*Journal of Economic Literature*
*Vol. XLIII (December 2005), pp. 989-1024*

# Economic Growth: Lessons from Two Centuries of American Agriculture

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*This paper reviews the growth experience of U.S. agriculture over the past two centuries in consonance with the view that growth is determined by the economic environment, which consists of the available technology, incentives, constraints, and institutions. Within this framework, the implemented technology is determined jointly with the resource allocation. The review covers the role played by resource endowment, resource flow, technical change and its factor bias, and product demand. It highlights the importance of the income elasticity of demand and the labor augmentation of the technical change. The total factor productivity (TFP) was almost nil at the beginning of the nineteenth century, increasing gradually to the point where it exhausted output growth in the latter part of the twentieth century. This pattern is consistent with the postulate emerging from this framework, where the TFP is endogenous and determined jointly with growth rather than determining it. The more recent performance of U.S. agriculture is placed within a global perspective in order to generalize the discussion.*

## 1. *Overview*

Aggregate single output growth models demonstrate the role of knowledge formation and of resource accumulation in raising output levels. Such models, however, lack the details needed to account meaningfully for cross-country variations in income levels or growth. This constructive lesson is drawn from the rapidly proliferating empirical analyses based on these models. If the models be taken seriously, the reason for the difficulties in the empirical validation is related to the imperfect flow of knowledge and resources needed to fully utilize the production potential at any given time or place. The utilization of knowledge and resource flow is connected, and restrictions on the resource flow thus have a direct and indirect effect on the performance of the economy. To examine this line of thinking, we need to allow for heterogeneous technology where more than one technique of production exists. We do this by reducing the level of aggregation to a two-sector economy, with different sectoral technologies.

It has long been known that modern economic growth involves changes in the sectoral composition of the economy (Simon

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Kuznets 1957a), and the change in the relative importance of agriculture constitutes the most dramatic illustration of this process. The structural change is not a result of the growth process but part of it, and without the growth in agricultural productivity the history of economic development would have taken a completely different course. More formally, the sectoral composition is endogenous and the study of its changes over time provides an insight into the growth process, which is concealed in the analysis of the aggregate—single output—economy. Specifically, dealing with sectoral growth highlights the importance of demand, incentives, resource allocation, the determination and the nature of technical change, the differential growth in productivity, and the implication of all these for the relationship between poverty and growth. The importance of these determinants is examined here against the background drawn from the development of U.S. agriculture.

The experience of U.S. agriculture is of interest for a variety of reasons. From the vantage of economic development, and of historical perspective, the United States made the transition from an agriculture-based economy to a nonagricultural economy in a relatively short time. "The first census of the United States found that 95 percent of the population was rural, and it was not until 1830 that the urban population exceeded 10 percent of the total" (D. Gale Johnson 1997, p. 3). With U.S. agriculture accounting currently for only about 2 percent of the labor force, the United States nevertheless accounts for about 14 percent of world agricultural production; it has been a major player in international agricultural markets, it has had elaborate agricultural programs, and it has maintained a high level of productivity in agriculture and in the economy. In addition, it has been studied extensively in writing and, above all, it has data covering the complete period of the transformation, which is essential for the task.

The study of sectoral growth extends the analysis of aggregate growth by adding the sectoral demand, and in this respect agriculture constitutes an interesting case because of the low income elasticity of food. It is this attribute that has played a critical role in the structural development of the economy. The world would have been entirely different if, for instance, the demand for food had an income elasticity of 1.2 rather than somewhere in the range of 0.2–0.5. In this hypothetical case, agriculture would have become a growing sector of the economy, and would have attracted resources rather than supplying them to the rest of the economy. The emphasis on the role of demand in development leads to a different paradigm from that obtained from models that attribute the shrinkage in the relative importance of agriculture to the accumulation of human or physical capital in the economy (e.g., Robert E. Lucas 2004, Diego Restuccia 2004).

When we talk about agriculture as a sector we are implicitly dealing with a dual, or a two-sector, economy. For some reason, one gets the impression that discussions of the dual economy are associated mainly with countries where agriculture, or the rural sector, is still dominant. Such an association is unjustified because, if the model is geared to dealing with sectors of unequal relative size, its pertinence should not depend on which sector is dominant. The power of the model is rooted in the decisions made at the margin, and these determine the trade-off between the sectors in resources and in products. This point cannot be overemphasized. It is the exchange and the behavior of the product and factor markets which are crucial for the development process. These, naturally, change across countries and over time, and it is this variability that makes the analysis interesting and useful. What varies across samples is the economic environment, which consists of all the elements that determine the economic decisions.

The empirical study of growth deals with the decomposition of output growth to factor accumulation and technical change. Underlying this exercise rests the broader and more fundamental question of what determines the flow of technology and resources. To answer this question, we have to examine how the economic environment affects these flows, a subject largely absent from discussions based on the common, but naïve, assumption of homogenous technology. The dependence of technology on the economic environment causes variability in the use of more advanced technology. This in turn causes variability in the observed technology and in the parameters chosen to represent it. Consequently, a summary of the production function with parameters estimated or calibrated to fit one sample has only a limited value, and its generalization is bound to be misleading. More generally, there is a connection between the technology in use, or the implemented technology, and the resource availability. This connection affects the empirical analysis, as well as the conclusions with respect to the source and the identification of factor augmentation and factor bias.

This paper is bifocal in its coverage and, in addition to the dynamic aspects of agricultural growth and their implications, in it I discuss general issues related to dynamic aspects of resource allocation, productivity, and growth. The methodology of the paper is rather simple; I try to integrate the discussions in the literature into a framework that I believe is helpful for interpreting the data. I begin with an overview of the evidence, where I rely heavily on the writings of economic historians and quote their interpretation of issues important to our task. I devote much of the paper to gaining an insight into the role played by technology. To do this, I start with the basics, namely partial productivity, followed by total factor productivity (TFP), and the bias in the technical change. This is then followed by the introduction of heterogeneous technology, which provides a framework for linking productivity changes to resource flow. Available data and studies make it possible to discuss the problems encountered in inferring the form of the technical change from production data. The paper concludes with comments on the welfare implications of agricultural growth and some general final remarks.

## 2. *Evidence*

The nineteenth century was a period of strong growth in agriculture and more so in the economy, supported by the inflow of labor and capital from abroad.[1] For the economy as a whole, the growth rate of GNP was roughly 4 percent, and this was achieved mostly by resource growth, whereas the contribution of TFP accounted for only 15 and 18 percent of output growth in the first and second halves of the century respectively.[2]

The developments in agriculture are summarized in figure 1 in terms of growth rates for output and the major inputs for five subperiods. The growth rate of output in the nineteenth century was high relative to that of the twentieth century. Much of this growth came from the expansion to new land. U.S. land consigned to farming, in millions of acres, amounted to 300 in 1850, 1,159 in 1950 which was nearly the peak year, and 930 in 1990.[3] The U.S. agricultural labor force was approximately 11 million in 1900, reaching a peak of 11.6 million around 1910 and declining to nearly 3

[1] The information for the nineteenth century, particularly for the first half of the century, is more sparse and of inferior quality compared with that available for the twentieth century. The judgment on the quality of the data is made explicit in some of the sources on which we depend in our discussion.

[2] Robert E. Gallman (2000). Throughout, the term "rate of change" or "growth rate" implies the annual compounded average rate of change.

[3] A. S. Tostlebe (1957, table 6), and Bruce L. Gardner (2002, figure 1.1).

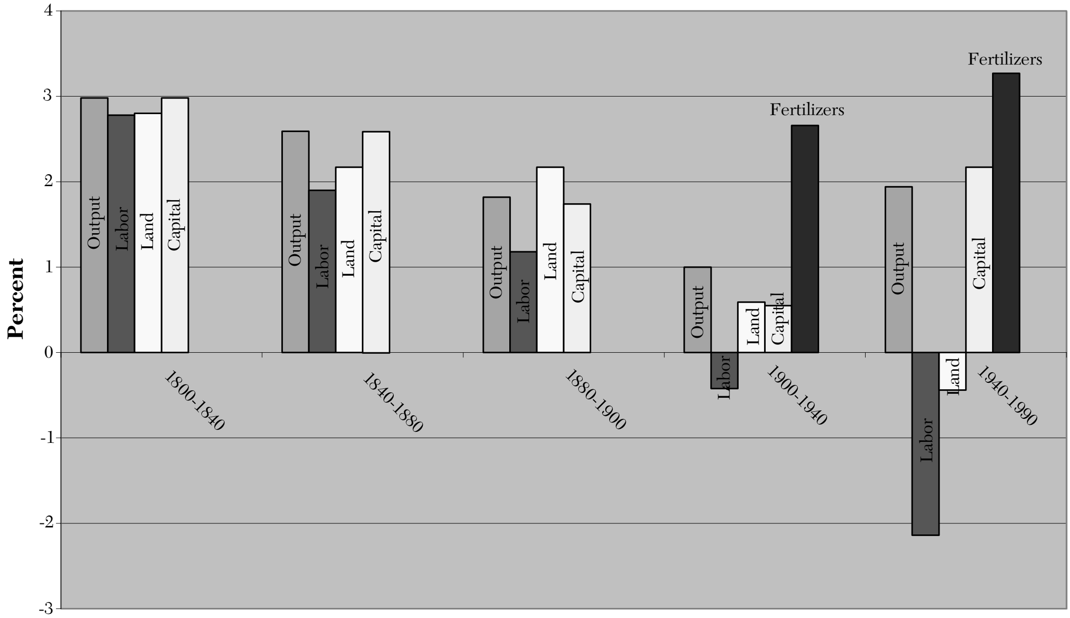


*Figure* 1: U.S. Agriculture 1800–1990—Growth Rates

Notes:
Output: Nineteenth century, computed from the growth rates of labor and of output–labor ratio (Weiss 1993). Twentieth century, Gardner (2002, figure 8.1).
Labor: Based on Robert A. Margo (2000) tables 5.1 and 5.3, Tostlebe (1957, tables 4 and 9), Gardner (2002, figures 8.1 and 8.2.
Land: 1800–1840–1900 Gallman (2000) and Gardner, figure 1.1. The growth rate of land of 2.17 is the average for the period 1840–1900.
Capital: Gallman (1986, table 4.8), Tostlebe (1957, table 9), and Gardner (2002). For the period 1840–80, Gallman reports the ratio of capital to value added in constant prices. The ratio was 2.67 in 1840 and 2.73 in 1880. For lack of better information, we assume it to be constant, and thus approximate the growth rate of capital to be the same as that of output. In the same spirit, we apply the same assumption to the period 1800–1840. For later years, Tostlebe provides capital values starting with 1870 (John W. Kendrick 1961, p. 355, and table B-III, modifies Tostlebe data, but the effect on the growth rates is negligible for our discussion). The growth rate in 1880–1900 comes out close to that of the output growth. Note, however that the rate for 1870–80 was 3.6. Thus, the average rate for 1870–1990 is 2.35, which is in the range of the values used. For 1940–90, the source is Gardner (2002, figure 8.4).
Fertilizers: Gardner (2002, figure 2.6a).

million in 1990.[4] As figure 1 shows, land, capital, and labor grew (or are assumed to have grown) at similar rates at the beginning of the nineteenth century, but as the century wore on the growth rate of labor started to lag behind that of land, leading to a rise in the land–labor ratio.[5] The decline in the growth rate of labor—unlike that of output, land, and capital—continued throughout the century and accelerated in the twentieth century.

Capital grew faster than labor, and more so in the economy than in agriculture. The major part of the agricultural capital was comprised initially of land improvement,

[4] Data up to 1950 come from Tostlebe (1957, table 4); for later years I use figures based on census data reported by Andrew P. Barkley (1990) for the period 1940–85. The extension to 1990 is based on growth rates derived from Gardner (2002, figures 8.1 and 8.2).

[5] Wayne D. Rasmussen (1962, pp. 573–74).

but that changed with time.[6] The percentage share of farm improvement in agricultural capital (total capital) was 61 (38) in 1840 and 54 (12) in 1900.[7] It appears that strong credit constraints prevailed, which necessitated making important choices: "Farming became increasingly expensive in the late nineteenth century. The real price of land was rising throughout the period until World War I. Moreover, mechanization, a growing imperative for successful farming, further strained the financial resources of farmers. For many, tenancy was the only way to farm, but others chose to borrow" (Jeremy Atack, Fred Bateman, and William N. Parker 2000, p. 274). "Mortgages typically lasted three years or less and might be renewed, though renewal terms were never certain. The long-term, amortized mortgages so familiar today did not begin to appear until the 1920s" (Atack, Bateman, and Parker 2000, p. 274). Labor was diverted to new land, or the extensive margin, and there was little growth in the output–land ratio, which represents the intensive margin. This is mirrored in the rise of the output–labor ratio. Supporting evidence is drawn from data on the production of corn, wheat, and cotton in the nineteenth century presented in Rasmussen (1962, table 1). The data show a continuous rise in the land–labor ratio for all three crops, at a faster rate than that observed for total agriculture.

Historians mark two revolutions in American agriculture due to technical change: first, the change from manpower to animal power which centered on the Civil War. The second is the change from animal to mechanical power, plus the adoption and adaptation of chemistry and genetics to agricultural production, starting circa 1940. There is a debate on whether these changes constituted revolution or evolution, because the transition, as important as it was, evolved gradually. This debate documents the existence of a time lag between changes in the available technology and its complete implementation, and the uneven implementation between regions.[8] To anticipate our subsequent discussion, we note that the uneven implementation of the available technology is an economic decision, which reflects changes in the pertinent economic environment. Indeed, Rasmussen (1962, pp. 578–79) argues that the rate of adoption of machinery and other technological advances benefited from the sharp rise in demand in the Civil War and in World War II.[9] There was

[6] "The structural changes in the composition of capital influenced the means by which the capital stock was assembled. In the antebellum years, almost half of the depreciable capital stock (constant prices) consisted of agricultural land improvements, many of them created by family labor, or labor attached to plantation on which they were constructed, or by other local sources of labor. These improvements were typically carried out in the off season . . . Little external finance was required to carry them out. But the structural changes of modernization brought to the fore industries, forms of capital, and organizational scales of operation that enhanced the roles of markets and of external finance in the provision of capital" (Gallman 1986, p. 200).

[7] Gallman (1986, table 4.2).

[8] Ross suggested that transitions in agriculture had been "delayed, halting, hesitant, as well as uneven between regions and even, at times, adjoining farms. The same year, Clarence H. Danhof showed that even as simple a device as the revolving horse rake had slow acceptance among farmers" (Rasmussen 1962, pp. 578–79). "Although agriculture was expanding onto the more fertile midwestern soils during the 1820s and 1830s, these years do not seem to have been ones of marked practices, or techniques, whereas in the Civil War years and immediately thereafter, mechanization was proceeding rapidly and there were more organized and systematic efforts to diffuse knowledge about best-practice farm methods" (Atack, Bateman, and Parker, p. 258). Thomas Weiss (1993) reviews the debate and the data revisions and concludes that "The Civil War, or at least the decade of the 1860s, may have marked a turning point in productivity, as has been suggested by many earlier writers" (p. 339).

[9] In the case of the first American agricultural revolution, "It is important to note that every stage in the growing of grain was amenable to the use of horse-drawn machines by 1860 . . . A backlog of technology, particularly in the form of horse drawn machinery, was available by 1860. The Civil War provided the incentive and the opportunity for its adoption, especially in the Midwest. The rate of investment in farm machinery and the implements increased rapidly from 1850 to 1880, and then declined" (Rasmussen, pp. 580–81).

a connection between the implemented technology and inputs, to which we refer as the *jointness* property: "The results of the confluence of technological advances, manpower shortages, better prices, and greater demand may be seen, at least in part in table 1" (Rasmussen 1962, p. 582).[10]

The growth rates of output and inputs, with the exception of fertilizer, continued to decline in 1900–1940, which can be viewed as a transition period from the nineteenth century to more recent times.[11] The tendency of declining output growth rates changed in the period 1940–90. This period is the most relevant to current changes in world agriculture, and it is instructive therefore to compare the U.S. performance in this period with the global experience. To do so, I draw on the database and the presentation by Mundlak, Donald F. Larson, Al Crego, and Rita Butzer in the references that appear below. This consists mostly of data for the years 1967–92, and thus the comparison is related to the more active period of U.S. agriculture in terms of land productivity.

The average growth rate of U.S. agricultural output was 1 and 1.94 percent in the periods 1900–1940 and 1940–90 respectively. The global experience draws on distributions of agricultural output growth rates in 130 countries during 1967–92.[12] Two distributions were examined. In the uniform distribution each country is assigned an equal weight, whereas in the weighted distribution each country is weighted by its value output. I report here results for the weighted distribution. The median growth rate is 2.25 percent, while the U.S. rate in this series is 1.4 percent, (figure 2). In fact, 70 percent of the countries achieved higher rates than the United States in that period. This comparison provides an important perspective for viewing the U.S. experience. It is a conventional wisdom that U.S. agriculture has performed so well because of its elaborate research and extension system. Without questioning the quality of the U.S. system, we see here that the U.S. growth rates were not outstanding.

To bring in demand, I turn to per capita production. As shown in figure 2, the median of the country distribution is 0.7 percent, as compared to 0.4 percent in the United States. The output growth was directed in part to markets abroad, and in part caused price decline. The index of real prices received by U.S. farmers (1992 = 100) was 192 in 1900, 150 in 1940, and 75 in 2000.[13] The implied rates of change are –0.6 percent for the period 1900–1940, and –1.4 percent for the period 1940–90. The global experience is based here on the distribution of 112 countries in the period 1967–92. The median rate is –0.6 percent, whereas the U.S. rate in this series is –2.1 percent, showing a

[10] There is no unanimous agreement on the foregoing description of causality. Alan L. Olmstead (1976) attributes the mechanization to a decline in the real prices of harvesting equipment which was triggered by increasing competition in the industry. This caused nominal prices to remain constant, while other prices and specifically wages rose. Thus, the pace of the implementation is related to changes in the price environment. Paul P. Christensen (1981, p. 326) argues that the availability of cheap power and high labor costs were the incentives for mechanization. The emphasis here is on a comparison with England, and not on the timing of the implementation in the United States. As such, this is a cross-country comparison of fundamentals, rather than of time series variability.

[11] Fertilizer is not part of the database for the nineteenth century.

[12] The number of countries was dictated by the available information, and it is therefore not the same for the various variables under consideration. In addition to differences among sources in time coverage, variables may differ also in their definitions even though they may carry the same names. An important difference is the way the variables are converted from nominal to real terms. In the country study quoted here, output and prices are measured by the Fischer index, which is not the case in the variables presented by Gardner (2002). The purpose of this note is to indicate a source of differences, not to judge the quality of the series.

[13] Gardner (2002, figure 5.1).

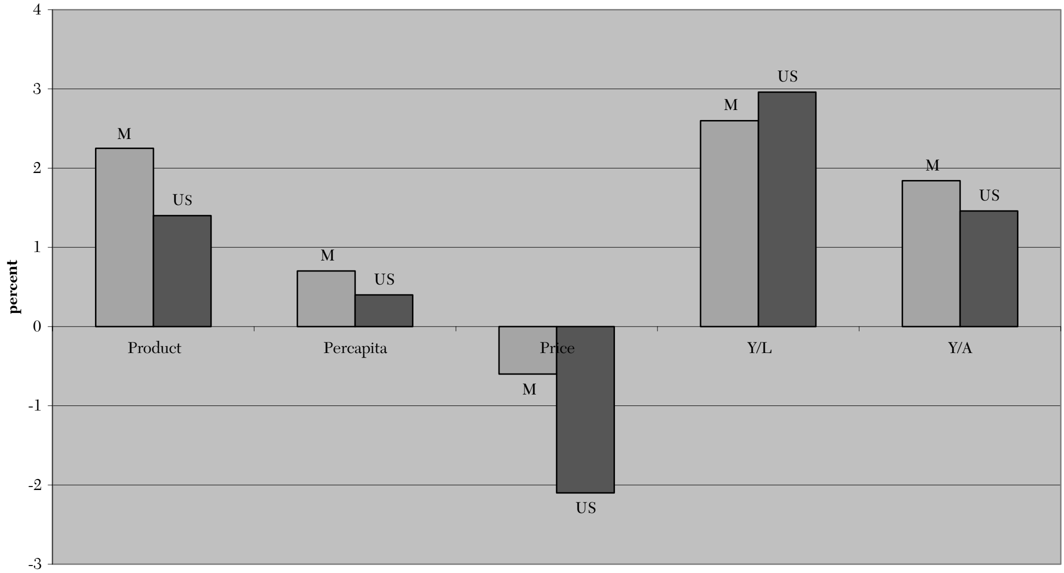


*Figure* 2: Agriculture Growth Rates: Global Perspective

Source: Mundlak, Larson, and Crego (1998).
Notes: M stands for the median of the following empirical distributions of growth rates:
1967–92: Product is Fischer index for 130 countries; per capita is derived from the production series; price is the Fischer price index for 112 countries, where the country prices are deflated by the domestic cpi.
1960–92: 87 countries; Y is agricultural gdp, Y/L is agricultural labor productivity, and Y/A is land productivity.

stronger price decline than in most other countries, even though its growth rate was not outstanding. The price decline was pervasive; and in that period 71 percent of world output was produced in countries where the real agricultural price was declining. The continuous price decline indicates that supply exceeded demand, reflecting the fact that the demand for agriculture is income inelastic. It is for this reason that in the United States, as in most countries, the growth rate of *per capita* output in agriculture is lower than that of *total per capita* output. Ignoring trade for a moment, I note that for a closed economy under constant prices the ratio of these two growth rates (agriculture to total) is a rough indicator of the income elasticity for food. I say rough, because the price is not constant, and because agriculture is not identical with food. The median of the distribution of the ratio for ninety-one countries during 1960–92 is 0.82.[14] Allowing for the price decline mentioned above, an income elasticity of 0.5 is consistent with the data, and in line with common wisdom (e.g., H. S. Houthakker 1957). Continuing with this approximation, we note that the growth of *total* agricultural output at a smaller rate than that of *total* nonagricultural output, and a nonrising agricultural price, is a sufficient indication of income inelastic demand for agriculture.[15] In the United States, the ratio

[14] Mundlak, Larson, and Crego (1998, figure 8.4).

[15] Ignoring trade, we approximate the demand for the agricultural product by the equation $\ln Y_a = \eta \ln Y_e + (1 - \eta) 1n N - \sigma \ln P_a$; $\eta > 0$, $\sigma > 0$, where $Y_a$ is the total output in agriculture, $Y_e$ is the total output in the economy, $N$ is population, and $P_a$ is the price of agriculture relative to that of nonagriculture. Label the growth rate of $x$ by $gx$, ignore the price change, and note that $gY_a < gY_e$ implies $\eta < 1$. Bringing in price and trade may add details but will not change the conclusion.

of the two rates was 0.76 for 1800–1840, 0.67 for 1840–80, and 0.44 for 1880–1900.[16] It was also below 1 in the twentieth century. As this ratio is below 1 in most countries, it is unreasonable to ignore the dominating role of demand in the differential sectoral growth. In this exercise I have ignored trade, but because the price decline was largely a global phenomenon, this omission does not distort the overall picture.

## 3. *Productivity*

Much of the discussion of productivity is based on the assumption that at any given time the technology is unique and is represented by a well defined production function. An improvement in technology with inputs held constant increases the average productivity of all inputs. This property, and perhaps the simplicity of the average productivity measure, explains its common use. The assumption of constant inputs is binding, however, because with time both inputs and technology change, and therefore a change in the average productivity reflects both. Still, the changes in the average productivity convey some information, as will be seen below. The differentiation between the impacts on output of changes in technology and changes in factors is accomplished with the calculation of TFP. This differentiation is subject to the tacit assumption that the changes in inputs and technology are independent. This assumption, however, is invalid when the inputs change in response to technical change, or when the technology consists of more than one technique. This claim has been demonstrated in the foregoing discussion, and is discussed below. Aside from this, TFP computed from a given production function does not reveal the differential impact of technical change on factor demand. To do this, it is necessary to determine the factor bias of technical change. In what follows, we review the empirical evidence to obtain a quantitative perspective of these measures and discuss some conceptual problems which arise in the attempt to draw conclusions from the data.

### 3.1 *Partial Productivity*

The growth rates of the average productivity in U.S. agriculture are summarized in figure 3. The growth of land productivity was generally anemic until the post-1940 period when it accelerated to 2.38 percent.[17] The performance of labor productivity is a different story; its growth rate increased continuously from 0.2 percent in 1800–1840 to 4.08 percent in 1940–90. The difference between the growth rates of labor and land productivity is simply an outcome of the decline in the rate of change of the labor–land ratio from practically nil in 1800–1840 to –1.7 percent 1940–90. This impressive change was achieved by the gradual mechanization of agriculture.

As shown in figure 2, the rise of land and labor productivity in the more recent period is not unique to the United States. For 1960–92, the median of the distribution of eighty-seven countries is 2.6 percent for labor productivity, and 1.84 percent for land productivity. The corresponding rates for the United States in this sample are 2.96 percent and 1.46 percent respectively. The U.S. performance was higher than the median of the labor productivity rate and lower than that of the of the land productivity rate. The slower rise of land productivity in the United States reflects the lower growth rate in output as mentioned above. The faster rise of labor productivity in the United States reflects the faster migration of labor out of agriculture,

[16] In this calculation, we use the following growth rates for the economy: 3.92, 4.0, and 4.1 for the three subperiods respectively.

[17] The crop output per acre shows no trend during 1910 to 1939, implying no growth in yield in that period. For instance, the corn yield was trendless in the period 1865–1940 (A. F. Troyer 1990; I am indebted to A. Ashri for this reference). Crop yields started to increase around 1940. The average growth rate was 2.1 percent in the period 1939–94 (Gardner 2002, figure 2.5).

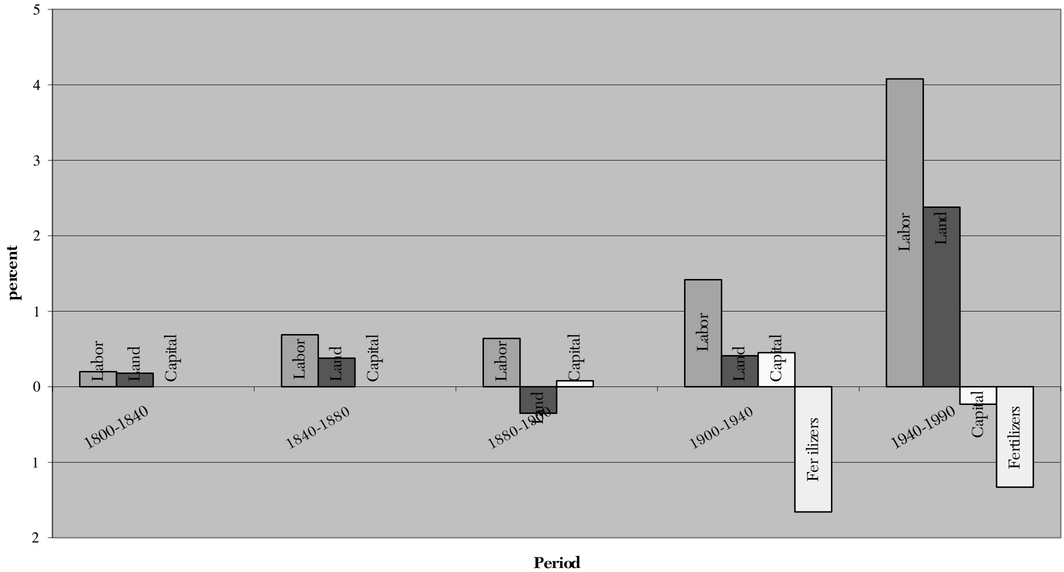


*Figure* 3: U.S. Agriculture Average Productivity Growth Rates

Note: The values are based on figure 1.

which picked up steam with time as will be shown below.

In contrast to the rise in the productivity of labor and land in the United States, the average productivity of fertilizer declined in the twentieth century. The rate of change of this measure was –1.66 percent and –1.33 percent for the two subperiods respectively.[18] This decline underscores the fact that fertilizer consumption grew faster than output. To interpret this result we should note that with constant technology, the decline in the average productivity of fertilizer in response to an increase in the intensity of its application is consistent with a concave production function. The decline in the output–fertilizer ratio can be triggered by a decline in the real fertilizer price. Indeed, the price of fertilizer relative to that of the aggregate input declined at the rate of 1.9 percent in 1912–40 and 5.1 percent in 1940–68.[19] Nevertheless, the concavity of the function is not sufficient to account for the fast growth in the fertilizer–output ratio over a very long time period. This can only be accounted for by a fertilizer-intensive change of the implemented technology, as explained below.

The growth rate of capital productivity was practically nil in the nineteenth century; it increased to 0.45 percent in 1900–1940 and then declined to –0.23 percent in 1940–90. As in the case of fertilizer, the negative value is attributed to capital deepening, triggered by capital-intensive technical change and possibly declining real prices of capital.

The view of agriculture as being an economic sector with stagnant productivity is completely divorced from the evidence. It is striking that in 80 percent of the countries

[18] U.S. use of fertilizer, in millions of tons, was approximately 3.5 in 1900, 10 in 1940, and around 50 in 1990 (Gardner 2002, figure 2.6a). A similar growth pattern took place in the use of pesticides. The increased use of fertilizers was pervasive. For a comparison, the average growth rate for a sample of thirty-seven countries for the period 1970–90 was 3.04 percent (Mundlak, Larson, and Butzer 1999, table 2).

[19] Hans P. Binswanger (1978, table 7-1).

in a sample of eighty-eight countries for 1960–92, labor productivity in agriculture grew faster than in the rest of the economy. The median of the growth rates of average labor productivity in agriculture exceeded that in nonagriculture by 1.58 and 1.1 percent for the uniform and weighted distributions respectively. This performance is not restricted to the high-income countries.[20]

### 3.2 *Total Factor Productivity*

To introduce notations, consider the production function:

$$(1) \quad Y = F(V_1,\ldots,V_J),$$

where $V_j = T_j X_j$, $X_j$ is input $j$ measured in physical terms, $V_j$ measures the input in terms of quality or efficiency units, and $T_j$ is the augmenting function which represents technical change. F(.) is a constant returns to scale, and twice differentiable function in $V_j$. Then

$$(2) \quad \frac{d\ln(Y/X_1)}{dt} = \sum_{j=2} \beta_j \frac{d\ln(X_j/X_1)}{dt} + \frac{d\ln \mathrm{T}}{dt},$$

where $\beta_j$ is the production elasticity of $V_j$, and $d\ln\mathrm{T}/dt = \Sigma_j \beta_j d\ln \mathrm{T}_j/dt$.

Assume $X_1$ to be land, then the rate of change of land productivity is the sum of two effects: factor intensity and technical change. The technical change component is a weighted average of the rates of change of the factor-augmenting functions, and it does not identify their individual contribution. Specifically, a rise in the average land productivity is not a sufficient statistic for concluding that the technical change is land augmenting, and narratives based on such an assumption are misleading. It is well known, but often neglected, that the explanation of changes in productivity requires an explanation of the changes in factors intensity in addition to the changes in technology. As I explain below, the two components are not independent.[21] The identification of the augmenting functions requires a different approach, to which I return below.

When the inputs do not grow at the same rate, as in figure 1, the calculation of the change in the total factor (TF) is sensitive to the weights assigned to the various inputs in the aggregation. There are two basic practices in the choice of weights: constant weights and varying weights. In practice, weights derived from empirical production functions are mostly constant for the sample, whereas varying weights are mostly based on factor shares. Ideally, the factor shares are thought of as proxies for the production elasticities. There are various estimates of the TFP growth in the United States.[22] They differ in period coverage, definition of inputs, quality adjustments, and their choice of weights. The studies cover mostly the postwar years. The growth rates of the TFP typically vary in the range of 1.5 to 2.0 percent. Ball, Bureau, Nehring, and Somwaru (1997) extend the period of analysis and pay more attention to quality adjustments.[23] The average growth rates for the extended period of 1948–94 are 1.88, –0.07, and 1.94 percent for output (including intermediate products), TF, and TFP respectively. They then "[c]onclude that the productivity growth was the principal factor responsible for economic growth in

[20] Mundlak, Larson, and Crego (1998, figure 8.11). See also Will Martin and Devashish Mitra (1999).

[21] As a matter of definition, this formulation does not support the assertion that "In agriculture it appears consistent with technical conditions of production to consider growth in land area per worker and output per hectare as somewhat independent, at least over a certain range" (Yujiro Hayami and Vernon W. Ruttan 1985, p. 171).

[22] For instance, S. M. Capalbo and T. T. Vo (1988), Dale W. Jorgenson and Frank M. Gollop (1992), V. Eldon Ball, Jean-Christophe Bureau, Richard Nehring, and Agapi Somwaru (1997), Gardner (2002). In a search for improvement of the measures, Ball (1985) uses Tornquist-Theil indexes of outputs and inputs and reports a growth rate of 1.7 percent for the period 1948–79, which is very similar to the rate reported by U.S.D.A. using more pedestrian procedures.

[23] The adjustment of the data made a difference; the growth rate for output calculated for the period 1947–79 from this new series is 1.47 percent, as compared to 1.7 percent in Ball (1985).

agriculture" (Ball, Bureau, Nehring, and Somwaru 1997, p. 1062).

This conclusion applies to the postwar period, which differs dramatically from the earlier periods. There are no comparable studies for the earlier periods, so in what follows I try to fill the gap and cover the nineteenth century. To place the exercise in perspective, I first choose weights that reproduce the TFP growth rate of 1.94 percent for the period 1940–90, and then apply the weights to the earlier periods, making allowances for the lack of data for some input categories used in Ball, Bureau, Nehring, and Somwaru (1997). My choice of weights is motivated by the following considerations. Starting with land, crop-sharing arrangements provide the landlord with one half of the crop, so a value of 0.5 for the share of land is a good point of departure. This number should be adjusted downward for two reasons. First, under crop-sharing the landlord has some responsibilities which use capital inputs. Second, crop-sharing arrangements do not cover livestock, which constitutes an important component of output. I thus settle on 0.3. Fertilizer in my case represents other chemicals, primarily insecticides, and perhaps other purchased inputs. A value of 0.1 seems to be reasonable for the share of output used for chemicals.[24] Some empirical studies show larger values for the elasticity of fertilizer, but this should be attributed to statistical bias. My weight for labor is 0.35, which is lower compared to other studies. The choice is based on the supposition that labor force data exaggerate the labor input in agriculture. This appears to be a common problem, particularly in developing economies. Finally, the weight for capital is 0.25.

[24] The chosen weight for fertilizer is consistent with the evidence on the share of expenditures on manufacturing inputs in total production (Gardner 2002, Fig 3.5). The group is an aggregate of "[e]xpenditures on tools, fuels, machinery, fertilizer, pesticides, and other purchased inputs" (Gardner 2002, p. 62). The growth of this share was faster in the first half of the twentieth century, from 5 to 12 percent. Thereafter, the share fluctuated between 12 to 16 percent.

The outcome of this calculation is summarized in figure 4. The result for the TFP growth rate is 1.95 percent for 1940–90, and 0.57 percent for 1900–1940. The first value exhausts the growth in output, whereas the second accounts for 57 percent of output growth in the period. The next step is to adjust the weights for the nineteenth century, in which the use of fertilizers was not important enough to be included. The choice is 0.4 for land and labor and 0.2 for capital. The outcome is a TFP growth rate in the range of 0.13–0.44 percent in the three subperiods of that century. This accounts for 5 to 17 percent of the output growth.

The result points clearly to the changing importance of TFP in output growth. It was low in the nineteenth century, and quite similar to that reported by Gallman (2000) for the economy as a whole. This agreement is quite natural because of the prominent role of agriculture at the time. The share of TFP increased gradually in the twentieth century, culminating in the strong growth of the postwar period. The result no doubt reflects the assigned weights, and we return to the subject below.

## 4. *Factor Augmentation*

### 4.1 *Direct Approach*

A differential growth of the augmenting functions, or factor-biased technical change, has a differential effect on factor demands and, not independently, on the factor shares, and thereby on the cost structure. The empirical analysis deals in general with the measurement of the bias, and not with its causes. The latter has been widely discussed in the context of agricultural development, largely in relation to the proposition of induced innovation. The proposition relates the bias in technical change to factor prices, or resource endowment. Hayami and Ruttan (1971, pp. 123–24) propose that "In the United States the long-term decline in the prices of land and machinery relative to wages . . . could be expected to encourage

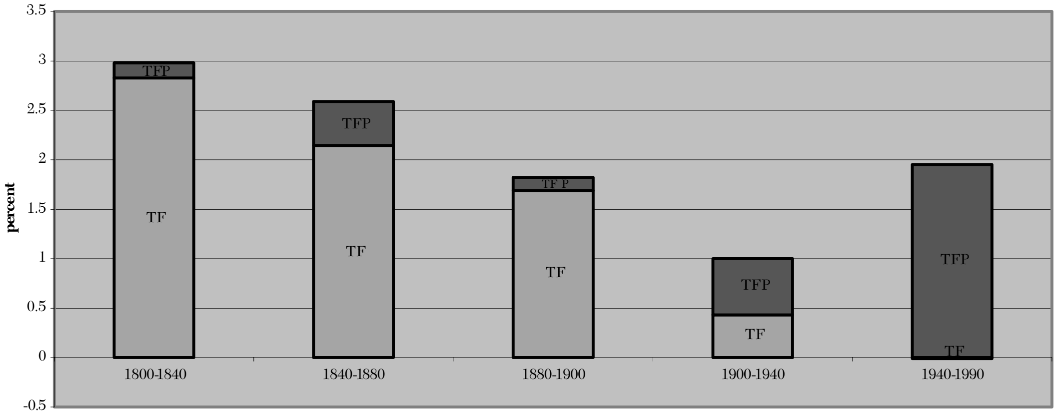


*Figure* 4: Output Growth Decomposition

Source: author's calculations, based on growth rates in figure 1, and the following weights for the nineteenth (twentieth) century: Land 0.4 (0.3), labor 0.4 (0.3), capital 0.2 (0.25), fertilizer 0 (0.1)

the substitution of land and power for labor . . . In Japan the supply of land was inelastic and the price of land rose relative to wages. It was not therefore, plausible to substitute land and power for labor. Instead the new opportunities arising from continuous declines in the price of fertilizer relative to the price of land were exploited through advances in biological technology."

The determination of causality in the changes of factor ratios, factor prices, and technical change is subject to identification problems, as will be clarified in the subsequent discussion. For now, we are sketching the big picture, which is expected to survive more refined scrutiny. The changes in the land–labor ratio in the United States are presented in table 1. The rising land–labor ratio is commonly attributed to mechanization, which represents labor-augmenting technical change. Labor augmentation, however, does not rule out augmentation of other inputs, and specifically land-augmenting changes. In a series of papers, Olmstead and Paul W. Rhode (1993, 2000, 2002) document relentless efforts at land augmenting activities in the nineteenth century, such as the development of new varieties, pest control, etc. If we accept the existence of such activities, the question is what we can say about the relative strength of the changes in the factor-augmenting functions.

To proceed, I examine the relationship between the marginal rate of substitution and the factor ratio. As the marginal rate of substitution is not observed, I utilize data on the price ratio of land to wages. During the mid-1800s land prices appreciated in response to market returns, and this was reflected in the price ratio of land to labor.[25] I use the information in Christensen (1981, table 1), which shows that the price of an acre of land increased from 1.1 labor weeks in 1790 to 2.9 labor weeks in 1850. The implied average growth rate of the land–labor price ratio for 1790–1850 is 1.3 percent. The price ratio stood at 33.8 in 1850, 64.7 in 1880, and 63.8 in 1900 (Olmstead and Rhode 1993, table 1). This translates to an

[25] "Despite vocal protests to the contrary, American farmers were not doing badly. They averaged return of 6 to 10 percent on current production, a usually realized capital gain of 3 to 7 percent" (Atack, Bateman, and Parker 2000, p. 277). Also, "Data are scarce before the midcentury mark, but standard historical accounts suggest that between 1790 and 1850 the number of days of farm labor required to purchase an acre of agricultural land increased two- to threefold" (Christensen 1981; Peter H. Lindert 1988; Olmstead and Rhode 1993, pp. 104–05).

TABLE 1
CRITICAL VALUE FOR THE ELASTICITY OF SUBSTITUTION OF LAND AND LABOR

| | 1800–40 | 1840–80 | 1880–90 | 1910–40 | 1940–90 |
|---|---|---|---|---|---|
| | Growth rates | | | | |
| Real ag wages | na | na | na | –0.32 | 2.22 |
| Real land price | na | na | na | –2.07 | 1.65 |
| wage/land price | –1.3 | –2.19 | 0 | 1.75 | 0.57 |
| Farm land | 2.8 | 2.17 | 2.17 | 0.61 | –0.44 |
| Ag labor | 2.78 | 1.9 | 1.18 | –0.77 | –2.14 |
| land/labor | .02 | .27 | 0.99 | 1.38 | 1.7 |
| | Elasticity | | | | |
| Critical $\sigma$ | 1 | 1 | 1 | 0.79 | 1 |

na: not available
Source: Nineteenth century: Farm land and labor taken from figure 1. Wage–land price ratio comes from Christensen (1981, table 1), and Olmstead and Rhode (1993, table 1). See text for explanation.
Twentieth century: Agricultural wages, Gardner (2002, figure 4.4a). The wages are deflated by the GDP deflator.
Real land prices, Mundlak, Larson, and Crego (1997). The prices are deflated by the CPI.
Farm land, Gardner (2002)
Agricultural labor, 1900–1940 Tostlebe (1957, table 4), 1940 on, Gardner (2000, figures 8.1 and 8.2).
Critical $\sigma$—positive values of $\sigma$ below the critical value are consistent with labor-augmenting technical change.

average growth rate of 2.19 percent between 1850 and 1880, and to practically no growth between 1880 and 1900.

In what follows, I deal with a world of two factors, labor and land, most pertinent to our discussion. As in reality there are more inputs, my analysis is applicable to the case where the production function is separable in the sense that the marginal rate of substitution of labor and land is unaffected by the level of the other inputs. This restriction is a reasonable first order approximation to more general cases, and in fact it is commonly embedded in empirical analyses. I turn to the production function in (1), and label the inputs (in physical units) as $K$ for land and $L$ for labor. The average (physical) labor productivity is $y = \mathrm{T}_L \mathrm{f}(\tau k)$, where $\tau = \mathrm{T}_K/\mathrm{T}_L$ is the measure of the technology bias. The function f(.) is defined in terms of the efficiency units; it is concave and maintains: $\mathrm{f}(0) = 0$, $\mathrm{f}'(0) = \infty$, $\mathrm{f}(\infty) = \infty$, $\mathrm{f}'(\infty) = 0$. When the wage–rent ratio, $\omega(\omega^e)$, is equal to the ratio of the marginal productivity of labor to land in physical (efficiency) units, we can write[26]

$$(3) \quad \tau\omega(k) = \omega^e(\tau k).$$

Label the elasticity of the function $\omega^e(\tau k)$ as $1/\sigma$, refer to $\sigma$ as the elasticity of substitution, and note the restriction, $\sigma > 0$. Differentiate (3), and rearrange terms:

$$(4) \quad (1-\sigma) d\ln\tau = \sigma\, d\ln\omega - d\ln k.$$

To apply this result empirically, I approximate the time derivatives with average growth rates, using the notation $d\ln x/dt = gx$. I assume that the changes in the factor price ratios reflect with sufficient precision

[26] An expository discussion of (3) is given in Mundlak (2000, chapter 5). An empirical testing of the bias in the technical change is discussed in Binswanger (1978).

the changes in the marginal rate of substitution, and that the average growth rate of the rent on land is equal to that of the price of land. I apply the assumptions to averages over long periods, and as such they are not as strict as if they were applied to annual variations. I can then use the rate of change of the labor–land price ratio as the rate of change of $\omega$.

I note that for positive growth of the land–labor ratio and negative growth of the wage–rent ratio, the right hand side of equation (4) is negative. To isolate $g\tau$ we need the value of $\sigma$, but we have only one equation to solve for the two unknowns, $\sigma$ and $g\tau$.[27] We can, however, tell the direction of the technical change bias for reasonable values of $\sigma$. Specifically, when the right hand side of (4) is negative, values of $0<\sigma<1$, are sufficient for $g\tau<0$ meaning that in this case the technical change bias is labor-augmenting. This conclusion does not require that $\sigma$ be constant throughout the period; the result applies as long as $\sigma<1$. The combination of $0<\sigma<1$ and labor-augmenting technical change yields a decline in the ratio of the factor share of labor to that of land.[28] By definition, this means that the technical change was labor-saving. Table 1 summarizes the pertinent information, and by its inspection it is clear that, given $\sigma<1$, the technical change in the nineteenth century was labor-saving.

As for the twentieth century, our data on land prices begin in 1910, and this determines the starting year. Here the sign on the right hand side of equation (4) is ambiguous in that both $gk$ and $g\omega$ are positive. There are two possibilities, the first being where $gk>g\omega>0$. By inspection of equation (4), and given $\sigma<1$, we conclude that $0>g\tau$. The second case is where $g\omega>gk>0$. In this case we derive an upper limit for $\sigma$ for which $g\tau$ is negative, and refer to it as the critical value. The results are reported in the last line of table 1. Thus, the values of $\sigma$ which are consistent with labor-augmenting bias are limited from above by 0.79 for the period 1910–40, and by 1 for 1940–90.[29] The period 1910–40 is interesting because it was the prelude to the jump in land-augmenting technical change. It has the lowest critical value, but to have a land augmentation bias it would still require $\sigma$ to exceed 0.79, and this is unlikely. Also note that in the subsequent periods when the big jump in yields took place, the bias was still labor-augmenting.

We can now go one step further and obtain orders of magnitude for the growth rates of the augmenting functions. Equations (2) and (4) and the definition $g\tau=gT_K-gT_L$ allow a solution for these rates for assumed values of $\sigma$. I do it for the nineteenth century, concentrating on the role of land and labor and ignoring the role of capital. In this exercise, I assume equal weights for labor and land, $\beta=0.5$. This assumption gives initial values for the TFP which are slightly different from those in figure 4.[30] The discrepancy does not change the qualitative nature of the results. I also calculate the rates for three leading crops, using the data in Rasmussen (1962, table 1). The results are presented in table 2 for two possible values of $\sigma$, 0.2 and 0.5. In most cases, the growth rate of the labor-augmenting component is sizable, whereas that of the land-augmenting component is either negative, or positive but weak. The

[27] The identification problem is discussed in Peter Diamond, Daniel L. McFadden, and Miguel Rodriguez (1978).

[28] Alternatively, we can express (4) in terms of factor shares. The ratio of the factor shares of labor to that of land is $\theta\equiv\omega/k$, hence $d\ln\theta\equiv d\ln\omega-d\ln k$. Substitute in (4), and rearrange to obtain: $(1-\sigma)d\ln\tau=d\ln\theta-(1-\sigma)\,d\ln\omega$.

[29] The jump in the average land productivity beginning around 1940 has made it of interest to examine if this has affected the results, and for this reason we examine also the periods 1940–50 and 1950–90. The critical value was 0.94 and 1 for 1940–50 and 1950–90 respectively.

[30] Atack, Bateman, and Parker (2000, table 6.1) provide estimates of TFP for total agriculture, which are said to be based on Weiss. Weiss (1993, table 4) presents these very same figures as growth rates for output per worker of farm gross product ("broad definition"). I thus suspect that these values are actually growth rates of average labor productivity, rather then of TFP, and therefore do not use them here.

TABLE 2
U.S. AGRICULTURE: DECOMPOSITION OF TECHNICAL CHANGE (PERCENT)

| | 1800–1840 | 1840–80 | 1880–1900 | 1800–1840 | 1840–80 | 1880–1900 |
|---|---|---|---|---|---|---|
| | $\sigma=0.2$ | | | $\sigma=0.5$ | | |
| | Total agriculture | | | | | |
| TFP | 0.19 | 0.56 | 0.15 | 0.19 | 0.56 | 0.56 |
| Labor TL | 0.37 | 1 | 0.76 | 0.86 | 1.92 | 1.13 |
| Land TK | 0.015 | 0.11 | –0.47 | 0.48 | –0.81 | –0.85 |
| | Wheat | | | | | |
| TFP | 0.58 | 0.4 | 1.08 | 0.58 | 0.4 | 1.08 |
| Labor TL | 1.48 | 1.54 | 1.99 | 2.4 | 2.9 | 2.51 |
| Land TK | –0.31 | –0.75 | 0.19 | –1.2 | –2.1 | –0.34 |
| | Corn | | | | | |
| TFP | 0.27 | 0.6 | 0.47 | 0.27 | 0.6 | 0.47 |
| Labor TL | 0.78 | 1.5 | 1.07 | 1.47 | 2.7 | 1.42 |
| Land TK | –0.23 | –0.3 | –0.12 | –0.92 | –1.5 | –0–1.5 |
| | Cotton | | | | | |
| TFP | 0.39 | 0.79 | 0.2 | 0.39 | 0.79 | 0.2 |
| Labor TL | 1.04 | 1.26 | 0.39 | 1.82 | 2.2 | 0.5 |
| Land TK | –0.26 | 0.32 | 0.01 | –1.04 | –0.61 | –0.01 |

Notes: $\sigma$ is the elasticity of substitution; TL and TK are the labor and land augmenting terms. The source for the TFP for total agriculture is table 1. The values for the individual crops are calculated from data presented in Rasmussen (table 1). The source for Rasmussen is M. R. Cooper, G. T. Barton, and A. P. Brodell, Progress of Farm, Mechanization, U. S. Agricultural Department, Misc. Pub., No. 630. Washington D. C.: Govt. Printing Office, 1947. Land: 1800–1840–1900 Gallman (2000). The original units were hours of labor, acres of land, bushels of wheat and corn, and pounds of cotton. The years are defined in the source as "about 1800," "about 1840," etc. Following the discussion, we use for the growth rates of the rent–wage ratio of 1.3 for the first period, 2.19 percent for the second period, and 0 for the third period. The TFP are taken based on the values in table 2, equations (2) and (4), and on the assumption of equal weights for land and labor.

difference in the growth rates of the two augmenting functions broadens for $\sigma=0.5$.

It is hard to believe that there was a deterioration of the land-augmenting function, particularly in light of the various efforts made to improve the biological practices. If this is the case, how can we explain the results? Olmstead and Rhode (2002) argue that the new lands brought under cultivation were of lower quality, or needed changes in varieties, or other practices to maintain the observed yield level.[31] In

[31] Also, "The westward drift dragged down the average quality of American farm land faster than the 0.29 percent annual quality of improvements on fixed sites" (Lindert 1988, p. 51). See also Willard W. Cochrane (1993, chapter 5).

accordance with this claim, the average yield should have declined, and if it did not, this is an outcome of the land-augmenting technical change. The question is whether the allowance for heterogeneous land quality is sufficient to elevate the growth rate of the land-augmenting function to that of the labor-augmenting function. To answer this, I take a different tack and explore the issue without resorting to the average yield, and the answer is negative.

### 4.2 *Land of Heterogeneous Quality*

In what follows I outline the model with heterogeneous land, and state the pertinent results.[32] I change the notations slightly, labeling the area of quality $q$ land as $A(q)$, where $q$ is assumed to be a continuous variable that takes on nonnegative values; the higher the value of $q$, the better the land. The cultivated land, $A = \int_z^\infty A(q)dq$, is all the land of quality $q \geq z$, where $z$ is the marginal quality, characterized by zero rent. To simplify the discussion, I assume that there are only two inputs, land and labor; $L(q)$ is the amount of labor allocated to quality $q$ land, and $x(q)$ is the ratio of labor to land adjusted for quality, $x(q) = L(q)/qA(q)$.[33]

The production function is linearly homogeneous in labor and land measured in quality units, $qA(q)$:

$$(5) \quad Y(q) = F[\mathrm{T}_A qA(q), \mathrm{T}_L L(q)] = \mathrm{T}_A qA(q) f[\alpha x(q)],$$

where $\alpha = \mathrm{T}_L/\mathrm{T}_A$ represents the bias in the technical change. The land-augmenting technical change $\mathrm{T}_A$, serves here as the neutral component, and hereon is denoted by T. The bias is labor (land)-augmenting when $\alpha$ is larger (smaller) than 1. The output per unit of quality $q$ land is $Y(q)/A(q) = \mathrm{T}qf(\alpha x)$, and total output is $Y = \mathrm{T}\int_z^\infty qf[\alpha x(q)]A(q)dq$. The quantities $A$, $L$, and $Y$ are functions of $z$ and $x(q)$; these in turn are determined by the state variables which vary with the specification of the model. Let $w$ be the wage rate of physical labor, $p$ the product price, and $c$ the unit cost of using land, independent of its quality. The rent on quality $q$ land is $R(q) = p\mathrm{T}qf[\alpha x(q)] - c - wqx(q)$, and note that it is increasing in $q$. The neutral component of technical change and the product price play a similar role in the equation, so we combine them conveniently, $H = p\mathrm{T}$. The optimization problem is to choose $x(q)$ and $z$ that maximize the total rent:

$$(6) \quad R = \int_z^\infty \langle Hqf[\alpha x(q)] - wqx(q) - c \rangle A(q)dq.$$

The details of the analysis appear in the appendix, and the impact of technical change and prices on the two margins is summarized in table 3.

An increase in $\alpha$ increases the rent on land of all qualities, and thereby marginal land is brought under cultivation. As labor becomes more productive, there is an expansion of the supply of efficiency labor, which presses down the wage rate and thus increases the quantity demanded. The extent of the employment response to the wage decline depends on the elasticity of labor demand. When the demand is inelastic, the increase in the quantity demanded of efficiency labor is insufficient to match the increase in its supply, and the labor–land ratio declines. Thus when agriculture is a price taker, labor-augmenting technical change increases the rent on land of all qualities, thereby reducing the marginal quality land and increasing the cultivated area. The labor–land ratio declines when the elasticity of labor demand is smaller than one.

This outcome is consistent with the evidence for U.S. agriculture in the nineteenth century, where the cultivated land, the land–labor ratio, the rent, and the rent–wage ratio all increased. Moreover, these changes are inconsistent with the other forms of technical change allowed by the specified production function. For instance, land-augmenting technical change

[32] The discussion is based on Mundlak (2000, pp. 157–61).

[33] Thus, compared to the foregoing discussion, $A$ replaces $K$, $x = 1/k$, and $\alpha = 1/\tau$.

TABLE 3
MARGINS' RESPONSE TO THE ECONOMIC ENVIRONMENT

| | Intensive (x) | Extensive (z) |
|---|---|---|
| Labor augmenting bias ($\alpha$) | negative for $\varepsilon > -1$ | negative |
| Neutral TC (T) | positive | negative |
| Product price (p) | positive | negative |
| wage rate (w) | negative | positive |
| land charge (c) | no effect | positive |

acts in the opposite direction and thus increases the labor–land ratio, which is inconsistent with the data. Neutral technical change and the product price have a positive effect on the intensive margin and are therefore ruled out by the data. Aside from this, real product prices trended down as a result of the technical change, and thus the impact of the technical change was offset in part by the price decline.

This analysis yields the same qualitative result of labor-augmenting bias obtained above under the assumption of homogeneous land. This, however, does not rule out land-augmenting or neutral changes; all it says is that the labor-augmenting change was dominant.

In this discussion, I have concentrated on the impact of technical change and neglected the impact of the cost involved in the operation of land, $c$, and the nature of the labor supply. The cost can have various interpretations, depending on the context. In the case of expansion to new territories, it would represent the cost of reaching the site and of bringing the land under cultivation. As reviewed above, there was a considerable investment in infrastructure of the land-augmenting nature, and also in investment in land clearing and improvements. To take this into account, the model would have to be extended to multiperiod optimization. The cost term could also include tax or subsidy, as well as the payments for land set aside under government programs of supply control. The cost could also be made a function of $q$. As to labor supply, we assumed it to be perfectly elastic at the ongoing wages, but this could be modified to upward-sloping market supply. All these are interesting possibilities, but they are unlikely to modify my qualitative conclusion and therefore are not pursued here.

## 5. *Technology*

### 5.1 *Innovations*[34]

The United States has an elaborate system of agricultural research, which has advanced agricultural technology over the years.[35] In the foregoing discussion, we have noticed that there may be lags in the implementation of new technology. Also, the international comparison has taught us that the

[34] In what follows we do not differentiate between innovations, inventions, and other forms of knowledge creation. This lack of distinction between the various nuances simplifies the discussion, which is motivated by our interest in the determinants of the actual implementation of the new knowledge in production, rather than in its creation. In this spirit, we use the term available technology to describe all the knowledge that can be applied, and the term implemented technology to describe that part of the knowledge that is actually used in production.

[35] See for instance Wallace E. Huffman and Robert E. Evenson (1993).

advanced research in the United States has not translated into outstanding growth rates. These observations raise the question regarding what can be learned empirically about the innovations from the observed changes in factor productivity. The answer is not much, and definitely less than some studies suggest. As has already been indicated, the experience of U.S. agriculture is an important component of the paradigm of the development of American and Japanese agriculture expounded by Hayami and Ruttan, in which the hypothesis of induced innovation plays a central role. The hypothesis views innovations "[a]s a process of easing the constraints on production imposed by inelastic supplies of land and labor" (Hayami and Ruttan 1985, p. 4). This is translated into price signals: "The Hicks theory of induced innovation implies that a rise in the price of one factor relative to that of other factors induces a sequence of technical changes that reduces the use of that factor relative to the use of other factor inputs" (Hayami and Ruttan, p. 85). This is not meant to be just another theory; it aspires to replace "The process by which technical change is generated [which] has traditionally been treated as exogenous to the economic system—as a product of autonomous advances in scientific and technical knowledge" (Hayami and Ruttan, p. 84). It should be pointed out right at the outset that the scope of this theory is narrow in that it is limited to the bias in technical change, and excludes the neutral component.

Limitations of the paradigm of induced innovation as applied to U.S. agriculture are discussed by Olmstead and Rhode (1993). In addition to questioning some stylized facts, they dismiss the theory on two basic grounds. First, the hypothesis that the abundance of land relative to labor in the United States would result in an increase of the wage–land–price ratio is inconsistent with the evidence. As has already been indicated above, during the period of sizable land expansion in the nineteenth century the price of land increased substantially relative to wages. Such a rise, however, is to be expected and is consistent with the foregoing analysis of the impact of labor-augmenting technical change. Thus, land price responded to the technical change and not vice versa, so that the expected causality is consistent with the evidence and not with the hypothesis. Second, Olmstead and Rhode document various research efforts in land-augmenting activities in the nineteenth century.[36]

My conclusion of a labor-augmenting bias in the United States is in line with the Hayami–Ruttan paradigm. On the other hand, the decline in the wage–land–price ratio during the period of land expansion is not. This, however, is only part of the story, and for the paradigm to apply, it should also be consistent with the evidence for Japan. To complete the story, therefore, I make a detour and repeat the calculations to include Japan. The analysis is presented in the appendix. The conclusion is that the bias in the technical change was labor-augmenting in Japan, just as in the United States. Thus, whatever merits the Hayami–Ruttan paradigm might have, their data do not support it.

Besides the message concerning the direction of the technical change, there is a broader implication concerning the approach to the empirical verification of the hypothesis. The fundamental weakness is that the judgment on the intended innovations is based on the observed changes in factor productivity and not on the innovation

[36] For instance, "[t]he nineteenth and early twentieth century witnessed a stream of "biological" innovations that rivaled the importance of mechanical changes on agricultural productivity growth. These new biological technologies addressed two distinct classes of problems. First, there was a relentless campaign to discover and develop new wheat varieties and cultural methods to allow the wheat frontier to expand into the Northern Prairies, the Great Plains, and the Pacific Coast states" (Olmstead and Rhode 2002, p. 929). The second effort aimed at pest control. This is a direct report on research effort, not blurred by the productivity of the research and by the degree of the implementation of the available technology.

activities. To hone the discussion, we should distinguish between two activities: the first, labeled generically as research, produces changes in the available technology, while the second is the implementation of the technology in production. The connection between the research effort and the realization in terms of measured productivity gains is not immediate. First, there is the subject of identifying and measuring the research effort, which should deal directly with the resources devoted to research. This direct approach can also help in judging what induced the research, and what its objectives and the time profile of the expected results were. Specifically, it may also shed light on the extent to which the research builds on "autonomous advances in scientific and technical knowledge." If we take the term "induced innovation" nominally, this is the only stage which is pertinent to the hypothesis and the rhetoric of the induced innovation. Second, there is the subject of research productivity, which relates the effort to outcome. Good intentions, in research as in other matters, do not always lead to the desired results. In research, the gap is related to the fundamental fact that there is no production function for knowledge, and the popular concept of an innovation opportunity frontier, purely speaking, is nonexistent.[37] Consequently, the judgment has to be passed on less solid ground. Not independently, there is the question of the timing of the realization, as sometimes the results are obtained with long lags. For instance, Olmstead and Rhode (2002) argue that the green revolution has its roots in the research efforts made in the nineteenth century. Work on hybrid corn started at the beginning of the twentieth century, but it was not put into effect until the 1930s (Zvi Griliches 1957). When in 1916–19 an economic way was found to produce seeds of high-yielding varieties, "[t]he director of the USDA breeding program and several directors of Corn Belt State Agricultural experiment stations were convinced that hybrid corn had no practical value" (Huffman and Evenson 1993, p. 157). Whatever the motivation may have been, this illustrates research activity with the objective of land augmentation, but the outcome was a late bloomer.

Finally, there is the question of implementation. Not everything that is known is immediately implemented. After all, the inventors and users are two different groups; each is motivated by different criteria, sets of incentives, and constraints. This is illustrated by the claim made by Rasmussen with respect to the implementation of new technology in response to the changes in the economic environment following the Civil War and World War II. The technology was already there, and it was a change in the economic environment that triggered the implementation. Similarly, Gavin Wright (1986) and Willis Peterson and Yoav Kislev (1986) relate the adoption of cotton pickers to the economic environment. In fact, Hayami and Ruttan (1985) state that in Japan, "The tractor was not adopted extensively until World War II" (p. 171). This is a statement about implementation and not about innovation.

To sum up the argument, it was not for lack of trying that land-augmenting technical change was slow. Simply, the outcome was less dramatic than that of labor augmentation, because the mechanical innovations were so much more effective. This edge, most likely, reflects possibilities generated by the overall technological developments in the economy, largely exogenous to agriculture. The most dramatic changes in technology originated in the manufacturing sector, and it would be hard to assume that profit on the production of the new machines was overlooked by their developers and producers. To this we might add that narrowing down the research objective to labor-saving innovations would fail to explain the growing success of agricultural research in the United States and the world in spite of the continuous decline in real agricultural prices.

[37] Mundlak (2000, p. 362).

This effort, both public and private, can only be justified by expectations that the research will pay off, privately and socially, regardless of the direction of the augmentation, and that the innovations will be implemented.

As for the methodological aspect, we should recognize that the empirical analysis triggered by the hypothesis of induced innovation in agriculture has mostly dealt with the implementation of technologies rather than with innovations.

### 5.2 *Heterogeneous Technology*

It is convenient to assume that technology is homogeneous, but reality is more complex, and we have already alluded to the coexistence of techniques in production. The heterogeneity of technology affects the empirical analysis in various ways. For instance, the foregoing calculations of the TFP (table 2) were conducted with imposed production elasticities that were held constant for long periods. The outcome is sensitive to the chosen elasticities, and it is therefore reasonable to examine the empirical validity of the assumption. The elasticities are unobserved so we have to resort to factor shares, and these varied as can be seen in figure 5.[38] There are several ways to account for the variability in factor shares. First, it can be attributed to random shocks, but the variability is too large for this approach to be meaningful. Second, it can be attributed to a quadratic or higher order, production functions where the factor shares vary with the factor ratios, but the connection between variations in shares and the variations in the factor ratios are not always consistent. Similarly, the variability in the shares can be attributed to changes in prices, as is the case with functions derived from duality.[39] The alternative is to take seriously the fact that technology is not homogeneous.

The idea of heterogeneous technology has appeared in the literature in various forms. Kuznets (1957b, p. xi) made the following observation: "The point to be stressed—and it is simply illustrated in Dr. Tostlebe's discussion—is that physical capital assumes meaning only within a given technological and institutional framework, and it follows that in a progressive economy such as ours, this meaning changes all the time. Thus, while there is a continuous demand for capital replacement and addition, the magnitude needed is a function of an ever changing and ever increasing stock of knowledge." Later on Salter (1969, p. 13) stated, "At any one time there exists a body of knowledge relating known technical facts and the relationships between them. This knowledge is at a number of levels which differ in their proximity to production." To simplify the analysis, we group the various levels of knowledge under the title of the available technology. The distinction between the available technology and implemented technology blurs the economic analysis. "Essentially, the problem lies in the fact that there is a type of a twilight zone where economic and technical factors are so interwoven that any distinction between the two must be to some extent arbitrary" (Salter 1969, p. 15).[40]

To incorporate the idea of heterogeneous technology in the economic analysis, we view the choice of the implemented techniques subject to the economic environment as an economic decision.[41] The implemented technology is determined jointly with the

[38] The shares are derived from the U.S. accounts assembled by U.S.D.A., which are also the source for the TFP in Ball, Bureau, Nehring, and Somwaru (1997) that served as a basis for our calibration. The share of land is the complement of the sum to 1; it is not shown in the figure.

[39] The various approaches are evaluated in Mundlak (2001).

[40] The distinction between available technology and implemented technology appears in the more recent literature under different names; Paul M. Romer (1993) differentiates between "using ideas and producing ideas." Another model that is based on the implementation of available techniques is the Big Push model (Kevin M. Murphy, Andrei Shleifer, and Vishny 1989; Paul R. Krugman 1993). This model concentrates on the allocation of labor to the various available techniques, taking into account the noncompetitive structure of the economy.

[41] The discussion is based on Mundlak (1988, 2000, chapters 6, 13).

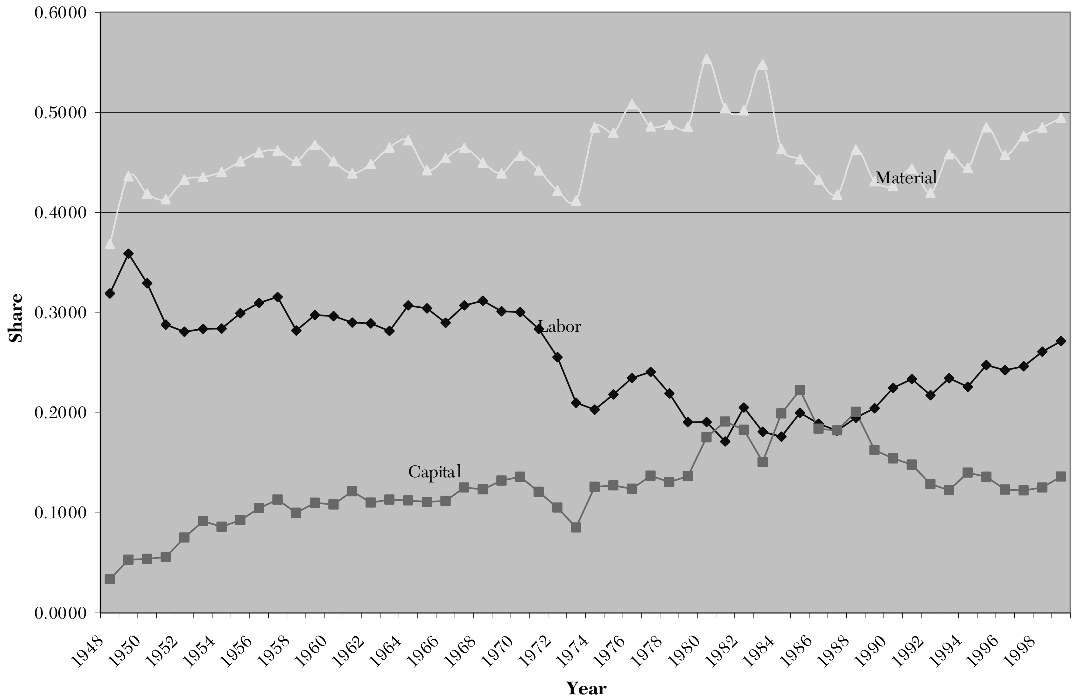


*Figure 5:* U.S. Agriculture Factor Shares

Source: Author's calculation based on the U.S. accounts assembled by U.S.D.A.

decisions on the composition and level of outputs and inputs. This is the *jointness* property, and it is fundamental to the discussion of many of the looming issues related to the productivity and the dynamics of agriculture, or any other sector. Thus, for instance, the demand for labor changed when tractors replaced animal draft power. As a corollary, I note that the implemented technology is endogenous, and I refer to this as the *endogeneity* property.

By definition, the empirical work on productivity deals only with the implemented technology, because this is where the data are generated, and what is not observed is not measured. The *jointness* property is the source for the correlation between inputs and technology shocks. Technology, as well as other, shocks affect the intensive and extensive margins, a subject discussed above. The change in the extensive margin induces an expansion of cultivated area. The change in the intensive margin calls for an increase in inputs associated with the new technology. For instance, "Our regression analysis indicated that farm scale and the tractor adoption were co-determined. Large scale induced greater adoption and greater adoption, larger scale" (Olmstead and Rhode 2001, p. 693).

We refer to the determinants of the choice as state variables. They include the available technology, constraints, incentives, and institutional factors. The state variables change over time and vary across countries, and the coefficients of the empirical production function, the levels of inputs and of outputs, change accordingly. For this reason, strictly speaking, a production function obtained by aggregating outputs of various techniques, or simply the aggregate production function, cannot be identified. The calculated empirical aggregate production function is an approximation to a hypothetical function that is locally invariant to changes in the state variables. The quality of this approximation increases with the errors in the first order conditions for optimization.[42]

The implemented technology can be summarized by a second-degree approximation which looks like a Cobb–Douglas function, but where the elasticities are functions of the state variables:

$$\ln y = \Gamma(s) + \beta[s, x(s)]\ln x(s) + u \tag{7}$$

where $y$ is the aggregate output, $x$ and $s$ are vectors of inputs and state variables respectively, $\Gamma(s)$ and the vector $\beta(s,x)$ are the intercept and the slope of the function respectively, and $u$ is a stochastic term. This expression illustrates the problem of identification, in that a change in $s$ may affect both the coefficients of the function and the inputs. The key to estimation is to have changes in $s$ which affect only the inputs and not the technology shocks, such as errors in optimization.[43] This is not a rare situation. For instance, "We find credible evidence in U.S. agricultural production of errors in optimization compared to errors of measurement, and thus reject the typical specification" (Rulon Pope and Richard E. Just 2003, p. 357).

The dependence of the coefficients on the state variables generates variability in the coefficients when the units of observations (firms, states, countries) operate under different sets of state variables. The variability is relevant to the analysis of panel data. Panel data are popular because they contain more observations than the strict cross-section, and this increases the efficiency of the estimators. This apparent blessing of a large sample is realized when the data are generated by the same process, in which case the estimates should be the same, up to the sampling error, independent of the way the data are pooled. But this is seldom the case, as it is obvious from the long standing discussions related to the fact that "within" and "pooled" regressions give different results. The various possibilities of pooling the panel data in regression analysis generate estimates which are weighed averages of three canonical regressions, based on variations between time, between units (say countries), and within units and time. In the case of homogeneous technology, all the coefficients of these regressions should be the same up to the sampling error. To test the hypothesis that the technology that generates the sample is homogeneous, it is necessary to test the equality of the coefficients obtained from the canonical regressions. Such a test was performed in estimating an agricultural production function from a sample of thirty-seven countries for the period 1970–90. The results of the three regressions are very different, and this is inconsistent with the assumption of homogeneous technology.[44] The lack of robustness is considered by researchers to be a negative result, but this should not be the case. We should view the lack of robustness as a wind at our backs in the empirical analysis, because it is instrumental in the search for understanding the production structure in all its complexity.

The function in (7) is an outcome of an aggregation over techniques, and as result it loses important properties of a micro production function. Specifically, the aggregate function is not restricted by the concavity of the individual functions. It is often reported that aggregate production functions display increasing returns to scale. Under heterogeneous technology, the empirical function can be viewed as a locus of observations generated by different micro functions rather than

[42] This framework should narrow down the scope of the assertion that theories of growth "[f]ocus more on the consequences of growth than on causes. They incorporate investment and technological change, but do not analyze the adoption of technology"(Gardner 2002, p. 255).

[43] This is a generalization of the information embedded in such deviations in the estimation of production functions (Mundlak 1996).

[44] Mundlak, Larson, and Butzer (1999).

the outcome of scale externalities. Similarly, empirical quadratic functions fail to display the concavity. This is equally true for primal functions and for cost or profit functions, because the dual functions should conform to the primal function and are therefore affected by the same state variables. The lack of concavity is inconsistent with the underlying specification of the function given homogeneous technology, but it is admissible under the specification where the coefficients are affected by the economic environment.

There is great variability among farms or firms in general in the scale of operation, which indicates that technology is not the only factor in the determination of the farm size. The scale of operation reflects the implemented technology, and as such it is also influenced by idiosyncratic factors such as managerial ability, financial constraints, discount rate, and expectations. These attributes determine the differential response of farms to the changing technological and market situation. This variability in attributes explains the concentration of large farms in acreage, and in output.[45] In addition, there is the impact of attrition in family farms where the family continuity in operation is not always secured. In this case, the incentive to expand for farmers who do not anticipate family continuity is rather weak.

It should be clear from this discussion that the decomposition of output growth to that of TF and TFP is endogenous in the system. The endogeneity of TFP is inconsistent with the claim that TFP is the main trigger of growth.[46] The growth accounting exercise is bound to yield different results under different environments. To illustrate this claim, I refer to information on U.S. agriculture provided by Ball, Bureau, Nehring, and Somwaru (1997). The years 1973–79 were generally good for agriculture, and in that period output grew at a rate of 2.5 percent and TFP at a rate of 1.3 percent. On the other hand, the 1980s were difficult for agriculture, but we find that in the period 1979–89 the respective growth rates for output and TFP were 0.86 percent and 2.56 percent. Thus, in the high-growth period TFP accounted for about 50 percent of the output growth, whereas in the low-growth period TFP growth was almost three times higher than the output growth. Clearly, TFP is sensitive to changes in the economic environment, and as such is not a trigger of growth.

Extending this argument, it can be shown that when changes in the available technology increase the demand for inputs, the supply of which is constrained, most of the technical change will be absorbed by a rise of the shadow price of the restricted inputs, and this will increase the share of the total factor and reduce the share of the TFP. This is illustrated by the experience of Asian countries.[47]

To sum up, it is the available technology that generates growth, but the pace of change is determined by the economic environment, and this is captured in the measurement of TFP, which like inputs and outputs is endogenous. Is it then useful to decompose output growth into its TF and TFP components? Yes, very much so, because the exercise paves the way for studying the role of the economic environment in affecting growth.

## 6. *Incentives and Response*

### 6.1 *Resource Flow*

The discussion of productivity brings us to the subject of resource flow. Changes in the state variables such as the available technology and incentives change the demand for the various inputs. The response to such changes depends on the supply of the inputs when more are needed, as in the case of capital, or

[45] Gardner (2002, table 3.4).

[46] Edward C. Prescott (1998).

[47] Mundlak, Larson, and Butzer (2004).

on alternative employment when less are needed, as in the case of labor. Both the demand and supply may depend on constraints, which affect the timing of the adjustment. Consequently, a gap may be generated between the instantaneous shadow price and market price of the inputs. On the assumption that inputs move from employments of low returns to employments of high returns, the gap will be narrowed with time. The pace of the adjustment depends on the magnitude of the gap. The gap is sometimes interpreted as an indication that the economy is in disequilibrium. This is the case with the assertion—made by Theodore W. Schultz (1947), and adopted by Griliches (1963) and Gardner (2002)—that U.S. agriculture has been in disequilibrium over a very long period.[48] This assertion focuses on static equilibrium, but as such it is not very revealing in our attempt to understand the behavior of the economy. The behavior of forward looking producers calls for considering the future consequences of their decisions, and taking into account the uncertainty involved and the setup or adjustment costs. We thus are dealing here with dynamic behavior and the relevant concept is that of dynamic equilibrium. Making this switch, we find ourselves in a search for the determinants of such equilibrium and of the pace of the resource movements. This is well illustrated by the changes in the agricultural labor force.

Labor: The occupational migration from agriculture is caused by the decline in the demand for labor in agriculture, and the rise in the demand for labor in nonagriculture. From the micro point of view, the potential migrant chooses between the anticipated streams of income in the various occupations. It is postulated that the larger the gap between the income in nonagriculture and agriculture, the more workers will migrate. This postulate provides the conceptual framework for empirical migration studies using country time-series data and cross-country data. The driving variable in such studies is the intersectoral income differential, where income is proxied by the average labor productivity.[49] Barkley (1990) studied the off-farm labor migration in the United States. The dependent variable is the migration rate, measured as the ratio of migration to the agricultural labor force. The elasticity of the migration rate with respect to the intersectoral income differential obtained from regressions covering the period 1940–85 is 4.5 for total agricultural labor and 3.34 for farm operators. This result is consistent with other country studies, as well as cross-country studies.[50]

The average annual U.S. off-farm migration rate in the period 1940–85 was 2.3 percent.[51] This rate is somewhat higher than the rates obtained for a large number of countries, which are closer to 2 percent.[52] This difference, however, is not sufficiently large to be the sole reason for the fast decline of agricultural labor in the United States relative to other countries where the pace was slower, or the change sometimes even in the opposite direction. The pace of the change in the size of the labor force is determined by two variables, the migration rate and the natural growth rate of the labor force. Formally, let $m$ be the migration rate, and $n$ the population (or labor force) growth rate, then the change of the agricultural labor force between $t-1$ and $t$ is given by:

[48] "The main focus of this paper is upon factor disequilibria that are causing widespread economic inefficiency in the American economy and affecting adversely especially farming in the United States" (Schultz 1947, fn 5, p. 646). The supporting evidence consists of a large disparity in average labor productivity within agriculture, and between agriculture and other sectors, and an inequality of value marginal productivity of labor and capital with the alternative returns.

[49] Income is considered to be a more appropriate measure of the expected stream of future consumption than wages.

[50] Larson and Mundlak (1997) and Mundlak (2000, chapter 9).

[51] This is the average of the series reported in Barkley (1990, table 1).

[52] Larson and Mundlak (1997).

$L_t - L_{t-1} = L_{t-1}(n - m)$. When $n$ is smaller than $m$, the agricultural labor force declines. This has been the U.S. experience. In other countries, primarily developing countries, the natural growth rate is still slightly higher than the migration rate and therefore the agricultural labor force rises, even though its share in the total labor force declines. Does the decline of the U.S. agricultural labor force from eleven million at the beginning to three million at the end of the twentieth century indicate that throughout the century agriculture was in disequilibrium? The answer is no. During the century, the state variables, and specifically the available technology, changed in agriculture and in nonagriculture, causing changes in the demand and supply of labor in agriculture. In each period, the individuals made their choice given the prospects available to them. People differ in many respects pertinent to such a decision (e.g., age, gender, education, health, family composition, ability, attitude toward risk), and consequently some move out and others stay.

Capital: The major swings in the agricultural capital stock are the outcome of opportunities and constraints. Initially, the growth of the agricultural capital stock was triggered by the investment opportunities associated with the opening of the frontiers. In the nineteenth century investment was largely related to land expansion, and the capital-land ratio was fairly constant (figure 1). As noted earlier, the opportunities associated with land expansion created financial constraints, which restrained mechanization. The situation was significantly different in the twentieth century, where the impact of the changes in the available technology and incentives caused considerable variations in the capital stock. The stock rose between 1900 and 1920, declined in 1920 to 1940, and rose again from 1943 to 1980. The stock peaked in 1980, and declined thereafter.[53] The average growth rate for the period 1940–90 is 2.17 percent.

The aggregate data do not reveal the dramatic change in the composition of the capital stock which took place in the post–World War I period, when the draft power was changing from animals to tractors. The number of tractors, practically zero in 1910, rose to about 4.8 million in 1965. This is an example of investment response to changes in the available technology. The change in the technology was not, however, the only factor. The variability in investment was influenced by the changes in the terms of trade of agriculture. Product demand expansion during World War I brought the real prices received by farmers to a level of 317 in 1917, about 58 percent above their level in 1900.[54] This rise generated a short-lived boom in land prices. Prices soon began to deteriorate, declining from 1917 to 1940 by a factor of 2, and then again by the same factor between 1973 and 2000.[55] This fall in prices was followed by a fall in farm income and liquidity, and a collapse in the price of farm land from the post–World War I period to the 1940s (figures 6a, 6b). This drop in product and land prices caused a financial crisis that was not conducive to investment.

The rise in investment demand, which followed from the fact that the new techniques were capital intensive, faced financial constraints. Alluding to the debts accumulated following the events of WWI, Clarke (1994, p. 248) writes that "[s]uch debts had precluded many individuals from making cash outlays for new equipment . . . Critics found that creditors set maturities for all types of loans too short to suit many farmers." There were geographical differences in the response to the financial situation; "But what was striking about this

[53] Gardner (2002, figures 8.3, and 8.4).

[54] "Between the outset of the war and 1920, the price of corn nearly doubled . . . The peak came in 1920. Within two years, corn prices had dropped more than 50 percent" (Sally H. Clarke 1994, pp. 106, 107).

[55] Gardner (2002, figure 5.1).

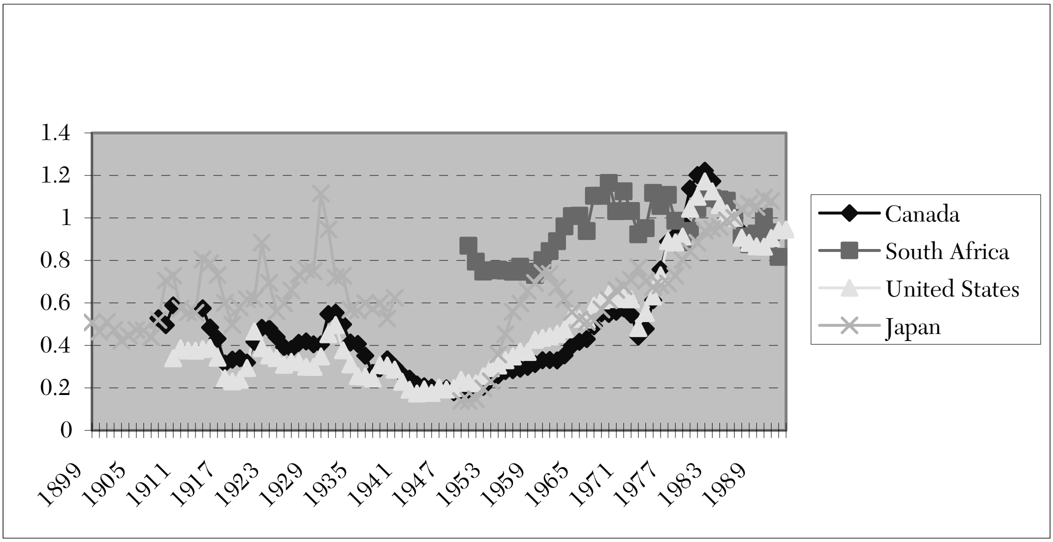


*Figure* 6a: Real Land Price Using Ag Deflators (1986=1)

Source: Mundlak, Larson, and Crego (1998).

geographic variance was that the lag in tractor's adoption varied systematically with farmers' financial problems: their margin of cash between receipts and outlays, the variability of corn yields, the relative burden of debts, the proportion of indebted farmers, and the relative deposit holdings of commercial banks" (Clarke 1994, p. 248). This is supported by the information embedded in Gardner (2002, figure 3.7), which indicates that during 1900–40 interest payments as a share of output fluctuated between 6 to 16 percent, as compared to a range of 2 to 6 percent in the period of fast growth of 1940 to 1973. This suggests an easier financial environment in the post–World War II years.

These developments demonstrate how the incentives and resource constraints affected the pace of the implementation of new productive techniques and, jointly with it, the inputs level and intensity.

### 6.2 *Implementation and Incentives*

The spread of technology is often viewed as a process of diffusion. This term is somewhat misleading in that it gives the impression of a passive process, whereas in reality entrepreneurs are active in their decisions on the implementation of the available technology. To underline the effect of the state variables on the TFP, I differentiate equation (7), holding inputs constant:

$$(8) \quad \partial \ln y/\partial s_i\,|_x = \partial\Gamma(s)/\partial s_i + \ln x(s)[\partial\beta(s,x)/\partial s_i].$$

The impact of a change in the state variable $s_i$ on productivity depends on the level of the other state variables. This also applies to the case where $s_i$ stands for the available technology, and thus the degree of implementation of a change in the available technology depends on the economic environment. Similarly, the productivity may change in response to changes in the environment even when the available technology is held constant. The generalization to a change in more than one state variable is obvious.

The empirical evaluation of (8) requires an estimation of (7). I do not deal here with

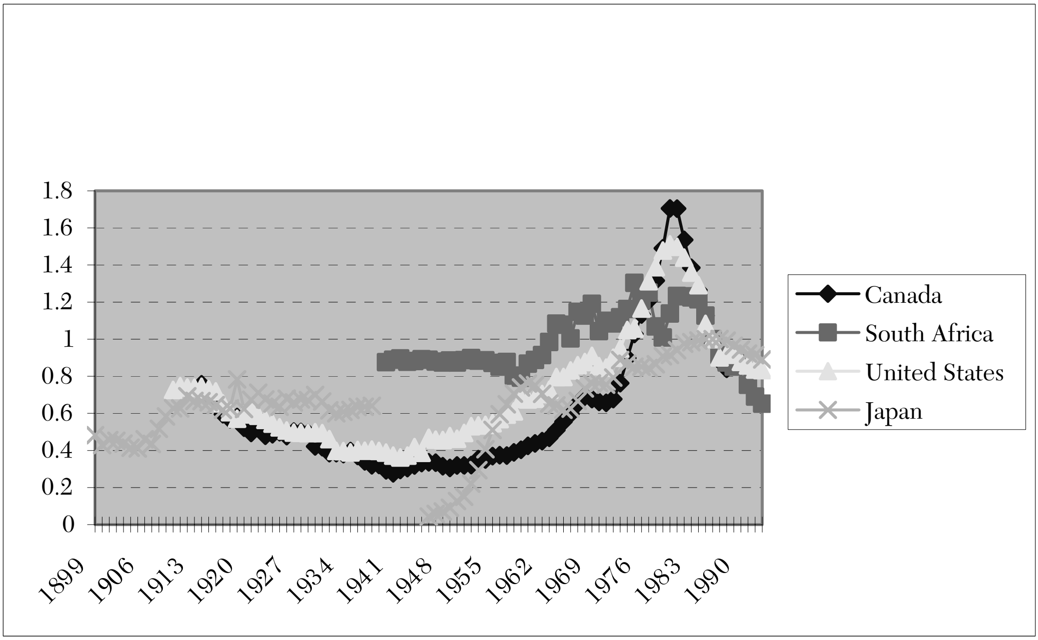


*Figure* 6b: Real Land Price Using CPI Deflator (1986=1)

Source: Mundlak, Larson, and Crego (1998).

the statistical issues of the estimation, and restrict our comments to some conceptual problems.[56] To simplify the discussion, assume that the slope is kept constant, and the state variables appear only in the intercept. This simplification covers most of the empirical analyses. The state variables often used in empirical analysis include carriers of technology, such as measures of human capital, research, and infrastructure. These variables are generally subject to trend. As productivity generally increases with time, trended variables turn out to be "good" explanatory variables. For the same reason, nontrended variables, such as incentives, seem to perform poorly.

In what follows, I review some evidence and fundamental difficulties encountered in capturing the impact of incentives in empirical analysis. To clarify what stands behind this difficulty, I have to ask why the introduction of more profitable techniques should depend on prices. If the new technique is more productive, it is likely to be profitable even under a price decline. This is, after all, the big picture with respect to technical change in agriculture in the last century, which took place under a declining price environment. In fact, the causality has been mostly from technical change to prices.

To a large extent, the scope for the positive role of prices in the implementation of new techniques is related to the *jointness* property. This is the case when the implementation of the new techniques requires new investment. In part this is due to embodied technical change.[57] The foregoing discussion has shown the importance of mechanization in the development of agriculture. To benefit from the productivity of

[56] The subject is discussed in Mundlak (1988, 2000, 2001).

[57] Robert M. Solow (1959).

the tractor, someone must acquire the tractor. The investment responds favorably to higher product price, lower factor price, and lower risk over its lifetime.[58]

The embodied technical change constitutes a sufficient, but not a necessary, condition for the *jointness* property. The green revolution in Asia, where new productive varieties of rice and wheat were introduced, provides an example of jointness generated by disembodied technical change. These varieties have reached their potential under irrigation and heavy doses of fertilizer. The progress of their implementation was therefore paced by the mobilization of resources for expanding the irrigated area and fertilizer production.[59] But resources move with incentives, and this is where prices and risk come in. Once the investment has been made, and the necessary infrastructure put in place, it is usable in future improvement, such as new varieties. At that stage the shift to new varieties will not depend on prices to the extent it did at the time of the initial investment. Consequently, in the case of disembodied technical change, we can observe a ratchet effect, where investment made for the implementation of a new technology accommodates future technical changes. When this feature is ignored in empirical analysis, the price effect is distorted.

There are various findings on the relevance of prices to the implementation of new technology. Griliches (1957) relates the trend in the adoption of hybrid corn to market forces. Cochrane and Ryan (1976, p. 373) attribute the surge in productivity to the price and income support programs, which provided both stability and a desirable income. Clarke (1994) makes a convincing case for the important role played by capital and liquidity constraints in the mechanization of U.S. agriculture in the post–World War I period.

Reservations with respect to the importance of prices come from more structural empirical analysis, where a production function is estimated and then used to generate the TFP series. In turn, the series is analyzed to find variables that explain the variability in TFP.[60] This procedure assumes the existence of an orthogonal decomposition of output change to its inputs and productivity component. This assumption is inconsistent with the *jointness* property of the implemented technology. The procedure thus conceals the contribution of the technology and of the other state variables to the variability of the inputs, thereby distorting the estimate of the TFP and the impact of the variables associated with it. The distortion here is similar in concept to that caused by ignoring fixed effects in the estimation of production functions from panel data. This recognition should provide a conceptual framework for the evaluation of the evidence, and should also help guide us to alternative approaches to the estimation. In essence, the state variables should be included in the empirical production functions in the same way as the inputs. Because many of the variables are trended, their inclusion would lead to multicolinearity. This problem, however, is an expression of the implementation process and not of the framework. The solution is to be found in the statistical techniques that overcome multicolinearity, but this subject is beyond the scope of the present paper.

## 7. *Welfare Consequences*

Consumers enjoyed a substantial decline in the price of the agricultural product and thus have benefited greatly from the growth

[58] Tractor prices deflated by the GDP deflator started at a level of 100 in 1910, declined sharply to roughly 30 in 1920, and remained there more or less with small variability until 1960. Quality adjustment would probably show further declined from 1920. Interestingly, the price of horses showed a similar pattern until 1942, but realized a sharper decline thereafter to the level of the 1920s (Olmstead and Rhode 2001).

[59] AnyaMcGuirk and Mundlak (1991), Mundlak, Larson, and Butzer (2004).

[60] See for instance Huffman and Evenson (1993) and Munisamy Gopinath and Terry L. Roe (1997).

in agricultural productivity. Another positive outcome of agricultural growth has been the supply of labor to the nonagricultural sector, which facilitated the growth of nonagriculture. This is true for the United States as well as for most countries.

It remains to consider how the growth has affected farmers. This is not a trivial question because it requires defining who a farmer is for this purpose. Over the twentieth century, the number of workers in U.S. agriculture was sized down to almost one fourth, and the number of farms declined to one third. Obviously, the farmers who moved out of agriculture decided that the opportunities in nonagriculture were superior to those in agriculture. Some farm households have even had to supplement their income by devoting resources to nonagricultural activities, to the extent that the proportion of income from nonagricultural activities in the income of farm households has reached one half. The difference in opportunities is the only way to explain the sizable occupational migration from agriculture. If we contemplate what the income in agriculture would have been in the absence of such migration, we cannot avoid the conclusion that off-farm migration played a major role in the alleviation of rural poverty.[61]

And what about those who remained in farming? There are two specific factors that absorb the rent of the sector: land for the sector as a whole, and the returns to entrepreneurship or management of farm operators. Figures 6a and 6b present the land prices in the United States, Canada, Japan, and South Africa for a long time period.[62] Figure 6a shows the real prices obtained by deflating the nominal land prices by the agricultural GDP deflator. As such, the price is expressed in terms of the agricultural product, say cereals. The level of this land price in 1993 was about three times higher than in 1910. In fact, it was about four times higher around 1980, but declined thereafter. This development reflects the fact that technical change made land more valuable in terms of the agricultural product. The pattern is common to the other countries shown in the figure, indicating that the technical change was pervasive. The price pattern, however, is very different in figure 6b where the land prices are deflated by the consumer price index. In this case, the graph presents the price in terms of consumer goods. For the United States, the index of the consumption-based land price in 1993 stood at a level of 0.833 as compared to a level of 0.727 in 1910, an increase of 15 percent over a period of eighty-three years. By this measure, there was little difference in the welfare of land-owners (or their families) who kept the land for most of the century. This is an indication that the benefits of the technical change have been distributed to the economy at large and have not been retained in agriculture. Here again, the pattern is the same for the other countries in question, indicating that the main shocks affecting agriculture, and leading to the decline in real agricultural prices, were pervasive.

Land prices, like agricultural prices, have undergone cyclical variations. At its peak in 1980, the consumption-based U.S. land price was twice as high as in 1910, or four times as high as its trough value in 1942. This highlights the sensitivity of this measure of agricultural welfare to changes in the economic environment. Another view of the same phenomena is obtained from a comparison of the index of agricultural output and the agricultural GDP.[63] The output index measures changes in output in terms of agricultural prices, and thus is the analogue of figure 5a. The second measure is GDP in 1992 dollars, obtained by applying the overall GDP deflator to the nominal agricultural GDP. Because the GDP deflator is close to the CPI, this measure is the analogue of figure 5b. In 1910 the value of the real agricultural GDP was 74 billion of

[61] Mundlak (1999).

[62] Mundlak, Larson, and Crego (1998).

[63] Gardner (2002, figure 8.1).

1992 dollars, and this was also the value in 1996 (it was even lower in 1993). For comparison, the output index increased from 26 in 1910 to 86 in 1996, more than a threefold rise. It should be noted that the two measures differ not only by the deflator but also in the coverage of the components included in each. This difference in coverage is, however, of secondary importance compared to the deflator. To sum up, the difference is dramatic.

The big changes in agriculture—where the labor force shrank drastically, the number of farms declined, and there has been a lack of long term trend in the consumption-based land price—have had their impact on the income of those who stayed in agriculture. "USDA's detailed economic surveys of individual farms in the 1980s and 1990s indicate that about 40 percent of U.S. farms operate at a loss in any given year" (Gardner 2002, p. 269). The survival in the sector underlines the importance of the idiosyncratic qualities for success.

The discussion of the welfare aspects of the U.S. agricultural growth is incomplete without accounting for the important role of government intervention and the fiscal burden of agricultural policies. For instance, payments to maintain the Commodity Credit Corporation (CCC) program in the mid-1980s reached twenty-five billion 1997 dollars, or over twelve thousands dollars per farm. These payments accounted for roughly one third of agricultural GDP. In principle, the subsidies were supportive, but the production response to the programs was affected by production constraints which shifted in form over the years.[64] It is conjectured that on a net basis the programs encouraged production when compared to the alternative of no intervention. This, however, is merely a statement on the expected production response to the programs and not on their social value. A serious attempt to contemplate the development of U.S. agriculture without the various support programs requires another effort using a dynamic framework.[65]

The United States has maintained an intensive level of agricultural research activity. Direct evaluations suggest that the returns to research have been high.[66] Recall, nevertheless, that the growth rate of U.S. agriculture was not outstanding in terms of its location in the country distribution of growth rates. At first sight, this seems counterintuitive, but it is consistent with our emphasis that a change in the available technology is not sufficient to generate growth. In the specific case of the United States, it is possible that the worsening terms of trade of agriculture and its strong dependence on export markets restrained growth. This has been supplemented by the policy constraints which resulted in less than capacity production, given the level of support of the programs. Besides this point, there is a good global transmission of agricultural knowledge, supported by research in other countries and by an international network of agricultural research stations.

## 8. *Final Remarks*

### 8.1 *Agriculture*

The general picture, common to U.S. agriculture and to trends in world agriculture, is that over the last century world agricultural production grew faster than demand. As a result, real world prices of agricultural products declined roughly by a factor of 2. The output growth was triggered largely by new technology, which in large part was labor-saving. This, together with the development of nonagriculture, resulted

[64] For a discussion of the various programs, see Gardner (2002, chapter 7).

[65] The direction of the outcome can be anticipated by the comparison of the United States with Argentina, which was taxing agriculture. As a consequence, its agricultural productivity and growth lagged behind that of the United States. (Mundlak, Domingo Cavallo, and Roberto Domenech 1989).

[66] Evenson (2001).

in off-farm occupational migration of labor. The decline in food prices improved consumers' welfare, and labor mobility to nonagriculture contributed to overall economic development. The off-farm migration was a major factor in the alleviation of rural poverty.

Agriculture is sometimes considered to be the traditional stagnant sector of the economy, which shrinks in relative importance due to the accumulation of human capital in nonagriculture. The experience of the United States, and of other countries, offers a different perspective. The time path of the sectoral development is triggered by the sectoral changes in technology and their nature, and is affected by the sectoral demand. The income and price elasticities for food are relatively low, and they tilt output growth away from agriculture. Consequently, some resources are released to the rest of the economy. The composition of the released resources is determined by the bias of the technical change in agriculture. Since the middle of the nineteenth century, the technical change in the United States has been labor-saving. The process generated income differences between the sectors, and this attracted labor to nonagriculture. To be integrated in nonagriculture, migrating labor had to accumulate the human capital needed in that sector. Thus, the human capital doesn't trigger the process but is determined by it.

It is possible to consider agriculture in the United States and other high-income countries as part of the modern sector, and to narrow the paradigm of traditional sector to low-income countries. This classification raises two questions: First, is the story supported by the evidence and, second, if it is, what is the reason that some countries have performed differently than others? The country distributions of various measures of growth performance, some of which were presented here, show that in the more recent period the U.S. performance is by no means unique, and in some of the important measures it is near the median of the distribution of a large sample of countries. Thus, the classification is not that clear. It ought to be remembered that in historical perspective the biological revolution in agriculture is a relatively recent phenomenon. Mechanization began much earlier, but its full implementation has required resources and the supporting market conditions. The process, however, is progressing in most countries. The biological revolution has gained an impetus in recent years with the breaking of the genetic code. Its potential is huge, to the extent that it endangers existing rents and has thus generated political and institutional forces to restrain its progress. This development is not consistent with a stagnant sector, as will become clearer when this revolution has been fully utilized.

The reasons for the differences in country performance are the menu of the day in the growth literature. Agriculture is an interesting case because much of the rapidly changing technology is produced and distributed by public institutions. The fact that there is diversity in its use is an indication of the gap between the available and implemented technology. The implementation is determined by the economic environment. The diversity in the economic environment is the reason for the spread in performance. The recognition of the prevailing gap between the available and implemented technology has various ramifications, some of which have been reviewed in our discussion. Among them is the joint decision on the technology and resource allocation. Thus, resource constraints or lack of incentives are likely to discourage progress. The resource constraints may be physical, institutional, political, or an outcome of monopolistic power.[67] Part of the success of U.S. agriculture can be attributed to the relatively smooth flow of resources in agriculture and in the economy. This is not pervasive,

[67] For a discussion of programs countries use, see Maurice Schiff and Alberto Valdès (1992).

and country differences in barriers to resource flow contribute to the country diversity.

### 8.2. *General*

Advances in the available technology affect output only to the extent that they are implemented in production. The domain of empirical analysis is comprised of observations generated by the implemented technology. By its very nature, empirical analysis deals with observations dated by calendar time, and this complicates empirical analysis based on theoretical models which are not dated. What differentiates the present framework from much of the empirical work on growth is the implications of the jointness property that ties together the resource supply, its allocation, and the implemented technology. Restrictions on resource mobility affect resource productivity and returns. This in turn also affects the decomposition of total growth to its factor and total factor productivity component. Thus the measures of TFP do not represent the degree of technical change caused by the changes in the available technology in a given year, or the period of analysis. The available technology affects output only when it is implemented. Thus, slow implementation of new technology may show growth even when there is no new flow of technology, and may show no growth when the new technology is not implemented.

The implication for the empirical analysis of the production function is that the parameters of the function are themselves functions of the state variables. Because the state variables vary across countries and with time, there is no reason to assume that all the observations in a sample are generated by the same function. This is why regression results based on panel data differ with the way the data are pooled. In other words, lack of robustness is a property of the model rather than evidence against it.

## *Appendix*

### A.1. *Factor Bias—The Case of Japan*

To complete the foregoing discussion on the empirical validity of the paradigm of induced innovation and the history of development of U.S. and Japanese agriculture, we hereby present the calculations including Japan. To avoid data disputes, we use the Hayami and Ruttan data, including the United States, as reported in Ruttan, Binswanger, Hayami, William Wade, and A. Weber (1978, tables 3-1, and 3-2). The results are presented in table 4.

As background, I note that the growth rate of output in the period 1880–1930 was 1.62 percent in Japan and only 1.03 percent in the United States. This difference in rates disappears in the period 1930–70. Japan, where "the supply of land was inelastic," plays the role of a land-scarce country, but nevertheless realized an area growth rate of 0.47 percent in the first period. In the same period, the wage–land–price ratio declined. These changes are consistent with those in the United States, and this is the period when it is claimed that Japan followed a different innovation path. The land growth came to a halt in Japan in the second period. There is also a great deal of similarity between the two countries in the change in agricultural labor in the first period. The trend is also similar in the second period, but the decline was stronger in the United States. The fast decline in the United States is related to the off-farm migration, and has more to do with the development of nonagriculture than with the induced innovation hypothesis. With these changes, the right hand side of equation (4) is negative, and for $\sigma < 1$ the bias in the technical change is labor-augmenting. For the other cases in table 4, I compute the critical $\sigma$, as I did in table 3. The result is 1 in the United States in both periods and in Japan in the first period, and 0.7 for Japan in the second period. P. Yeung and Roe (1978) estimate a CES production function, with a variety of

TABLE 4
CRITICAL VALUE OF THE ELASTICITY OF SUBSTITUTION—U.S. AND JAPAN

| Growth rates | 1880–1930 | 1930–1970 | 1880–1930 | 1930–1970 |
|---|---|---|---|---|
| | Japan | | United States | |
| Output | 1.62 | 1.64 | 1.03 | 1.72 |
| Land | 0.47 | -0.08 | 0.87 | 0.28 |
| Labor | –0.18 | –1.48 | –0.08 | –3.27 |
| Output/land | 1.15 | 1.73 | 0.16 | 1.43 |
| Output/labor | 1.79 | 3.13 | 1.1 | 4.99 |
| Land/labor | 0.64 | 1.38 | 0.94 | 3.5 |
| Wage/land price | –0.89 | 1.97 | 0.9 | 0.16 |
| | Elasticity | | | |
| Critical $\sigma$ | 1 | 0.7 | 1 | 1 |

Source: Ruttan and Binswanger (1978, tables 3-1 and 3-2). Except for the last row, the entries are average annual growth rates in percent.
Critical $\sigma$—Positive values of $\sigma$ below the critical value are consistent with labor-augmenting technical change.

modifications aiming to capture the induced innovation effect, using data for Japan 1880–1940, and reach a similar conclusion. This leads us to conclude that the bias in the technical change was labor-augmenting in both countries.[68] Recall, labor-augmenting technical change and $\sigma < 1$ implies labor-saving technical change.

### A.2. *The Impact of Technical Change on the Margins*

The first order conditions for the maximization of (6) are:

(A1) $\alpha f'[\alpha x(q)] = w/H$

(A2) $Hzf[\alpha x(z)] = [wzx(z) + c]$

Total labor is $L = \int_z^\infty x(q)qA(q)dq$. The elasticity of labor demand is $\varepsilon = \partial \ln x/\partial \ln w/H$; $\varepsilon < 0$. Differentiate (A1), and rearrange terms to obtain:

(A3) $d\ln x(q) = -(\varepsilon + 1)d\ln\alpha + \varepsilon d\ln(w/H)$

Hence $\partial \ln x(q)/\partial \ln\alpha < 0 \Leftrightarrow 0 > \varepsilon > -1$.

To simplify, normalize $w$ and $c$ by $H$, and note that $dx(z)$ vanishes by the envelope theorem. We thus rewrite (A2) as: $f[\alpha x(z)] = wx(z) + c/z$. Let $f(.) \equiv f[ax(z)]$, then

$$f'(.)x(z)d\alpha = x(z)dw - cdz/z^2 + dc/z\ .$$

Note that $f'(.) = w/\alpha$ and rearrange

$$zwx(z)d\alpha/\alpha = zwx(z)dw/w - cdz/z + dc\ .$$

Hence $\partial \ln z/\partial \ln\alpha < 0$.

[68] Incidentally, the highest estimate of the elasticity of substitution that Yeung and Roe report for Japan is 0.26.

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