Productivity Growth in World Agriculture:
Sources and Constraints

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Before the twentieth century, almost all increases in crop and animal production occurred as a result of enlarging the area cultivated. By the end of that century, almost all increases were coming from increases in land productivity—in output per acre or per hectare. This was an exceedingly short period in which to make a transition from a natural resource–based to a science-based system of agricultural production. In the presently developed countries, this transition began in the latter half of the nineteenth century. In most developing countries, the transition did not begin until well into the second half of the twentieth century. For some of the poorest countries in the world, the transition has not yet begun.

During the second half of the twentieth century world population more than doubled—from approximately 2.5 billion in 1950 to 6.0 billion in 2000. The demands placed on global agricultural production arising out of population and income growth almost tripled. By 2050, world population is projected to grow to between 9 and 10 billion people. Most of the growth is expected to occur in poor countries where the income elasticity of demand for food remains high. Even moderately high income growth, combined with projected population growth, could result in nearly doubling the demands placed on the world's farmers by 2050 (Johnson 2000; United Nations 2001).

The most difficult challenges will occur during the next two or three decades as both population and income in many of the world's poorest countries continue to grow rapidly. But rapid decline in the rate of population growth in such populous countries as India and China lends credence to United Nations projections that by mid-century the global rate of population growth will slow substantially. The demand for food arising out of income growth is also expected to slow as incomes rise and the income elasticity of demand for food declines. In the interim, very substantial increases in scientific and technical effort will be required, particularly in the world's poorest countries, if growth in food production is to keep pace with growth in demand.

AGRICULTURE IN DEVELOPMENT THOUGHT

Economic understanding of the process of agricultural development has made substantial advances over the last half century. In the early post–World War II literature, agriculture, along with other natural resource–based industries, was viewed as a sector from which resources could be extracted to fund development in the industrial sector (Lewis 1954, p. 139; Ranis and Fei 1961; Rostow 1956). Growth in agricultural production was viewed as an essential condition, or even a precondition, for growth in the rest of the economy. But the process by which agricultural growth was generated remained outside the concern of most development economists.

By the early 1960s a new perspective, more fully informed by both agricultural science and economics, was beginning to emerge. It had become increasingly clear that much of agricultural technology was location specific. Techniques developed in advanced countries were not generally directly transferable to less developed countries with different climates and resource endowments. Evidence had also accumulated that only limited productivity gains were to be had by the reallocation of resources within traditional peasant agriculture.

In his iconoclastic book *Transforming Traditional Agriculture*, Theodore W. Schultz (1964) insists that peasants in traditional agrarian societies are rational allocators of available resources and that they have remained poor because most poor countries provide them with only limited technical and economic opportunities to which they can respond—that is, they are "poor but efficient." If given the inputs and know-how of their modern counterparts, they too could succeed, Schultz maintains:

> The principal sources of the high productivity of modern agriculture are reproducible sources. They consist of particular material inputs and of skills and other capabilities required to use such inputs successfully . . .
>
> But these modern material inputs are seldom ready-made . . .
>
> In general, what is available is a body of useful knowledge which has made it possible for the advanced countries to produce for their own use factors that are technically superior to those employed elsewhere. This body of knowledge can be used to develop similar, and as a rule superior, new factors appropriate to the biological and other conditions that are specific to the agriculture of poor countries. (pp. 146–147)

This thesis implies three types of relatively high-payoff investments for agricultural development: 1) the capacity of agricultural research institutions to generate new location-specific technical knowledge; 2) the capacity of the technology supply industries to develop, produce, and market new technical inputs; and 3) the schooling and nonformal (extension) education of rural people to enable them to use the new knowledge and technology effectively. The enthusiasm with which this high-payoff input model was accepted and transformed into doctrine was due at least as much to the success of plant breeders and agronomists in developing fertilizer and management-responsive green revolution crop varieties for the tropics as to the power of Schultz's ideas.[1]

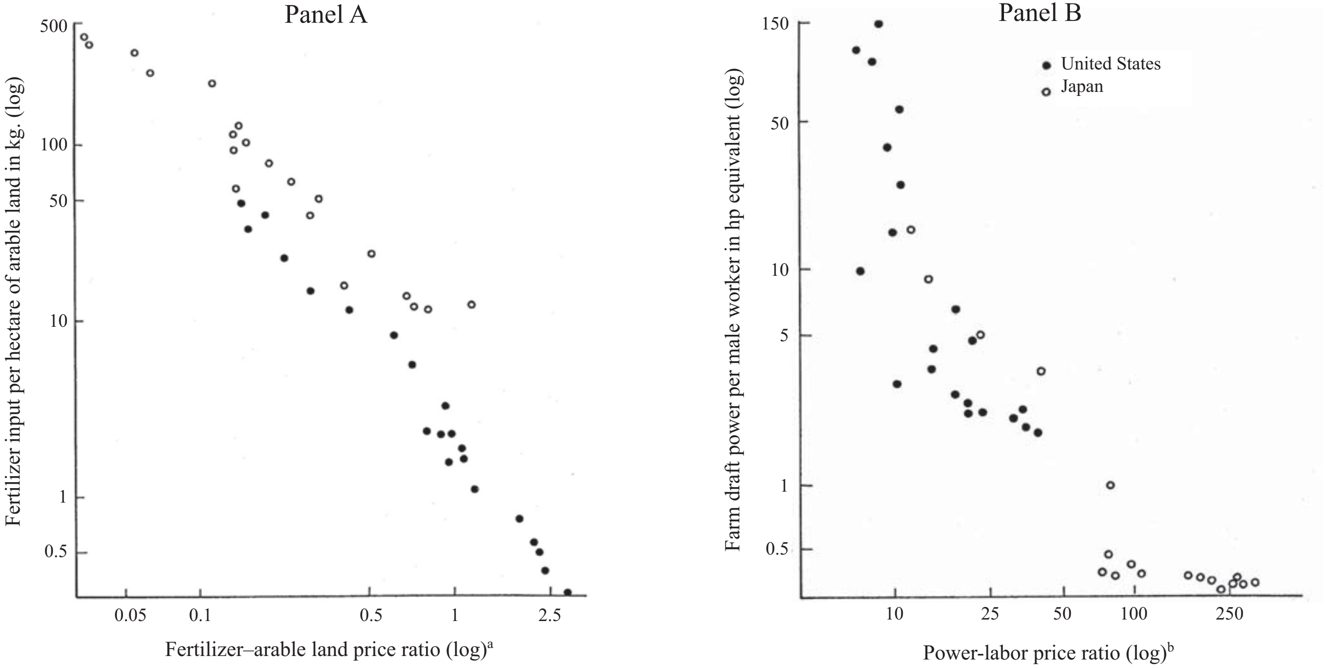
The Schultz "high-payoff input model" remained incomplete, however, even as a model of technical change in agriculture. It did not attempt to explain how economic conditions induce an efficient path of technical change for the agricultural sector of a particular society. Nor does the high-payoff input model attempt to explain how economic conditions induce the development of new institutions, such as public sector agricultural experiment stations, that become the suppliers of location-specific new knowledge and technology.

Beginning in the early 1970s, Hayami and Ruttan (1971, 1985) and Binswanger and Ruttan (1978) formulated a model of induced technical change in which the development and application of new technology is endogenous to the economic system. Building on the Hicksian model of factor-saving technical change and their own experience in southeast Asia, they proposed a model in which the direction of technical change in agriculture was induced by changes (or differences) in relative resource endowments and factor prices. In this model, alternative agricultural technologies are developed to facilitate the substitution of relatively abundant (hence cheap) factors for relatively scarce (hence expensive) factors. Two kinds of technology generally correspond to this taxonomy. Mechanical technology is labor saving, designed to substitute power and machinery for labor. Biological and chemical technology is land saving, designed to substitute labor-intensive production practices and industrial inputs such as fertilizer and plant- and animal-protection chemicals for land. Both the technical conditions of production and historical experience suggest that changes in land productivity and labor productivity are relatively independent (Griliches 1968).

The process of induced technical change can be illustrated from the historical experience of Japan and the United States, illustrated in Figure 4.1. In Panel A of Figure 4.1, the horizontal axis is the price of fertilizer relative to the price of land and the vertical axis the amount of fertilizer per hectare of agricultural land. In Panel B of Figure 4.1, the horizontal axis is the price of draft power—both animal and mechanical—relative to the price of labor and the vertical axis the amount of draft power per worker. Reading from right (1880) to left (1980), as the price of fertilizer declined relative to the price of land, fertilizer use per hectare rose in both countries (Panel A). Similarly, as the price of draft power declined relative to the price of labor, the use of power per worker rose in both countries (Panel B).

Throughout the period 1880–1980, Japanese farmers used more fertilizer per hectare than U.S. farmers, and U.S. farmers used more power per worker than Japanese farmers. These differences in use of fertilizer per unit of land and of draft power per worker between the two countries, and the changes in each country between 1880 and 1980, were not the result of simple factor substitution in response to relative price changes. The large changes in factor ratios were made possible only by the very substantial advances in biological and mechanical technology that facilitated the substitution of fertilizer for land and draft power for labor. These technical changes were induced by the differences and changes in relative factor price ratios (Hayami and Ruttan 1985, pp. 176–197).[2] Over time, particularly since World War II, there has been some convergence in relative factor prices and in relative intensity of factor use in the two countries.

Figure 4.1 Induced Technical Change in Fertilizer and Draft Power, the United States and Japan (quinquennial observations for 1880–1980)



[a] Relation between fertilizer input per hectare of arable land and the fertilizer–arable land price ratio: hectares of arable land that can be purchased by one ton of $N + P_2O_5 + K_2O$, contained in commercial fertilizers.

[b] Relation between farm draft power per male worker and power labor price ratio: hectares of work days that can be purchased by one horsepower (hp) of tractor or draft animal.

SOURCE: Hayami and Ruttan (1985, pp. 179–180).

Advances in mechanical technology in agriculture have been intimately associated with the industrial revolution. But the mechanization of agriculture cannot be treated as simply the adaptation of industrial methods of production to agriculture. The spatial dimension of crop production requires that the machines suitable for agricultural mechanization be mobile—they must move across or through materials that are immobile (Brewster 1950). The seasonal characteristic of agricultural production requires a series of specialized machines—for land preparation, planting, pest and pathogen control, and harvesting—designed for sequential operations, each of which is carried out for only a few days or weeks in each season. One result is that a fully mechanized agriculture is typically very capital intensive. Advances in biological technology in crop production involve one or more of the following three elements: 1) land and water resource development to provide a more favorable environment for plant growth; 2) the addition of organic and inorganic sources of plant nutrition to the soil to stimulate plant growth and the use of biological and chemical means to protect plants from pests and pathogens; and 3) selection and breeding of new, biologically efficient crop varieties specifically adapted to respond to those elements in the environment that are subject to management.

Advances in mechanical technology are a primary source of growth in labor productivity; advances in biological technology are a primary source of growth in land productivity. There are, of course, exceptions to this analytical distinction. For example, in nineteenth-century Japan, horse plowing was developed as a technology to cultivate more deeply to enhance yield (Hayami and Ruttan 1985, p. 75).[3] In the United States, the replacement of horses by tractors released land from animal feed to food production (Olmstead and Rhode 2001; White 2000). At the most sophisticated level, technical change often involves complementary advances in both mechanical and biological technology. For most countries, the research resource allocation issue is the relative emphasis that should be given to advancing biological and mechanical technology.

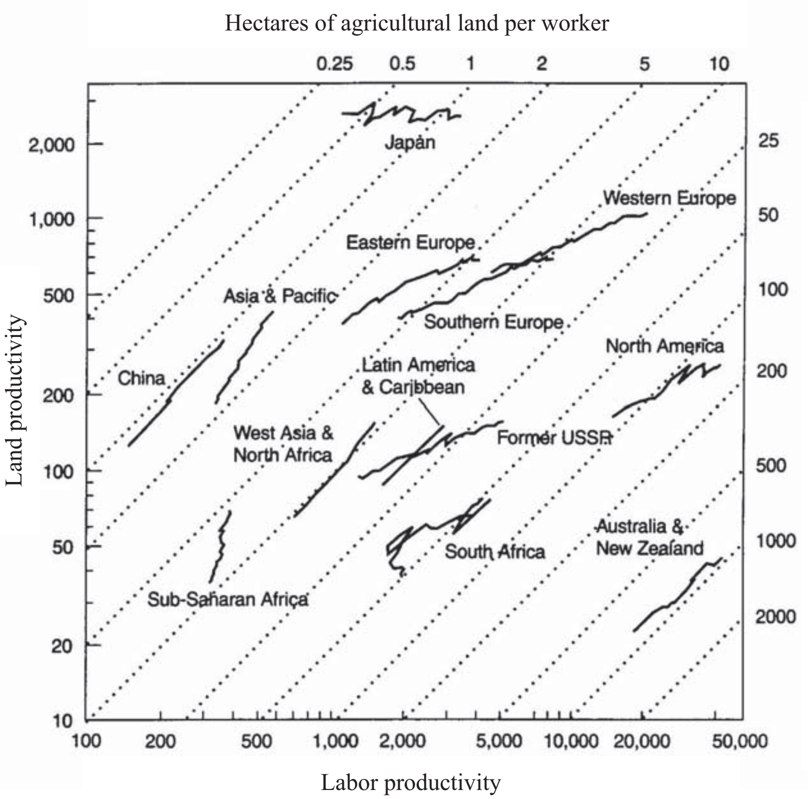
The model of induced technical change has important implications for resource allocation in agricultural research. In labor-abundant and land-constrained developing countries, like China and India, research resources are most productively directed to advancing yield-enhancing biological technology. In contrast, land-abundant Brazil has realized very high returns from research directed to releasing the productivity constraints on its problem soils. Discovery of the yield-enhancing effects of heavy lime application on acidic aluminum-containing soils has opened its *Campos Cerrados* (great plains) region to extensive mechanized production of maize and soybeans.

MEASURING THE RATE AND DIRECTION OF PRODUCTIVITY GROWTH

Comparative research on the rate and direction of productivity growth in agriculture has gone through three stages. Initially, efforts were directed to the measurement of partial productivity ratios and indexes, such as output per worker and per hectare. Intercountry cross-section and time-series comparisons of output per unit of land and labor were first assembled by Collin Clark in his pioneering study, *The Conditions of Economic Progress* (1940/1957). In the late 1960s, Clark's intercountry comparisons were revived and updated by Yujiro Hayami and associates (Hayami 1969; Hayami and Inagi 1969; Hayami, Miller, Wade, and Yamashita 1971). These early partial productivity studies identified exceedingly wide differences in land and labor productivity both among countries and among major world regions. Recent trends in land and labor productivity indicate that these wide differences have persisted.

In Figure 4.2, labor productivity (output per worker) is measured on the horizontal axis. Land productivity (output per hectare) is measured on the vertical axis. The dashed diagonal lines, with the units appearing across the top and down the right-hand side of the figure, trace the land-labor factor ratios (hectares of agricultural land per worker). The country and regional lines indicate land-labor trajectories for specific countries or regions. The partial productivity growth patterns of Figure 4.2 are displayed in much greater detail in the work of Hayami and Ruttan (1985, pp. 117–129). The several country and regional growth paths fall broadly into three groups: 1) a land-constrained path in which output per hectare has risen faster than output per worker, 2) a land-abundant path in which output per worker has risen more rapidly than output per hectare, and 3) an intermediate growth path in which output per worker and per hectare have grown at somewhat comparable rates. During the later stages of development, as the price of labor begins

Figure 4.2 International Comparison of Land and Labor Productivities by Region: 1961–1990.



SOURCE: Craig, Pardey, and Roseboom (1997, p. 1066).

to rise relative to the price of land, the growth path tends to shift in a labor saving direction. If land and labor productivity grow at the same rate, as in west Asia and North Africa, historical productivity follows a diagonal path. Partial productivity ratios such as those plotted in Figure 4.2 were employed by Hayami and Ruttan (1970, 1971, pp. 163–205) in their initial tests of the induced technical change hypothesis.

A second stage of the research on technical change in agriculture involved the estimation of cross-country production functions and the construction of multifactor productivity estimates. In these studies, factor inputs—typically land, labor, livestock, capital equipment (machinery), and current inputs (fertilizer)—were aggregated using either factor shares or statistical estimates as the weights for factor aggregation in multifactor productivity estimates or as elasticity coefficients in Cobb-Douglas type production functions.[4] Over time, improvements in data availability and estimation methods have contributed to greater reliability in the estimates.

The Hayami and Ruttan (1970) and the Kawagoe, Hayami, and Ruttan (1985) cross-country metaproduction functions (Lau and Yotopoulos 1989) have been used in growth accounting exercises to partition the sources of differences in agricultural labor and land productivity between developed and developing countries and among individual countries. The results indicated that internal resource endowments (land and livestock), modern technical inputs (machinery and fertilizer), and human capital (general and technical education) each accounted for approximately one-fourth of the differences in labor productivity between developed countries and less developed countries as groups. Scale economies, present in developed countries but not in less developed countries, accounted for about 15 percent of the difference.[5]

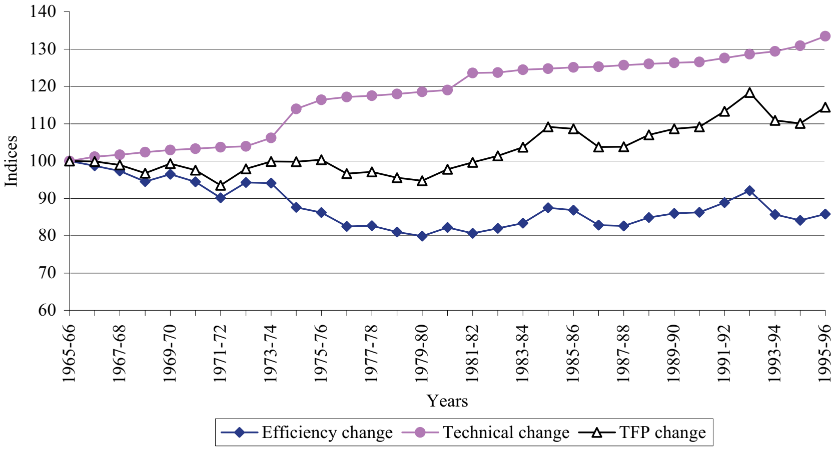
The implications of these results for potential growth of labor productivity in the agricultural production of less developed countries were encouraging. The pressure of population against land resources was not a binding constraint on agricultural production. Scale diseconomies were not an immediate constraint on labor productivity. Labor productivity could be increased by several multiples—to levels approximating the levels in Western Europe in the early 1960s—by investment in human capital and in agricultural research, and by more intensive use of technical inputs. The historical experience of Japan and the more recent experience of Korea and Taiwan did suggest, however, that as demand for labor, associated with rapid urban-industrial development, draws substantial labor from agriculture, small farm size could become a more serious constraint. As the agricultural labor force declines, farm consolidation results in a rise in the land/labor ratio and a rise in labor productivity.

A third stage in agricultural productivity analysis has involved efforts to test for the convergence of growth rates and levels of multifactor productivity between and among developing and less developed countries. Most of these studies have employed the Malmquist or frontier productivity approach. The basic idea of the Malmquist approach is to construct the best-practice, or frontier, production function and to measure the distance of each country in the sample from the frontier by applying a linear programming method known as data envelopment analysis. The combination of inputs is allowed to vary along an efficient frontier, rather than the fixed coefficient production functions employed in the second-stage studies, to partition changes in multifactor productivity into technical change and efficiency change components.[6] Technical change measures the shift in the best-practice or frontier production functions; efficiency change measures change in the difference between average practice and the best-practice productivity frontier.

These studies generally indicate a widening of the agricultural productivity gap between developed and developing countries between the early 1960s and the early 1990s. Within the group of developed countries, except for continuing divergence between northern and southern Europe, productivity levels have converged modestly. Developing countries as a group experienced declining total factor productivity relative to the frontier countries. There is, however, some evidence of convergence toward the still relatively low frontier productivity levels within African agriculture (Arnade 1998; Ball et al. 2001; Chavas 2001; Fulginiti and Perrin 1997, 1998; Suhariyanto, Lusigi, and Thirtle 2001; Thirtle, Hadley, and Townsend 1995; Trueblood and Coggins 2001).

The partitioning of total factor productivity into technical efficiency and technical change in Asian agriculture is illustrated in Figure 4.3. During the period from 1965–66 to 1995–96 the gap between average practice, as measured by technical *efficiency change*, and best practice, as measured by *technical change*, widened. As a result, average *total factor productivity change* (TFP) advanced more slowly than the rate of technical change in the countries on the efficiency frontier. Another way of making the same point is to say that technical efficiency has lagged behind technical change associated with the rapid adoption of green revolution seed-fertilizer technology in the frontier countries (Rosegrant and Hazell 2000, pp. 123–60). The results are not inconsistent with a technical trajectory implied by the induced technical change hypothesis. Technical change in Asia has been strongly biased in a land-saving direction, in response to the relatively severe constraints on land resources. This bias is reflected in both a land-saving shift in the pro-

Figure 4.3 Efficiency Change, Technical Change, and TFP Change in Asian Agriculture



SOURCE: Suhariyanto, Lusigi, and Thirtle (2001, p. 11).

duction function and the substitution of technical inputs, particularly fertilizer and pest and pathogen control chemicals, for land (Murgai 2001; Murgai, Ali, and Byerlee 2001). Similar trends have taken place in some of the more land-constrained, labor-intensive agricultural systems in Africa and Latin America.

TRANSITION TO SUSTAINABILITY

Growth in total factor productivity in agriculture, arising out of technical change and improvements in efficiency, has made an exceedingly important contribution to economic growth. Within rural areas, growth of land and labor productivity has led to substantial poverty reduction. Productivity growth has also released substantial resources to the rest of the economy and contributed to reductions in the price of food in both rural and urban areas (Irz et al. 2001; Shane, Roe, and Gopinath 1998). The decline in the price of food, which in many parts of the world is the single most important factor determining the buying power of wages, has been particularly important in reducing the cost of industrial development in a number of important emerging economies. These price declines have also meant that, in countries or regions that have not experienced such gains in agricultural productivity, farmers have lost competitive advantage in world markets and consumers have failed to share fully in the gains from economic growth. But what about the future? In the next two sections I will first address the environmental and resource constraints and then the scientific and the technical constraints that will confront the world's farmers as they attempt to respond to the demands that will be placed on them.[7]

RESOURCE AND ENVIRONMENTAL CONSTRAINTS

The leading resource and environmental constraints faced by the world's farmers include soil loss and degradation; waterlogging and salinity of soil; the coevolution of pests, pathogens, and hosts; and the impact of climate change. Part of my concern is with the feedback of the environmental impacts of agricultural intensification on agricultural production itself (Tilman et al. 2001).

Soil. Soil degradation and erosion have been widely regarded as major threats to sustainable growth in agricultural production in both developed and developing countries. It has been suggested, for example, that by 2050 it may be necessary to feed "twice as many people with half as much topsoil" (Harris 1990, p. 115). However, attempts to assess the implications of soil erosion and degradation confront serious difficulties. Water and wind erosion estimates are measures of the amount of soil moved from one place to another rather than of soil actually lost. Relatively few studies provide the information necessary to estimate yield loss from erosion and degradation. Studies in the United States by the Natural Resources Conservation Service have been interpreted to indicate that if 1992 erosion rates continued for 100 years the yield loss at the end of the period would amount to only 2–3 percent (Crosson 1995a). An exceedingly careful review of the long term relationship between soil erosion, degradation, and crop productivity in China and Indonesia concludes that there has been little loss of organic matter or mineral nutrients and that use of fertilizer has been able to compensate for loss of nitrogen (Lindert 2000). A careful review of the international literature suggests that yield losses at the global level might be roughly double the rates estimated for the United States (Crosson 1995b).

At the global level, soil loss and degradation are not likely to represent a serious constraint on agricultural production over the next half century. But soil loss and degradation could become a serious constraint at the local or regional level in some fragile resource areas. For example, yield constraints due to soil erosion and degradation seem especially severe in the arid and semiarid regions of sub-Saharan Africa. A slowing of agricultural productivity growth in robust resource areas could also lead to intensification or expansion of crop and animal production that would put pressure on soil in fragile resource areas—like tropical rain forests, arid and semiarid regions, and high mountain areas. In some such areas, the possibility of sustainable growth in production can be enhanced by irrigation, terracing, careful soil management, and changes in commodity mix and farming systems (Lal 1995; Niemeijer and Mazzucato 2002; Smil 2000).

Water. During the last half-century, water has become a resource of high and increasing value in many countries. In the arid and semiarid areas of the world, water scarcity is becoming an increasingly serious constraint on growth of agricultural production (Gleick 2000; Raskin et al. 1997; Seckler, Molden, and Barker 1999). During the last half century, irrigated area in developing countries more than doubled, from less than 100 million hectares to more than 200 million hectares. About half of developing-country grain production is grown on irrigated land. The International Water Management Institute has projected that by 2025 most regions or countries in a broad sweep from north China across East Asia to North Africa and northern sub-Saharan Africa will experience either absolute or severe water scarcity.[8]

Irrigation systems can be a double-edged answer to water scarcity, since they may have substantial externalities that affect agricultural production directly. Common problems of surface water irrigation systems include waterlogging and salinity resulting from excessive water use and poorly designed drainage systems (Murgai, Ali, and Byerlee 2001). In the Aral Sea Basin in central Asia, the effects of excessive water withdrawal for cotton and rice production, combined with inadequate drainage facilities, have resulted in such extensive waterlogging and salinity, as well as contraction of the Aral Sea, that the economic viability of the entire region is threatened (Glazovsky 1995). Another common externality results from the extraction of water from underground aquifers in excess of the rate at which the aquifers are naturally recharged, resulting in a falling groundwater level and rising pumping costs. In some countries, like Pakistan and India, these externalities have in some cases been sufficient to offset the contribution of expansion of irrigated area to agricultural production.

However, the lack of water resources is unlikely to become a severe constraint on global agricultural production in the next half century. The scientific and technical efforts devoted to improvement in water productivity have been much more limited than efforts to enhance land productivity (Molden, Amarasinghe, and Hussain 2001), so significant productivity improvements in water use are surely possible. Institutional innovations will be required to create incentives to enhance water productivity (Saleth and Dinar 2000). But in 50 to 60 of the world's most arid countries, plus major regions in several other countries, competition from household, industrial, and environmental demands will reallocate water away from agricultural irrigation. In many of these countries, increases in water productivity and changes in farming systems will permit continued increases in agricultural production. In other countries, the reduction in irrigated area will cause a significant constraint on agricultural production. Since these countries are among the world's poorest, some will have great difficulty in meeting food security needs from either domestic production or food imports.

Pests. Pest control has become an increasingly serious constraint on agricultural production in spite of dramatic advances in pest control technology. In the United States, pesticides have been the most rapidly growing input in agricultural production over the last half century. Major pests include pathogens, insects, and weeds. For much of the post–World War II era, pest control has meant application of chemicals. Pesticidal activity of dichlorodiphenyl-trichloroethane (DDT) was discovered by scientists in the late 1930s. It was used in World War II to protect American troops against typhus and malaria. Early tests found DDT to be effective against almost all insect species and relatively harmless to humans, animals, and plants. It was relatively inexpensive and effective at low application levels. Chemical companies rapidly introduced a series of other synthetic organic pesticides in the 1950s

(Ruttan 1982; Palladino 1996). The initial effectiveness of DDT and other synthetic organic chemicals for crop and animal pest control after World War II led to the neglect of other pest control strategies.

By the early 1960s, an increasing body of evidence suggested that the benefits of the synthetic organic chemical pesticides introduced in the 1940s and 1950s were obtained at substantial cost. One set of costs included the direct and indirect health effects on wildlife populations and on humans (Carson 1962; Pingali and Roger 1995). A second set of costs involved the destruction of beneficial insects and the emergence of pesticide resistance in target populations. A fundamental problem in efforts to develop methods of control for pests and pathogens is that the control results in evolutionary selection pressure for the emergence of organisms that are resistant to the control technology (Palumbi 2001). When DDT was introduced in California to control the cottony cushion scale, its predator the vedalia beetle turned out to be more susceptible to DDT than the scale. In 1947, just one year after the introduction of DDT, citrus growers were confronted with a resurgence of the scale population. In Peru, the cotton bollworm quickly built up resistance to DDT and to the even more effective—and more toxic to humans—organophosphate insecticides that were adopted to replace DDT (Palladino 1996, pp. 36–41).

The solution to the pesticide crisis offered by the entomological community was integrated pest management (IPM). IPM involved the integrated use of an array of pest control strategies: making hosts more resistant to pests, finding biological controls for pests, cultivation practices, and also chemical control if needed. At the time integrated pest management began to be promoted in the 1960s, it represented little more than a rhetorical device. But by the 1970s, a number of important IPM programs had been designed and implemented. However, exaggerated expectations that dramatic reductions in chemical pesticide use could be achieved without significant decline in crop yields as a result of IPM have yet only been partially realized (Gianessi 1991; Lewis et al. 1997).

My own judgment is that the problem of pest and pathogen control will represent a more serious constraint on sustainable growth in agricultural production at a global level than either land or water constraints.[9] In part, this is because the development of pest- and pathogen-resistant crop varieties and chemical methods of control both tend to induce the evolution of more resistant pests or pathogens. In addition, international travel and trade are spreading the newly resistant pests and pathogens to new environments. As a result, pest control technologies must constantly be replaced and updated. The coevolution of pathogens, insect pests, and weeds in response to control efforts will continue to represent a major factor in directing the allocation of agricultural research resources to assure that agricultural output can be maintained at present levels or continue to grow.[10]

Climate. Measurements taken in Hawaii in the late 1950s indicated that carbon dioxide (CO_2) was increasing in the atmosphere. Beginning in the late 1960s, computer model simulations indicated possible changes in temperature and precipitation that could occur because of human-induced emission of CO_2 and other greenhouse gases into the atmosphere. By the early 1980s a fairly broad consensus had emerged in the climate change research community that energy production and consumption from fossil fuels could, by 2050, result in a doubling of the atmospheric concentration of CO_2, a rise in global average temperature by 2.5°C–4.5°C (2.7°F–8.0°F) and a complex pattern of worldwide climate change (Ruttan 2001, pp. 515–520).

Since the mid-1980s, a succession of studies has attempted to assess how an increase in the atmospheric concentration of greenhouse gases could affect agricultural production through three channels: 1) higher CO_2 concentrations in the atmosphere may have a positive "fertilizer effect" on some crop plants (and weeds); 2) higher temperatures could result in a rise in the sea level, resulting in inundation of coastal areas and intrusion of saltwater into groundwater aquifers; and 3) changes in temperature, rainfall, and sunlight may also alter agricultural production, although the effects will vary greatly across regions. Early assessments of the impact of climate change on global agriculture suggested a negative annual impact in the 2–4 percent range by the third decade of this century (Parry 1990). More recent projections are more optimistic (Mendelsohn, Nordhaus, and Shaw 1994; Rosenzweig and Hillel 1998). The early models have been criticized for a "dumb farmer" assumption—they did not incorporate how farmers would respond to climate change with different crops and growing methods. Efforts to incorporate how public and private suppliers of knowledge and technology might adjust to climate change are just beginning (Evenson

1988). But even the more sophisticated models have been unable to incorporate the synergistic interactions among climate change, soil loss and degradation, ground and surface water storage, and the incidence of pests and pathogens. These interactive effects could combine into a significantly larger burden on growth in agricultural production than the effects of each constraint considered separately. One thing that is certain is that a country or region that has not acquired substantial agricultural research capacity will have great difficulty in responding to anticipated climate change impacts.

SCIENTIFIC AND TECHNICAL CONSTRAINTS

The achievement of sustained growth in agricultural production over the next half century represents at least as difficult a challenge to science and technology development as the transition to a science-based system of agricultural production during the twentieth century did. In assessing the role of advances in science and technology in releasing the several constraints on growth of agricultural production and productivity, the induced technical change hypothesis is useful. To the extent that technical change in agriculture is endogenous, scientific and technical resources will be directed to sustaining or enhancing the productivity of those factors that are relatively scarce and expensive. Farmers in those countries that have not yet acquired the capacity to invent or adapt technology specific to their resource endowments will continue to find it difficult to respond to the growth of domestic or international demand.

In the 1950s and 1960s, it was not difficult to anticipate the likely sources of increase in agricultural production over the next several decades (Millikan and Hapgood 1967; Ruttan 1956; Schultz 1964). Advances in crop production would come from expansion in area irrigated, from more intensive application of improved fertilizer and crop protection chemicals, and from the development of crop varieties that would be more responsive to technical inputs and management. Advances in animal production would come from genetic improvements and advances in animal nutrition. At a more fundamental level, increases in crop yields would come from genetic advances that would change plant architecture to make possible higher plant populations per hectare and would increase the ratio of grain to straw in individual plants. Increases in production of animals and animal products would come about by genetic and management changes that would decrease the proportion of feed devoted to animal maintenance and increase the proportion used to produce usable animal products.

I find it much more difficult to tell a convincing story about the likely sources of increase in crop and animal production over the next half century than I did a half century ago. The ratio of grain to straw is already high in many crops, and severe physiological constraints arise in trying to increase it further. There are also physiological limits to increasing the efficiency with which animal feed produces animal products. These constraints will impinge most severely in areas that have already achieved the highest levels of output per hectare or per animal unit—in Western Europe, North America and East Asia. Indeed, the constraints are already evident. The yield increases from incremental fertilizer application are falling. The reductions in labor input from the use of larger and more powerful mechanical equipment are declining as well. As average grain yields have risen from 1–2 metric tons per hectare to 6–8 metric tons per hectare over the last half century in the most favored areas, the share of research budgets devoted to maintenance research—the research needed to maintain existing crop and animal productivity levels—has risen relative to total research budgets (Plucknett and Smith 1986). Cost per scientist year has been rising faster than the general price level (Huffman and Evenson 1993; Pardey, Craig, and Hallaway 1989). I find it difficult to escape a conclusion that both public and private sector agricultural research, in those countries that have achieved the highest levels of agricultural productivity, have begun to experience diminishing returns.

Perhaps advances in molecular biology and genetic engineering will relieve the scientific and technical constraints on the growth of agricultural production. In the past, advances in fundamental knowledge have often initiated new cycles of research productivity (Evenson and Kislev 1975). Transgenetically modified crops, particularly maize, soybeans, and cotton, have diffused rapidly since they were first introduced in the mid-1990s. Four countries—the United States, Argentina, Canada, and China—accounted for 99 percent of the 109 million acres of transgenic crop area in 2000 (James 2000). The applications that are presently available in the field are primarily in the area of plant protection and animal health. Among the more dramatic examples is the development of cotton varieties that incorporate resistance to the cotton bollworm. The effect has been to reduce the application of chemical control from 8–10 to 1–2 spray applications per season (Falck-Zepeda, Traxler, and Nelson 2000). These advances are enabling producers to push crop and animal yields closer to their genetically determined biological potential. But they have not yet raised biological yield ceilings above the levels that have been achieved by researchers employing the older methods based on Mendelian genetics (Ruttan 1999).

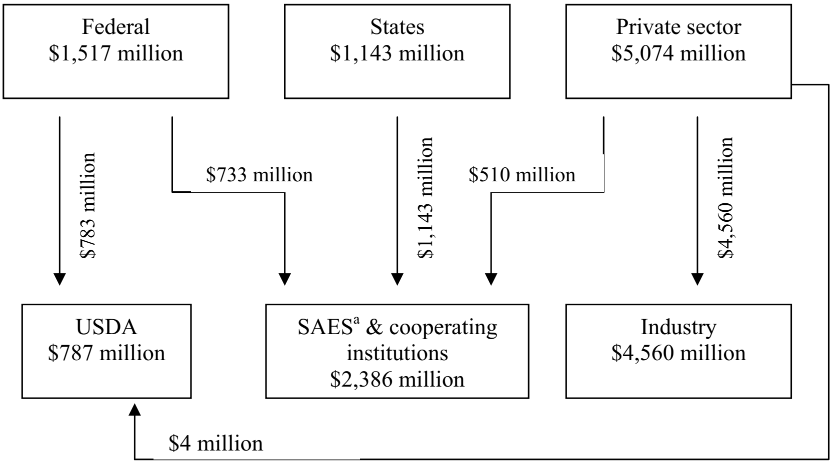
Advances in agricultural applications of genetic engineering in developed countries will almost certainly be slowed by developed country concerns about the possible environmental and health impacts of transgenetically modified plants and foods. One effect of these concerns has been to shift the attention of biotechnology research away from agricultural applications in favor of industrial and pharmaceutical applications (Committee on Environmental Impacts 2002, pp. 221–229). This shift will delay the development of productivity-enhancing biotechnology applications and agricultural development in less developed economies.

I find it somewhat surprising that it is difficult for me to share the current optimism about the dramatic gains to be realized from the application of molecular genetics and genetic engineering. One of my first professional papers was devoted to refuting the pessimistic projections for agricultural productivity and production that were common in the early 1950s (Ruttan 1956). Other students of this subject have presented more optimistic perspectives (Runge et al. 2003; Waggoner 1997). But I have not yet seen evidence that the new genetics technologies, although undoubtedly powerful, will or can overcome the long-term prospect of diminishing returns to research on agricultural productivity.

AGRICULTURAL RESEARCH SYSTEMS

To this point, I have given major attention to the role of agricultural research as a source of technical change and productivity growth. In this section I sketch the evolution and structure of national and international agricultural research systems.[11] The institutional arrangements for the support of agricultural research began in the middle of the nineteenth century. In 1843 John Bennet Lawes (subsequently knighted) established, and later endowed, an agricultural experiment station on his family estate of Rothamsted, in Hertfordshire, England. In Germany, the introduction by Justus von Liebig of the laboratory method of training in organic chemistry at Giessen led directly to the establishment of the first publicly supported agricultural experiment station at Mockern, Saxony, in 1852. The German method of public-sector agricultural research became the model for agricultural research in the United States. A number of American students who studied with Liebig were responsible for establishing the research program of the U.S. Department of Agriculture and the agricultural experiment stations at the new land-grant public universities in the late 1800s (Ruttan 1982). The basic structure of the U.S. agricultural research system has become increasingly complex, with the federal government, individual states, and the private sector each playing an important role. The sources and flows of funding for 1998 are shown in Figure 4.4.

Figure 4.4 Sources and Flows of Funding for Agricultural Research: 1998



[a] SAES stands for State Agricultural Experiment Station.

SOURCE: Adapted from Fuglie, Ballenger, Day, Klotz, Ollinger, Reilly, Vasavada, and Lee (1996, p. 9).

Substantial progress was made in the first several decades of the twentieth century in initiating public sector agricultural research capacity in Latin America and in the colonial economies of Asia and Africa. Research efforts were focused primarily on tropical export crops such as sugar, rubber, cotton, bananas, coffee, and tea. The disruption of international trade during the Great Depression of the 1930s and during World War II, followed by the breakup of colonial empires, aborted or severely weakened many of these efforts.

By the early 1960s, the U.S. development assistance agency and the assistance agencies of the former colonial powers were beginning to channel substantial resources into strengthening agricultural education and research institutions, with a stronger focus on domestic food crops in developing countries. The Ford and Rockefeller foundations collaborated in the establishment of four international agricultural research institutes: the International Rice Research Institute (IRRI) in the Philippines, the International Center for the Improvement of Maize and Wheat (CIMMYT) in Mexico, the International Institute of Tropical Agriculture (IITA) in Nigeria, and the International Center for Tropical Agriculture (CIAT) in Colombia. In 1971, the two foundations, joined by the World Bank, the Food and Agricultural Organization of the United Nations (FAO), the United Nations Development Program (UNDP), and a number of bilateral donor agencies, formed the Consultative Group on International Agricultural Research (CGIAR). By the early 1990s the CGIAR systems had expanded to 18 centers or institutes.

From the 1950s through the 1980s, the resources available to the new national and international research institutions from national and international sources expanded rapidly. Both the national and the international systems achieved dramatic success in the development of higher yielding, “green revolution” wheat, rice, and maize varieties (Alston et al. 2000; Ruttan 2001, pp. 203–223). Several developing countries—India, China, Brazil, Argentina, and South Africa—achieved world class agricultural research capacity. During the 1990s, however, growth of public sector support for both national and international agricultural research slowed substantially. Support for private sector agricultural research, which remains concentrated primarily in developed countries, has continued to grow rapidly.[12]

An active and vibrant global agricultural research system will be needed to sustain growth in agricultural productivity into the twenty-first century. But the system itself is still incomplete. When it is completed, it will include strong public national research institutions, linked to higher education, that can work effectively with the international system and other national systems. This network will be complemented by a scientifically sophisticated technology supply industry, composed of both national and multinational firms. The research systems in most developing countries have yet to establish sufficient capacity to make effective use of the existing advances in knowledge and technology. The private sector agricultural technology supply industry, although growing rapidly, still remains poorly represented in the poorest developing countries.

PERSPECTIVE

What are the implications of the resource and environmental constraints, the scientific and technical constraints, and the institutional constraints on agricultural productivity growth over the next half century? In those countries and regions in which land and labor productivity are already at or approaching scientific and technical frontiers, it will be difficult to achieve growth in agricultural productivity comparable to the rates achieved over the last half century (Pingali and Heisey 2001; Pingali, Moya, and Velasco 1990; Reilly and Fuglie 1998). But in most of these countries at the technological frontier, the demand for food will rise only slowly. As a result, these countries, except perhaps those that are most land-constrained, will have little difficulty in achieving rates of growth in agricultural production that will keep up with the slowly rising demand for food. Several of the countries near the technological frontier, particularly in east Asia, will find it economically advantageous to continue to import substantial quantities of animal feed and food grains (Rosegrant and Hazell 2000).

For those countries in which land and labor productivity levels are furthest from frontier levels, particularly those in sub-Saharan Africa, opportunities exist to enhance agricultural productivity substantially. Countries that are land-constrained, such as India, can be expected to follow a productivity growth path that places primary emphasis on biological technology. In contrast, Brazil, which is still involved in expanding its agricultural land frontier while confronting crop yield constraints in its older agricultural regions, can be expected to follow a more balanced productivity growth path. Most of the poor countries or regions that find it advantageous to follow a biological technology path will have to invest substantially more than in the past to acquire a capacity for agricultural research and technology transfer. These investments will include general and technical education, rural physical infrastructure, and appropriate research and technology transfer institutions. Moreover, gains in labor productivity will depend on the rate of growth in demand for labor in the nonfarm sectors of the economy, which in turn will create the incentives for substituting mechanical technology for labor in agricultural production. If relatively land-abundant countries, in sub-Saharan Africa for example, fail to develop a strong intersector labor market in which workers can move from rural agricultural jobs to urban manufacturing and service jobs, they will end up following an East Asian land-saving biological technology path.

I find it more difficult to anticipate the productivity paths that will be followed by several other regions. The countries of the former Union of Soviet Socialist Republics (USSR) have in the past followed a trajectory somewhat similar to North America (as shown in Figure 4.2). If they recover from recent stagnation, these countries may resume their historical trajectory.[13] The trajectories that will be followed by west Asia, North Africa, and other arid regions are highly uncertain. Very substantial gains in water productivity will be required to realize gains in land productivity in these areas, and very substantial growth in nonagricultural demand for labor will be required to realize the substantial gains in labor productivity that would enable them to continue along the intermediate technology trajectory that has characterized the countries of southern Europe. The major oil-producing countries will continue to expand their imports of food and feed grains. If the world should move toward more open trading arrangements, a number of tropical or semitropical developing countries would find it advantageous to expand their exports of commodities in which their climate and other resources give them a comparative advantage and import larger quantities of food and feed grains.

While many of the constraints on agricultural productivity discussed in this paper are unlikely to represent a threat to global food security over the next half century, they will, either individually or collectively, become a threat to growth of agricultural production at the regional and local level in a number of the world's poorest countries. A primary defense against the uncertainty about resource and environmental constraints is agricultural research capacity. The erosion of capacity of the international research system will have to be reversed, capacity in the presently developed countries will have to be at least maintained, and capacity in the developing countries will have to be substantially strengthened. Smaller countries will need, at the very least, to strengthen their capacity to borrow, adapt, and diffuse technology from countries in comparable agroclimatic regions. It also means that more secure bridges must be built between the research systems of what have been termed the "island empires" of the agricultural, environmental, and health sciences (Mayer and Mayer 1974).

If the world fails to meet its food demands over the next half century, the failure will be at least as much in the area of institutional innovation as in the area of technical change. This conclusion is not an optimistic one. The design of institutions capable of achieving compatibility between individual, organizational, and social objectives remains an art rather than a science. At our present stage of knowledge, institutional design is analogous to driving down a four-lane highway while looking only at the rear-view mirror. We are better at making course corrections when we start to run off the highway than at using foresight to navigate the transition to sustainable growth in agriculture output and productivity.

Notes

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1. The Schultz "poor but efficient" hypothesis was received skeptically by development economists who had posited a "backward bending" labor supply curve in developing countries' agriculture. See, for example, Lipton (1968). For a particularly vicious review of *Transforming Traditional Agriculture*, see Balogh (1964). Schultz was the recipient of the 1979 Nobel Prize in Economics, along with W. Arthur Lewis, for his contribution to development economics.

2. Hayami and Ruttan's (1985) induced innovation interpretation of technical change has been criticized on both theoretical and empirical grounds. See, for example, Olmstead and Rhode (1993) and Koppel (1995). For a response to these criticisms, see Ruttan and Hayami (1995).
3. Before that time, Japanese farmers prepared the soil by hand with shovels and hoes, or by using plows pulled by cattle, which were not as strong as horses and so could not plow as deep.
4. Multifactor productivity estimates for agriculture in the United States were first constructed in the late 1940s and early 1950s (Barton and Cooper 1948; Schultz 1953; Ruttan 1956). For a comparative review and analysis of the sources of differences in the several aggregate agricultural production functions that have been estimated for U.S. agriculture, see Trueblood and Ruttan (1995). Note that from the beginning agricultural economists were using what, in the recent literature, have been termed "augmented" neoclassical production functions rather than Solow-type, two-factor production functions. For a review of total factor productivity estimates in developing countries, see Pingali and Heisey (2001).
5. In cross-country growth accounting, it has not been possible to account directly for improvement in the quality of inputs. Attempts are made to capture improvements in the quality of labor input by including education and for improvements in the quality of capital and intermediate inputs by including investment in technical education or research and development in the cross-country production functions. Jorgenson and Gollop (1995) have estimated that during 1947–85, when total factor productivity in U.S. agriculture grew at an annual rate of 1.58 percent, input quality change accounted for about one-third of the total factor productivity growth. Using a somewhat different approach, Shane, Roe, and Gopinath (1998) estimated that private research and development embodied in factor input quality accounted for about 25 percent of total factor productivity between 1949 and 1991.
6. The advantages of the Malmquist or frontier productivity index, in addition to the decomposition of total factor productivity into efficiency change and technical change, are twofold: 1) it is nonparametric and does not require a specification of the functional form of the production technology, and 2) it does not require an economic behavior assumption such as cost minimization or revenue maximization (Färe, Grosskopf, and Knox Lovell 1994; Färe et al. 1994). The contemporaneous Malmquist approach employed by Trueblood and Coggins (2001) identifies the best-practice countries in each period and measures the change in each country's performance relative to the change in the frontier. A country that shows a positive growth in total factor productivity may show negative Malmquist productivity change because it may lag relative to the best-practice frontier. The sequential Malmquist approach that has been employed by Suhariyanto, Lusigi, and Thirtle (2001) does not permit negative technology shifts.
7. The issues discussed in this section are addressed in greater detail in Ruttan (1999).
8. Countries characterized by "absolute water scarcity" do not have sufficient water resources to maintain 1990 levels of per capita food production from irrigated

agriculture, even at high levels of irrigation efficiency, and also meet reasonable water demands for domestic, environmental and industrial purposes. Countries characterized by "severe water scarcity" are in regions in which the potential water resources are sufficient to meet reasonable water needs by 2025, but only if they make very substantial improvements in water use efficiency and water development (Seckler, Molden, and Barker 1999).

9. Estimates of losses in crop and animal production due to pests vary greatly by commodity, location, and year. However, estimates by reputable investigators run upwards of 33 percent of global food crop production. Losses represent a higher percentage of output in less developed countries than in developed countries. Among major commodities, the highest losses are experienced by rice (Yudelman, Ratta, and Nygaard 1998).
10. I have not in this paper discussed the potential impacts of health constraints on agricultural production. The increase in use of insecticides and herbicides associated with agricultural intensification have had important negative health effects on agricultural workers. The health effects of the resurgence of older diseases such as malaria and tuberculosis, are greatest in rural communities in developing countries. It is not too difficult to visualize situations in particular villages in which the coincidence of several health factors, including AIDS, could result in serious constraints on agricultural production (Pingali and Roger 1995; Bell, Clark, and Ruttan 1994; Haddad and Gillespie 2001).
11. For a more detailed discussion of the evolution and structure of national and international agricultural research, see Ruttan (1982) and Huffman and Evenson (1993).
12. In 1995 it was estimated that global agricultural research expenditures amounted to $33 billion (in 1993 dollars). Of this amount public sector expenditures amounted to $12.2 billion in developed countries and $11.5 billion in developing countries. Private sector expenditures for agricultural research amounted to $10.8 billion in developed and $0.7 billion in developing countries. Support for the CGIAR system declined from $334 million in 1990 to $305 million (1993 prices) in 2000 (Pardey and Beintema 2001).
13. Between 1962 and 1990, crop yields in the former Soviet Union experienced modest gains relative to the world's leaders. From the early 1990s, however, yield growth rates became negative, and by 1997 the yield gap between the countries of the former Soviet Union and the world leaders exceeded the levels of 1962 (Trueblood and Arnade 2001).

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