980-86			3.18			
		1965-85			1.14			
	b)	1965-79			2.23		Factor shares	Fan (1990)
		1980-86			5.15			
		1965-85			3.11			
China		1970-78			-0.71			Kalirajan et al. (1996)
		1978-84			1.24			
		1984-87			0.91			
Brazil		1968-1987	3.96	2.25	1.71	Price weights	Tornqvist (unchained) (Constant returns to scale)	Arnade (1992)
Mexico, all agriculture		1960-91	4.1	1.3	2.8	Price weights	Tornqvist (chained) (1997)	Fernandez-Cornejo and Shumway
South Africa, all agriculture		1947-91	3.0	1.8	1.2	Revenue shares	Tornqvist (chained)	Thirtle et al. (1993)
Zimbabwe, commercial agriculture		1970-89	2.86	-0.56	3.43	Price weights	Tornqvist (chained)	Thirtle, von Bach, and van Zyl (1993)
Zimbabwe, communal agriculture		1975-90	7.32	2.56	4.76	Price weights	Tornqvist (chained)	Thirtle, von Bach, & van Zyl (1993b)

cont'd

Table 2. (continued)

Country	Time period	Output growth	Input growth	TFP growth	Aggregation procedures	Indexing methods	Reference
(For all the following countries, estimates are for aggregate agriculture (crops and livestock)							
		—Average annual rate—					
Burkina Faso	1971-86	3.77	2.20	1.57	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Burundi	1971-86	1.24	-1.44	2.68	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Cameroon	1971-86	1.65	0.67	0.98	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Central African Rep.	1971-86	2.16	0.40	1.76	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Peoples Rep. of the Congo	1971-86	2.01	3.41	-1.40	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Congo (formerly Zaire)	1971-86	2.28	0.74	1.54	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Ethiopia	1971-86	1.30	0.56	0.74	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Ghana	1971-86	-0.49	-1.07	0.58	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Côte d'Ivoire	1971-86	3.92	2.62	1.30	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Kenya	1971-86	3.25	2.66	0.59	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Malawi	1971-86	2.41	1.84	0.57	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)

cont'd

Table 2. (continued)

Country	Time period	Output growth	Input growth	TFP growth	Aggregation procedures	Indexing methods	Reference
		—Average annual rate—					
Mali	1971-86	3.31	1.11	2.20	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Nigeria	1971-86	1.40	0.39	1.01	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Rwanda	1971-86	3.98	0.82	3.16	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Senegal	1971-86	0.00	0.04	-0.04	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Sierra Leone	1971-86	1.59	1.27	0.32	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Sudan	1971-86	1.93	2.24	-0.31	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Tanzania	1971-86	3.19	1.15	2.04	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Togo	1971-86	1.73	1.65	0.08	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Zambia	1971-86	0.89	1.87	-0.98	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)
Zimbabwe	1971-86	1.08	0.78	0.30	PPP conversion (international dollars)	Chained Malmquist index	Thirtle, Hadley, and Townsend (1995)

Second, some studies (e.g., Rosegrant and Evenson 1993; Fernandez-Cornejo and Shumway 1997) show higher growth rates in TFP at times of known rapid technological change, such as the rapid diffusion of high-yielding varieties and fertilizer. In other cases and countries, TFP growth rates have been high in periods *before* classic Green Revolutions; and in yet others, TFP has grown rapidly where no easily defined Green Revolutions have taken place. More disaggregated studies not summarized in Table 2 (e.g., Murgai 1997; Sidhu and Byerlee 1992) sometimes found that TFP growth rates can be higher during immediate post-Green Revolution periods than in the initial diffusion of seed/fertilizer technology, suggesting that TFP growth is low because of extremely rapid input growth during Green Revolution periods. In post-Green Revolution periods, TFP can grow more rapidly as input growth slackens but inputs are used more efficiently. Other authors of disaggregated studies (e.g., Cassman and Pingali 1995; Ali and Velasco 1993; Ali 1998) find evidence of agricultural resource degradation in recent slowing and even negative trends in TFP. Some studies (e.g. Fan 1991; Lin 1992; Kalirajan, Obwona, and Zhao 1996; Arnade 1992; Block 1993) discern relatively short periods of rapid increases in agricultural TFP associated with major policy reforms. In all these cases, TFP evidence can lend strong support to the argument but is insufficient in and of itself to conclude the case. We turn now to some empirical studies that analyze causes of differences in growth rates over time and across regions, and the relative importance of those sources.

Sources of Total Factor Productivity Growth in Developing Country Agriculture

Table 3 reports the results of studies that formally decomposed sources of growth in agricultural TFP in developing countries, or that used regression analysis to explore these sources without a formal decomposition. Though the studies are disparate and use different methodologies, several common themes emerge.

There is a consistent emphasis on agricultural research among these studies. It is the most commonly cited source of productivity growth and its effect is nearly always found to be positive and quantitatively important. A few authors (e.g., Evenson and McKinsey 1991; Rosegrant and Evenson 1995; Fernandez-Cornejo and Shumway 1997) analyze direct research and research spillovers separately; Evenson and colleagues sometimes further distinguish between public and private research.

Relatively few studies examine efficiency changes over time, although several more look at the related area of the effects of policy changes. These studies (e.g., Fan 1991; Lin 1992; Arnade 1992; Thirtle, Hadley, and Townsend 1995), and related studies that do not formally decompose TFP growth (Kalirajan, Obwona, and Zhao 1996; Block 1993) suggest that relatively strong gains through technical change can sometimes be partially or even totally negated through inefficiency. They also find that policy reform can have a strong positive effect on productivity growth; however, the effect is usually short term (3–5 years).

Infrastructure, another less-studied, but interesting and complicated, determinant of TFP growth in developing country agriculture, is an important factor, but a difficult one to operationalize. Some proxy variables include market density and irrigation. In the studies cited in Table 3, these variables have mixed, but usually positive, effects. Accounting for

Table 3. Decomposition of agriculture productivity growth

Country or region	Time period	Crop or sector	Sources	Annual growth	Percent share TFP growth explained	Source
China	1965-85	Aggregate agriculture	Institutional change		62.9	Fan (1991)
			Technological change		37.1	
China	1978-84	Aggregate agriculture	HH farming reform		46.89	Lin (1992)
			Multiple cropping		1.94	
			Ratio of non-grain crops		3.69	
	1984-87	Aggregate agriculture	HH farming reform		0	
			Multiple cropping		20.90	
			Ratio of non-grain crops		27.79	
India	1971/72 1988/89	Rice	Research	5.86	57.2	Kumar and Rosegrant (1994)
			Markets	5.60	14.4	
			$P_2 0_5$: N ratio	1.87	9.9	
			Agricultural Terms of trade	-1.56	18.9	
			Canal share in total irrigation	-0.56	-0.3	
India (5 states)	1970/71 1988/89	Wheat	Market infrastructure		High	Kumar and Mruthyunjaya (1992)
			Literacy		Negative	
			Research		High	
			Mechanization		High	
			January-March rainfall		Inter- mediate	
India (10 states)	1972/74 1982/84	Crops	HYV expansion		38?	Evenson and McKinsey (1991)
			Public research		18?	
			Private research		36?	
			Irrigation		<1?	
			Markets		1?	
India	1956-87	Crops	Modern varieties		7	Rosegrant and Evenson (1995)
			Foreign research		25	
			Domestic public research		25	
			Domestic private research		15	
			Extension		33	
			Infrastructure		10	
			Residual		-15	

cont'd

Table 3. (continued)

Country or region	Time period	Crop or sector	Sources	Annual growth	Percent share TFP growth explained	Source
India irrigated districts	1956-64	Crops	HYV area	0	0	Fan and Hazell (1997)
			Literacy	2.55	Negative	
			Irrigation	0	0	
	1967-77		HYV area	19.58	High	
			Road density	3.94	Low	
			Literacy	2.05	Negative	
			Irrigation	0.12	Low	
	1978-90		HYV area	3.38	Negative	
			Road density	2.87	Low	
			Literacy	2.29	Negative	
			Irrigation	1.20	Medium	
India rainfed districts	1956-64	Crops	HYV area	0	0	Fan and Hazell (1997)
			Road density	2.60	Low	
			Literacy	2.44	Negative	
			Irrigation	0.93	High	
	1967-77		HYV area	20.41	High	
			Road density	5.45	Low	
			Literacy	1.90	Negative	
			Irrigation	3.64	High	
	1978-90		HYV area	4.92	Low	
			Road density	3.30	Low	
			Literacy	1.91	Negative	
			Irrigation	3.29	High	
India	1950/51 1988/89	Aggregate agriculture	Use of modern inputs (irrigation, fertilizer, HYV)		High	Dholakia and Dholakia (1993)
Pakistan	1955-85	Crops	Modern varieties		Important	Rosegrant and Evenson (1993)
			Research		Important	
			Infrastructure		Important	
			Human capital		Important	

cont'd

Table 3. (continued)

Country or region	Time period	Crop or sector	Sources	Annual growth	Percent share TFP growth explained	Source
Brazil	1968-89	Crops	Efficiency changes		-3,100	Arnade (1992)
			Technical progress		800	
			Scale effects		2,200	
	1980-83	Crops	Efficiency changes		38	
			Technical progress		16	
			Scale effects		46	
	1984-87	Crops	Efficiency changes		-1,325	
			Technical progress		375	
			Scale effects		1,050	
Sub-Saharan Africa (22 countries)	1971-86	Aggregate agriculture	Efficiency changes		-60	Thirtle, Hadley, and Townsend (1995)
			Technical progress		160	
Sub-Saharan Africa (22 countries)	1971-86	Aggregate agriculture	Modern inputs		Low	Thirtle, Hadley, and Townsend (1995)
			Infrastructure		High	
			Research, extension and education		High	
			Policy		High	
			Weather		High	
Sub-Saharan Africa (22 countries)	1971-86	Aggregate agriculture, technical progress only	Tractor		Positive	Thirtle, Hadley, and Townsend (1995)
			Labor/land ratio		Positive	
			Research		Positive	
			Secondary education		Positive	
Zimbabwe	1970-89	Commercial agriculture	Research and extension		>90%	Thirtle et al. (1993)

infrastructural effects on TFP growth is an important example of the question of endogeneity. Do markets and irrigation investments tend to flow to areas with relatively high agricultural potential, and thus areas where, *a priori*, one would expect TFP growth to be higher?[4]

Finally, the results of the few studies that look at the relationships between education or agricultural extension and TFP have tended to detect effects that are problematic or even contrary to anticipated findings. In these cases, as in the others cited above, factors affecting TFP are often chosen based on a particular research interest. Very few studies begin with an explicit theoretical consideration of what factors might drive TFP changes in agriculture, other than the common presupposition that investment in knowledge generation, through agricultural research, contributes to technical progress.

Such a comprehensive approach to TFP growth in developing country agriculture awaits considerable future research. Recent findings suggest that developing countries have higher rates of agricultural output growth than developed countries, but that TFP growth accounts for a higher proportion of output growth in developed countries. This could indicate several things. First, agricultural output growth could tend to be higher in more closed agricultural economies with greater population pressures or little agricultural land per capita. Second, TFP growth could contribute relatively more to output growth in countries with better-developed market infrastructure, broadly defined, both because of greater input use efficiency and more efficient agricultural research institutions. Combining these two broad hypotheses leads to the schema illustrated in Figure 3.

Agricultural land per capita	Market infrastructure: Low	Market infrastructure: High
Low	Output: High TFP contribution: Low	Output:High TFP contribution: High
High	Output: Low TFP contribution: Low	Output: Low TFP contribution: High

Market infrastructure

Figure 3. Hypothentical output growth and TFP contribution to output growth by factor endowments and market infrastructure.
Source: Arnade (1994).

4 Binswanger, Khandker, and Rosenzweig (1993) in a paper accounting for output growth, not TFP growth, in India, argue that this is indeed the case.

Unfortunately, *within* the set of developing countries in the studies reported in Tables 2 and 3, the empirical evidence in support of these combined hypotheses is quite weak. As noted earlier, investigations that analyze the infrastructural contribution to TFP growth within individual countries usually find it to be important. Across the developing country studies, however, there are no relationships between readily available infrastructural variables, such as ocean access or road density, and the contribution of TFP growth to growth in agricultural output. Nor, for that matter, are there any relationships between these variables and TFP growth itself, or output growth.

Similarly, in the data reported in Tables 2 and 3, there is only one instance in which agricultural land per capita, corrected for land quality (as reported by Binswanger and Pingali 1988) is significantly related to any of the components of agricultural output growth. Within the set of sub-Saharan African countries analyzed (using identical methodology) by Thirtle, Hadley, and Townsend (1995), corrected population density is correlated significantly with growth in TFP. It is not, however, correlated with output growth or with the contribution TFP makes to output growth. In the wider set of country studies reported in the tables, corrected population density is not correlated with any of these TFP/output measures.

In summary, although there is a general consensus that agricultural research, infrastructure, and improvements in agricultural efficiency drive growth in agricultural TFP, there are a number of unanswered questions concerning the sources of such growth. To take a specific example, education or literacy have not often been analyzed as contributing factors to TFP growth, but when they have been considered, the results often differ from the study hypotheses.[5]

More generally, relative factor endowments clearly play a strong role in the direction of change in PFP productivities (see Hayami and Ruttan 1985; Craig, Pardey, and Roseboom 1997; and our earlier discussion), but their influence on TFP remains uncertain. Similarly, there are a number of reasons to believe that market infrastructure is important in the growth of agricultural TFP in developing countries. A more thorough analysis, however, awaits a clearer definition of "infrastructure," better ways of measuring it consistently across many world regions, and more careful consideration of whether infrastructure is better regarded as exogenous or endogenous in an agricultural growth model. Comparable conceptual and empirical advances concerning the concept of efficiency will also contribute to a better understanding of TFP growth.

Such definitional and measurement advances, particularly as they relate to input quality, are part of the research agenda of the future. So, too, are advances in the treatment of endogeneity and the relationship of TFP growth to the aggregate agricultural production function. In a particularly advanced model, even agricultural research investments might be considered endogenous. Insights from the endogenous growth literature might prove useful in the long run. So, too, would further research into the political economy of

5 Agricultural production function studies using non-conventional inputs suggest that better results might be obtained if technical education were used, rather than general education (Trueblood 1991).

agricultural growth, with more studies of the degree to which policy changes can influence TFP growth. In the intermediate term, however, the most pressing research need may be for studies that use a consistent framework to compare TFP growth across countries. Two major difficulties, particularly in developing countries, will be obtaining consistent data and selecting which factor, of the many that can affect TFP growth, to study. Indeed, such cross-country studies for agriculture in developed countries are only in their infancy, and to date, much more emphasis has been placed on improving the measurement of TFP growth than on explaining different patterns of that growth. Nonetheless, such investigations could complement other approaches, thereby improving our understanding of the sources of agricultural growth and fostering effective policies for promoting it.

Prospects for Further Productivity Growth

Virtually all future output growth in Asia must come from increased yield per unit of land, because the opportunities for further area expansion are minimal. This is also increasingly the case for many countries in parts of Africa and Latin America, although for some, such as Brazil, Sudan, Zambia, and Angola, there is still potential for expansion at the extensive margin. Meanwhile, there is increasing evidence that growth in cereal yields has leveled off, especially in the irrigated lowlands of Asia, which could herald future declines in yield growth (Pingali, Moya, and Velasco 1990). When countries are stratified by cropping intensities, the rate of deceleration in yields is higher for countries with higher cropping intensities (Pingali, Hossain, and Gerpacio 1997). These are invariably countries with an exhausted land frontier that have sought output growth through land augmenting technical change, such as yield-increasing technologies; China, Korea, and the Philippines are examples. Rapid yield growth in the 1980s came from an increase in intensification in low intensity countries such as Laos, Nepal, and Cambodia, resulting from an increase in irrigation infrastructure (Rosegrant and Pingali 1994). India and Vietnam, thanks to policy reforms in the mid-1980s, proved to be exceptions to these trends (Pingali and Xuan 1992).

The leveling off of cereal yields in Asia has occurred because of: 1) the lack of an exploitable yield gap between the technological potential yield and farm level yields; 2) unfavorable relative prices; and 3) the deterioration of the land resource base. The slowdown in rice and wheat productivity growth in Asia since the 1980s has been caused by world cereal price-induced factors and intensification-induced factors. World cereal prices have been declining in real terms since 1900 (Mitchell and Ingco 1995). For rice, declining prices have caused a direct shift of land out of rice and into more profitable cropping alternatives, while slowing the growth in input use and yields for the commodity. Probably more important in the long run, the declining world price for rice has caused a slowdown in investment in rice research and irrigation infrastructure (these issues are discussed in detail in Rosegrant and Pingali 1994). Lower investment in research on other cereal crops such as wheat is also evident (Traxler, Byerlee, and Jain 1996; Maredia and Byerlee, forthcoming).

Is There an Exploitable Yield Potential?

Starting with the commonly used concept of technology potential, what exactly does exploitable yield potential mean? The best yields obtained on experiment stations are often used as the indicator of technology potential. Experiment stations are often located on the best lands within a region and have reliable irrigation water supplies. Agronomic yield potential determined on experiment stations, with no physical, biological, or economic constraints, is the maximum achievable yield. Maximum experimental yields also reflect the knowledge frontier and best known management practices at any given point in time. When the objective of the experiment is changed from maximizing yields to maximizing profits, the yields obtained by experiment station researchers drop significantly (Herdt 1988). For a given location and set of prices, the latter yield can be referred to as the exploitable yield potential.

Is the national average yield an appropriate indicator of farm level performance and potential for growth? No, because the national average yield is an average across agroclimatic zones, soil types, crop ecologies, crop types, and across technologies. By comparing technological potential and national average yields, one inherently presumes that modern technology transcends biophysical and agroclimatic differences and underestimates the magnitude and nature of these differences.

To get a more reasonable measure of the performance of a technology in its target environments, researchers should use yield data from localities where these environments predominate. Pooling away heterogeneity is not a significant problem when examining district/provincial yields, especially if the geographic areas are small. Consider the state of Punjab, the most important agricultural state in India and the heart of the Green Revolution. The average rice yield in Punjab is around 5 t/ha, more than twice the national average and only around 2 t less than the technological potential. A comparison of experiment station yields with farmer yields in the same geographic area (with minimal agroclimatic and biophysical differences) reveals only a small gap between what is achievable and what is actually achieved. Studies in the Philippines have shown that more than one-third of the farmers in the rice bowl provinces of Laguna and Nueva Ecija have been matching the best yields of neighboring experiment stations since 1980 (Pingali, Moya, and Velasco 1990).

The bottom line is that in Asia’s high potential, irrigated rice areas, the economically exploitable gap between the technology frontier and farmer performance is very small. Given current technology and relative price levels, it is not profitable for farmers in these environments to further bridge this gap. Accordingly, one sees that yields in the "rice granary" provinces across Asia have leveled off. Dramatic shifts in productivity in these high potential areas, as seen in the 1960s and 1970s, would require new rice varieties with substantial improvement in yield potential.

In intensively cultivated irrigated wheat areas, such as the Yaqui Valley of Mexico and the Indian Punjab, a similar reduction of the economically exploitable yield gap can be seen. In other areas, including parts of irrigated Asia such as Pakistan, economically exploitable yield increases are still possible (Byerlee et al. 1986). There are far fewer regions in the developing world where maize appears to near its economic potential yield.

Is There an Intensification-Induced Decline in Cereal Crop Productivity?
Does intensified land use, independent of world price effects, lead to a long-term decline in cereal crop productivity? Pingali, Hossain, and Gerpacio (1997) argue that the practice of intensive rice monoculture contributes to the degradation of the paddy resource base and declining productivities. Declining productivity trends can be directly linked to the ecological consequences of intensive monoculture systems, including the buildup of salinity, waterlogging, declining soil fertility, increased soil toxicity, and increased pest populations, particularly soil pests. The relationship of intensification to system-wide productivity declines for wheat is most apparent where wheat is grown in rotation with another cereal, such as in the rice-wheat systems of Asia. Intensive maize production is more often associated with productivity declines in areas where cultivation has moved into hilly areas prone to erosion or areas of eastern and southern Africa, such as Malawi, where a virtual maize monoculture has arisen.

Cassman and Pingali (1993) provide evidence based on long-term experiment station data of declining yields and productivity under intensive rice monoculture systems. The essential message from the experiment station results is that under intensive rice monoculture systems, long-term productivity is difficult to sustain, even under the best scientific management. For the intensively cultivated, irrigated lowlands of Asia, which have been under rice monoculture systems for the past two decades, one should expect similar signs of declining productivity.

At the farm level, declining yield trends are usually not observed because input levels are not held constant over time. In areas where intensive rice monoculture has been practiced over the past two to three decades, however, one observes stagnant yields and/or declining trends in PFPs, especially for fertilizers, and declining trends in TFPs (Pingali, Moya, Velasco 1990; Pingali 1992; Cassman and Pingali 1993). In areas where intensification is not associated with a change in the inherent productivity of the paddy resource base, declining factor productivity indicates a movement along a production function. Where intensification leads to reduced productivity of the resource base, declining factor productivities signify both a shift downward of the production function and a movement along the new production function.

What Are the Prospects for Shifting the Yield Frontier in Cereals?
Pingali, Hossain, and Gerpacio (1997) presented evidence that the yield potential of modern semidwarf rice varieties has remained relatively stagnant since the release of IR-8 in 1965. Although substantial improvements have been made in later generation varieties in terms of improved pest resistance, grain quality, and reduced crop duration, yields have increased only marginally. Recent progress in plant breeding research indicates that a significant shift in the yield frontier is possible both in the medium and longer term. In the medium term, yield increases of around 20% could be possible through the adoption of hybrid rice (Virmani, Khush, and Pingali 1993). The longer term prognosis is for a new "plant type" that could yield about 12.5–13 t/ha and, as a parent of the hybrids, could increase yields to 15 t/ha (Khush 1995).

While the prospects are good for the generation of new seed technologies, current research and adaptation work is far from completion; continuing research investments are required to make widespread farmer adoption a reality. To secure productivity growth of rice, the new seed technologies should be complemented by continuing investments in irrigation and other rice-related infrastructure. Profitable adoption of new seed technologies would require high levels of input use, especially fertilizers and herbicides, to reach the yield potential of the new varieties.

In contrast to rice, the yield potential in wheat has continued to shift upwards by about 1% per year in irrigated areas since the Green Revolution. Data for rainfed environments are less available and more variable, but the rate of genetic improvement in general has been less than for irrigated environments (Byerlee and Moya 1993).[6] There is mixed evidence on continued yield progress. Traxler et al. (1995) suggest that although the latest advanced lines have continued to increase yield potential for the most favorable, irrigated environments, the rate of increase has begun to decline; however, it should be noted that yield variance has declined as well. Sayre, Rajaram, and Fischer (1997) argue that genetic rates of gain in wheat yield have not decelerated.

There are three major avenues for raising the yield frontier in wheat. The first is through continued investments in the conventional breeding methods of crossing and selection. It is likely that gains from conventional breeding for many developing country environments will continue for the next two decades or more (Evenson and Rosegrant 1995) but that the gains will probably come at a higher research cost than in the past. There are several promising, but untested, routes for increasing breeding efficiency. One is through exploiting heterosis, a process that is less understood for wheat than for either rice or maize. Although past efforts in industrialized countries were scaled back because of the apparent economic infeasibility of hybrid wheat (Knudson and Ruttan 1988), interest has revived with recent progress on understanding wheat's pollination control mechanisms and the possibility of interactions between hybrid seed and management techniques that permit reduced seed rates. Another route to breeding efficiency in wheat is to incorporate insights from wheat physiology. Research focusing on manipulating plant types, exploiting genetic variation in growth stages, and employing new techniques that allow more rapid assessment of favorable characteristics such as leaf canopy temperature is already underway (Reynolds, Rajaram, and McNab 1996).

A second way to shift the yield frontier in wheat is to develop new varieties through wide crossing. Of the three major cereals, wheat may be most advantageously placed, both in terms of knowledge and the availability of secondary and tertiary gene pools, to take advantage of wide-cross techniques (Mujeeb-Kazi and Hettel 1995). In the near term, wheats developed from wide crosses are most likely to provide resistance to abiotic and biotic stresses, thus shifting the anticipated yield frontier, if not the yield frontier under no-stress conditions. Longer-term goals include increasing photosynthetic efficiency.

6 In the particular acid soil environment of Brazil, breeders have made even more rapid progress, increasing wheat yield potential by 2–3% per year over a 20 year period.

The third approach to shifting the yield frontier is through the use of biotechnology. In this regard, wheat science is probably behind both maize and rice (Dalrymple and Srivastava 1994), hampered in part by relatively little private sector interest coupled with the large investments required. Marker-assisted selection, the link between biotechnology and mainstream plant breeding, is constrained by wheat's hexaploid genome. This makes the use of model species such as barley, or insights from other cereals generally, very important. Similarly, many experts contend that genetic transformation in wheat is unlikely to have a major impact for several decades. Two biotechnology niches from which more rapid impact might be obtained, again, interface with conventional breeding—molecular markers to clarify the inheritance of traits such as time-to-flowering and yield components (Snape 1996), and doubled haploids to produce pure lines in a single generation.

Of the three major cereals, the yield frontier for maize in the developing world could, theoretically, be shifted most readily, through technology transfer from the industrialized nations. This could take the form of near-direct germplasm transfer in the case of the temperate maize producing regions of China, or the transfer of knowledge and methods into subtropical and tropical maize environments. This type of transfer, however, is most likely to occur in China or other parts of Asia where rapidly expanding demand for feed maize will make the crop increasingly profitable in certain areas and large private sector seed companies should be willing to make the necessary investments given the appropriate institutional environment.

For regions that continue to rely heavily on maize for food, such as eastern and southern Africa and Mesoamerica, this type of transfer is far less likely. On the other hand, it is not clear that existing ways of shifting the yield frontier have been exhausted in these areas. Important issues that need to be addressed include public sector research support, innovative new ways of diffusing improved maize germplasm among farmers, and, in Mesoamerica, the ability of plant breeders to maintain or incorporate traits important to farmers in the zone of origin for the crop. Two areas in which considerable progress has been made in maize improvement include greater resistance to abiotic stresses through modified selection methods and greater resistance to biotic stresses through gene transfer. Apomixis, a process whereby plants reproduce asexually, is a technological option with a much longer horizon. This trait, when incorporated into maize, would eliminate the need to replace hybrid seed every year, while maintaining the yield advantage of hybrid maize. Scientists are closer to transferring a gene for apomixis to maize than they are for rice or wheat.

For all cereals, biotechnology's most likely immediate commercial impact in developing countries will be on simple traits that are likely to be controlled by a single gene. Many quantitative traits of commercial importance are polygenic. In areas such as yield or disease resistance in wheat, plant breeders have recognized and exploited this polygenic nature of traits for a long time, but basic molecular biology is just beginning to unravel the mysteries of gene interaction. Given the investments and the political support required for such basic research, the first fruits of this understanding are likely to come in the field of medicine. Over the long run, however, applications to agriculture and the production of cereal staples will probably be forthcoming. Even where transgenic crops are available, their farm level adoption may be constrained by regulatory impediments that restrict access to them. Intellectual property rights may further impede the availability of materials developed through biotechnology.

Can Profits be Sustained Through Improvements in Input Efficiencies?
The evidence we have presented suggests that in many areas, farmers using intensive multicrop systems are nearing the conventional yield frontier as modified by economic considerations. On the other hand, studies of economic efficiency in developing country agriculture usually find that many farmers, even those in areas where production approaches the yield frontier, are technically inefficient (Ali and Byerlee 1991). Some of the discrepancies between these findings may arise from differences in time period, location, and methodology. Our previous discussion of knowledge-intensive technologies has suggested some ways in which technical efficiency might be improved.

Meeting the long-term demand requirements for cereals requires more than a shift in the yield frontier. It also requires fundamental changes in the way fertilizers, pesticides, and labor are used. To sustain cereal productivity growth while conserving the resource base would require production increases to be achieved with less than proportionate increases in chemical inputs. Recent advances in the generation of efficiency-enhancing fertilizer and pesticide technology could help meet the complementary goals cited above.

<u>Fertilizers and pesticides</u>
Changes in fertilizer application, especially in timing and method of application, could contribute significantly to reducing nutrient losses through volatilization and seepage, while improving plant nutrient uptake. Efficiency gains made through such improvements could help reduce the overall fertilizer requirements for sustained productivity growth. Of the major cereals in the developing world, particularly in intensive production systems, insecticides have been most widely used on rice. Recent evidence indicates a very modest impact of insecticides on rice production. Farm-level experiences with integrated pest management (IPM) indicate that judicious decision making on insecticide use could lead to substantial reductions in its use without diminishing rice yields.

While the growth in fertilizer and insecticide use can be managed through the adoption of efficiency-enhancing technologies, herbicide use is expected to increase dramatically across Asia for the foreseeable future. The growth in its use is closely linked to increasing wage rates and the substitution out of manual weeding to chemical control. For rice, rapidly rising wages also contribute to the shift from the labor-intensive transplanting operation to direct seeding, a switch that cannot be accomplished without the complementary use of herbicides. Growing water scarcities in irrigated rice systems also contribute to increased herbicide use. Opportunities for reducing herbicide use through efficiency improvements are limited in tropical rice systems.

Phalaris minor is the major grassy weed affecting wheat production in the rice-wheat systems of Asia. Mixed strategies for weed control featuring rotations, bed planting, and judicious use of chemicals are currently the most promising options. Weed problems in wheat are less pronounced when it is grown in other rotations.

Although efficiency-enhancing technologies are available for fertilizers and insecticides, and savings in input costs per unit of output are possible, it should be recognized that the adoption of these technologies comes at a significant cost in terms of farmers' time. Most efficiency-enhancing technologies are knowledge-intensive and require substantial farmer time for learning, decision making, and supervision. Finally, the profitability of adopting efficiency-enhancing technologies will be lower in countries where the relative prices of inputs are kept low through explicit or implicit subsidies.

Labor and mechanization

Over the past three decades, Asia has seen an unprecedented level of mechanization of agricultural operations, especially in the high-potential, irrigated environments. Intensification of production systems created power bottlenecks around the land preparation, harvesting, and threshing operations. Alleviating the power bottlenecks through the adoption of mechanical technologies helped enhance agricultural productivity and lower the unit cost of production, even in the densely populated countries of Asia. Mechanization of agricultural operations was very selective; power-intensive operations such as land preparation, threshing, and milling were readily mechanized, while control-intensive operations such as weeding and rice transplanting continued to be performed manually. Economic growth and commercialization of agricultural systems is leading to further mechanization, including the spread of rice mechanization further into Southeast Asia and a shift to larger machines. The mechanization process, as part of the labor substitution phase of technological change in cereal crop production, in many instances is a more recent development than land augmenting technology and therefore should also provide opportunities for increased efficiency as farmers become more knowledgeable and better machines are developed.

Mechanization has been most pronounced in some of the "new continent" countries of Latin America, where labor is the limiting factor. Africa has also traditionally been regarded as land abundant, many countries now face increasing land scarcity. Even in relatively land abundant areas of Africa, but many factors condition whether increased mechanization is economically feasible, including the length of fallow period, the length of the growing season, and disease constraints to animal use (Pingali, Bigot, and Binswanger 1987).

Input inefficiencies as a source of production gains

In cereal systems that are less advanced along the path of intensification than those in Asia, input inefficiencies will likely be an inevitable accompaniment to technical change. Over time, in such areas there should be considerable scope for improved management efficiencies to make large contributions to cereal crop productivity. In many parts of sub-Saharan Africa, however, infrastructural constraints and higher input-output price ratios mean that despite outstanding yield advantages of land-augmenting technology such as fertilizer, the economic advantages are considerably less than they were in the land-augmentation phase in Green Revolution Asia. As a result, input use efficiency may become an issue earlier in the diffusion process for such technology in Africa than it did in Asia (Heisey and Smale 1995).

Two major investment possibilities outside the agricultural sector will condition the degree to which input use efficiencies will contribute to greater cereal productivity. The first investment possibility is improved farmer education (Byerlee 1987; Byerlee and Pingali 1994). In intensive systems in areas with rapid income growth, there will be interesting interactions as better education may increase employment opportunities for rural people and thus raise the opportunity cost of time. This, in turn, will make greater input use more profitable and counteract the drive to technical efficiency.

The other investment possibility is in agricultural research. From the research side, a major consideration is that knowledge-intensive technologies that lead to greater efficiency are fairly location specific; therefore, the cost of developing such technologies relative to the likely impacts may be high (Traxler and Byerlee 1992). Advances in crop modeling and geographic information systems may help to alleviate some of the constraints of location specificity. Such areas of inquiry, which may improve input use efficiency, are in one sense quite similar to biotechnological innovations that could shift the yield frontier—they are promising, but relatively untried.

Conclusions

Driven by increasing land scarcity or high land values, cereal crop productivity in the developing world has undergone tremendous increases during the past three decades. The most notable and widely cited evidence has been large increases in yields. Although a few studies that focused on international comparisons (e.g., Arnade 1994) have suggested that during periods of rapid technological change, TFPs have sometimes declined in developing countries due to large technical inefficiencies, the majority of analyses of single country or crop specific TFP indicate increasing TFP over various periods during the past 30 years. Nonetheless, there is some evidence that in the most intensively cultivated areas, particularly those with a double or triple cereal rotation, resource base limitations may now be leading to slackening productivity growth.

Productivity changes have occurred through a sequence of land augmentation, labor substitution, and knowledge intensification. Different developing countries and regions are at different stages in this process, making observation and analysis of the transformation more difficult, but the underlying processes are clear. Agricultural research, better farmer knowledge (both through greater experience and improved education), infrastructural and market development, and policy reform have all contributed to driving productivity changes. The punctuated nature of the benefits to be gained from infrastructural and policy changes makes the need for continuous investment in research and farmer education that much more critical. However, long-term declines in world cereals prices and structural adjustment within developing economies have often led to decreases in these investments in recent years.

Significant methodological advances have been made in productivity measurement, but there is still room for improvement in methods and their use. Developing countries particularly need better measurement of the factors of production and a clearer understanding of how the causes of productivity growth function and interact. Future analyses will also have to be increasingly cognizant of the growing integration of world cereals markets.

Future growth in cereal productivity is essential, driven both by population growth and income-induced demand shifts to varying degrees, according to crop and region. This growth will only come by shifting yield frontiers, improving input use efficiency, and, with increasing urgency, conserving the resource base. The needed growth in productivity will not be forthcoming unless investments in agricultural research and education are maintained or increased. In an era of serious constraints on such investments, better knowledge of the specific effects of specific investments in particular places at particular times is necessary to increase their marginal return.

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