

Part VII. Technical Change in Agriculture

The main purpose of this paper is to present the major theoretical and empirical developments in the area of technical change in agriculture from World War II to the early 1970s. Although the paper is in large part a literature review, we attempt wherever possible to contribute at least in a small way to the overall state of the art.

As in any other emerging field the study of technical change in agriculture has generated its share of controversy and disagreement. Our aim is to search out the controversial issues and present as objectively as we can both sides of the major arguments along with the available empirical evidence bearing on the question. At the same time we try to point out areas of apparent agreement and areas where a consensus seems to have been reached, recognizing that some controversies are never settled but merely fade away because of lack of interest or because they are replaced by more urgent questions.

In order to keep the paper to a reasonable length, we have limited our coverage mainly to United States agriculture. We do not mention empirical studies of technical change in the nonagriculture sector unless we feel they contribute to our understanding of technical change in agriculture. Somewhat more attention is devoted to the theoretical developments of technical change presented in the general economics literature. (For a survey of the general economics literature on technical change, see Kennedy and Thirlwall [92] and Nadiri [114].)

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W. P.

Y. H.

Technical Change in Agriculture

Willis Peterson

*Professor of Agricultural and Applied Economics
University of Minnesota*

Yujiro Hayami

*Professor of Economics
Tokyo Metropolitan University*

The Concept of Technical Change

It seems safe to say that during the post-World War II era technical change has been one of the most rapidly growing areas of study within agricultural economics. As an explanation for the growing interest in the topic, one can point to two major problem areas that have concerned agricultural economists since the end of World War II.

The first is the secular increase in the supply of agricultural products relative to demand in the developed countries, particularly the United States, leading to depressed farm prices and incomes and precipitating severe adjustment problems in the agricultural sector. As a consequence agricultural economists have sought to identify the sources of this output growth. Technical change is one such source, indeed a major source, which has become a subject of economic analysis.

A second problem area that seems to have contributed to the interest in technical change is the difficulty that the developing nations have experienced in increasing agricultural output. Many of these nations, particularly those with a rapid rate of population growth, have been faced with persistent food shortages and widespread malnutrition. It has become evident that development programs emphasizing the increased use of traditional inputs in agriculture have contributed only modestly to agricultural output gains.

Economists have increasingly turned to technical change as their major "engine of growth."

One should bear in mind that agriculture was the only sector of the United States economy for which the official statistical reporting agency collected and published input and output data and total productivity indexes [154]. Efforts to sort out and interpret these data, beginning with Griliches's seminal work, "Measuring Inputs in Agriculture: A Critical Survey" [50], no doubt contributed to the interest and research in the area of technical change.

The Definition of Technical Change

Technical change generally is defined in terms of either a productivity index or a production function. In the context of a productivity index, Ruttan's definition [122] of technical change as the production of a greater output with a given quantity of resources would seem to encompass most interpretations of the term. In other words, technical change results in an increase in output per unit of input. In a later article Ruttan [123] views technical change in a production function context and defines it as a change in the parameters of the production function or a creation of a new production function. In this case we can view technical progress as an upward shift in the production function.

Of course, these two ways of defining technical change are entirely consistent with each other. A productivity index implies the existence of a production function and vice versa. In fact, as Domar [35] points out, a Cobb-Douglas production function is simply a geometric index of inputs, each weighted by its elasticity of production. Conversely, the popular arithmetic productivity indexes such as the Laspeyres and Paasche type indexes imply an underlying linear arithmetic production function. Productivity indexes and production functions are discussed further in a later section of this paper.

It is important to recognize that in order to have changes in output per unit of input or to have shifts in a production function there must be changes in the quality of the inputs. The fact that we observe productivity changes means that some inputs have changed in quality and these quality changes are not reflected in the total input measure. (The problem of how to treat economies of scale is considered later in this section.) If a unit of input is defined in terms of its contribution to production, then total output must move in direct proportion to total input. It is just an accounting identity.

Schultz [141] argues that the ideal input-output formula is one in which the ratio stays close to one. But Heady [67] raises a relevant question: Of what value is it to keep the output/input ratio close to one? Surely, Heady argues, economists know about new inputs and technology and are aware that an increasing ratio is an indication that production is increasing faster than

conventional inputs. Is it not better, then, to have this ratio increase over time?

Schultz's reply [137] to Heady provides the rationale for maintaining an accurate accounting of productivity growth. Here Schultz stresses that technical change is not "manna from heaven." In other words, resources must be devoted to improving the quality of inputs, and we ought to know the costs of producing new technology and the returns from it. Without knowing how much quality improvements in input contribute to output, we cannot answer this question. Moreover, Schultz cautions that allowing the production function to shift is an all too convenient way of disposing of the problem. Such a procedure in effect treats economic growth as exogenous to the system — something we have no control over, like the weather.

Indeed, one might argue, the mere fact that we use the term "technical change" is an indication that we do not know where at least a part of the output is coming from. As Abramovitz [1] so aptly stated, it is a "measure of our ignorance."

On the other hand, it is possible to measure only conventional inputs, avoiding input quality adjustments, obtain a measure of technical change (the residual), and then explain the residual by measuring the contribution of any new, nonconventional inputs or making quality adjustments in the conventional inputs. As Tolley [31] observes, there seem to be two approaches to the analysis of technical change — the "no-quality-change approach" and the "explain-everything approach." For example, Denison [31, 33] states that adjusting for input quality changes obscures the changes that productivity indexes are designed to measure. However, if input quality adjustments are made, Denison argues, the quality adjustment should reflect only the cost to society of bringing the higher quality input into use with the remainder being pure technical change. This might be called a "partial-quality-change approach."

The difference between the "explain-everything approach" and the "partial-quality-change approach" comes to a head in the Jorgenson-Griliches versus Denison debate of the late 1960s and early 1970s. By adjusting total output and input data for errors of aggregation, errors in investment goods prices, and errors of utilization of capital and labor, Jorgenson and Griliches [83] are able to reduce the unexplained portion of total real output growth from 1.60 to 0.10 percent per year in the United States economy. In response to Denison's criticism [32], mainly in regard to the capital utilization adjustment, Jorgenson and Griliches [84] revise the unexplained portion of output growth upward to 1.03 percent per year and admit that perhaps not all output can be accounted for by input quality adjustments. However, they still maintain that this should not prevent us from trying to minimize the unexplained portion of output growth.

Whether we prefer to account for output growth by input quality adjustments or to measure indexes of total factor productivity and to attribute the increase in output per unit input to an increase in knowledge, we still face the basic question asked by Schultz — namely, what is the return to investment aimed at increasing the quality of inputs or of producing new knowledge? If this return is relatively high, then such investment is a relatively cheap source of economic growth. (We consider attempts to measure the return to this investment later in the paper.)

The phenomena of input quality improvements or an increase in knowledge leading to an increase in output per unit of input are commonly referred to as either technical change or technological change. The two terms often are used interchangeably. Schmookler [131], however, preferred to use the term technological change to denote the act of producing new knowledge and to define technical change as the incorporation of this new knowledge in the production processes of firms. In other words, a change in the state of the art would be technological change, whereas a change in actual production techniques would be technical change. In this paper we are concerned with both phenomena, but for convenience we refer to them both as technical change.

Embodied versus Disembodied Technical Change

Embodied technical change, according to its most popular definition, refers to the introduction of new technology in the physical capital input. Solow [144, 146], in an attempt to measure how much investment is necessary to support alternative rates of growth, seems to have provided the major impetus for the embodiment hypothesis. He assumes that new technology could be introduced into the production process *only* through gross investment in plant and equipment. Admitting that such an assumption is not literally true, he nevertheless argues that embodied technical progress is by a substantial margin the more important kind. Salter [128] also emphasizes the importance of embodied technical change at about this time.

To test the hypothesis Solow estimates an aggregate production function for the United States in which he adjusts the stock of plant and equipment by a factor λ , defining 100λ as the percentage of improvement in capital goods from the previous year. Allowing λ to vary from 0 to 0.04 for equipment, Solow reports an improvement in the fit of the production function at the higher levels of λ . The results suggest that the unexplained residual can be accounted for by quality improvements in the capital input.

In spite of its intuitive appeal the embodiment hypothesis has precipitated a substantial amount of controversy and little empirical support. Utilizing Solow's technique of adjusting the capital input for quality change, Berglas [10] extends the capital adjustment factor (λ) upward from a 3 percent an-

nual rate and finds that a 140 percent annual rate minimizes the sum of squares of the residuals. He concludes, therefore, that the embodiment hypothesis is implausible since a 140 percent annual rate of capital improvement is far removed from observed market behavior. In another attempt to test the embodiment hypothesis Griliches [51] uses the ratio of gross to net capital as a measure of the vintage of the capital stock in manufacturing and finds that the age of capital has little explanatory power in accounting for differences in output. For the embodiment hypothesis to be valid new capital should be more productive than old capital.

Denison [34] argues that the embodiment question is of little practical importance because it does not help to know the average fraction of technical progress embodied in capital goods because some innovation requires no investment in capital (unembodied), some requires a small amount of investment, and some requires much investment. Jorgenson [82], in an attempt to distinguish between embodied and disembodied technical change, argues that there is no way of distinguishing between the two if the assumption of a constant exponential rate of technical change is dropped. Solow [146] assumes that embodied technical change takes place at a constant exponential rate.

But why should we be concerned with the embodiment hypothesis? Isn't it little more than an academic question? Jorgenson [82] provides an answer to this question by pointing out that if Solow is right and embodied technical change is important, the rate of economic growth closely depends on the rate of investment. If it is not important, much can be done to stimulate growth without investment in capital goods.

A variant of the embodiment hypothesis seems to have emerged in agricultural economics even before the hypothesis became an issue in the general economics literature. Cochrane [22] in 1953 criticized Schultz [134] for placing too much emphasis on the weather and not enough on the unevenness of technical advance in explaining the uneven growth of the supply of agricultural products. Cochrane argued that technical change in agriculture involves the increased use of capital which in turn depends a great deal on favorable price relationships.

There is no reason, of course, why the embodiment hypothesis has to apply only to capital. Intriligator [77], for example, defines embodied technical progress as occurring because of quality improvements in both capital and labor. But pushed to its logical conclusion the embodiment hypothesis loses its empirical content. If we accept that technical change cannot be "mana from heaven," then all unexplained improvements are embodied in one or more of the factors of production, whether it be in capital, labor, or in any of the intermediate inputs such as fertilizer, new seed varieties, or herbicides.

Factor-Saving Bias

Technical change often is defined in terms of either Hicks or Harrod neutrality with respect to the direction of factor saving. According to the Hicks definition [75], technical change is neutral if the marginal rate of substitution between inputs is not affected. Nonneutral technical change in the Hicks context is generally described as either labor saving (capital using) or capital saving (labor using). Technical change is said to be labor saving (capital using) if the marginal product of capital rises relative to the marginal product of labor. (For a more thorough discussion of neutral and nonneutral technical change, see Brown [14].)

Harrod [58] defines technical progress as capital saving, neutral, or labor saving according to whether capital/output ratio decreases, remains unchanged, or increases with a constant rate of interest. Some controversy has arisen regarding the equivalence of the Hicks and Harrod definitions. Kennedy [89, 90] argues that the two are equivalent when technical change only takes place in the sector producing consumer goods. (See Amano [4] and Kennedy [89, 90] for a recent exchange over this question.)

We know that in the United States agriculture labor has been declining relative to other inputs. We can attribute at least a part of this change to an increase in the price of labor relative to other inputs. However, Stout and Ruttan [149] argue that technical change in United States agriculture has not been neutral because it seems unlikely that the rapid decline in farm employment from 1925 to 1955 can be accounted for entirely by the increase in the price of labor relative to other inputs.

In regard to the total United States economy David and Van de Klundert [29], using a CES function to measure labor and capital efficiency, cite evidence of a labor-saving bias in the technical change that has occurred between 1899 and 1960.¹ Utilizing a translog cost function which has the advantage of incorporating more than two inputs at a time, Binswanger [11] uncovers evidence of both factor-saving and factor-using biases in United States and Japanese agriculture since the turn of the century. In the United States there is evidence of a strong fertilizer-using and machinery-using bias during the period 1912-68. Technical change appears to be neutral with respect to labor until the 1930s and then exhibits a labor-saving bias, especially after World War II. Binswanger also reports that of the 60 percent decline in the labor share in United States agriculture between 1944 and 1968, the labor-saving bias accounts for about 35 percent and the direct price influence accounts for the remaining 25 percent. In Japanese agriculture efficiency gains take on a strong fertilizer-using bias even earlier than in United States agriculture, although after the 1920s fertilizer appears neutral with respect to technical change. Also in contrast to the positive machinery bias in the United States

Japanese agriculture exhibits an overall negative bias with respect to this input. Technical change is reported to be labor using until 1928 and then becomes labor saving, and land exhibits an overall negative bias over the period 1893-1962.

The David-Van de Klundert technique also was applied to Japanese agriculture by Sawada [129] and to New Zealand agriculture by R. W. M. Johnson [81]. Sawada reports that technical change in Japanese agriculture was biased toward the land-saving direction for the period before World War II, but the bias for the postwar period turned toward the labor-saving direction. The Johnson study indicates that the bias in technical progress in New Zealand agriculture was always toward labor saving during the period 1921-67.

Induced Innovation

Although it may be interesting to know whether technical change has progressed in either a capital-saving or a labor-saving fashion, an even more fundamental question is "Why?" The induced innovation hypothesis attempts to provide an explanation for the direction of technical progress. First proposed by Hicks [75] in 1932, the basic idea is that changes or differences in the level of relative factor prices influences the direction of innovative activity, hence the direction of technical progress. According to Hicks, "The changed relative prices will stimulate the search for new methods of production which will use more of the now cheaper factor and less of the expensive one" [75]. For example, if labor becomes high priced relative to capital, scientists and engineers will search for ways to save on the relatively high-priced labor and in so doing develop new forms of capital. The end result may be called biased technical progress in a labor-saving (capital-using) direction.

The contrasts in the direction of factor-saving bias in technical progress in agriculture between Japan and New Zealand as estimated by Sawada and Johnson seem to support the Hicks hypothesis. Technical progress was biased toward using labor in prewar Japanese agriculture, in which labor was more abundant (hence cheap) relative to land and capital, whereas it was biased toward saving labor in New Zealand agriculture, in which labor has traditionally been scarce (hence expensive) relative to land. As labor became increasingly more scarce in Japanese agriculture during the postwar period owing to rapid absorption of labor by expanding industry, the direction of technical progress began to bias toward labor saving. Those patterns are consistent with the Hicks theory of induced innovation. Comparisons of factor prices and factor proportions in the long-term agricultural development in the United States and Japan by Hayami and Ruttan [61, 63] also are consistent with the Hicks theory. In addition, Binswanger's study [11] comparing United States and Japanese agriculture provides empirical support of the Hicks hypothesis.

We should add, however, that the induced innovation hypothesis has not gained universal acceptance. For example, Salter [128] denies that relative factor prices influence the nature of invention: "When labour costs rise any advance that reduces total costs is welcome, and whether this is achieved by saving labour or capital is irrelevant. There is no reason to assume that attention should be concentrated on labour-saving techniques, unless, because of some inherent characteristic of technology, labour-saving knowledge is easier to acquire than capital-saving knowledge." On the other hand, Kennedy [91] maintains that if per-unit labor costs are high relative to per-unit capital costs, the entrepreneur will search for a labor-saving innovation because this will reduce his total cost in the greatest proportion. Thus Kennedy argues that it is only the level of relative factor prices and not changes in these prices that is essential for a theory of induced innovation.

Hayami and Ruttan [61] point out that part of Salter's disagreement with the induced innovation hypothesis stems at least in part from his broad definition of the production function, which he considers as embracing all possible designs conceivable by existing scientific knowledge. Hence, a change in relative factor prices would, according to Salter, amount to "factor substitution" rather than technical change.

Much of the early literature on the induced innovation hypothesis dealt with innovation in the context of the theory of the firm. Hayami and Ruttan maintain that no theory of induced innovation has been developed for the public sector. Since much of the new technology in agriculture is a product of public sector research, a rather large gap exists in our knowledge of how or whether relative factor prices in agriculture influence the direction of publicly sponsored research in agriculture. The authors attempt to fill this gap by extending the basic Hicksian theory of induced innovation to the public sector [61].

Farmers are induced, by shifts in relative prices, to search for technical alternatives which save the increasingly scarce factors of production. They press the public research institutions to develop the new technology, and also demand that agricultural supply firms supply modern technical inputs which substitute for the more scarce factors. Perceptive scientists and science administrators respond by making available new technical possibilities and new inputs that enable farmers to profitably substitute the increasingly abundant factors for the increasingly scarce factors, thereby guiding the demand of farmers for unit cost reduction, in a socially optimum direction.

As the authors point out, the response of research scientists and administrators represents the critical link in the inducement mechanism.

Of course, a certain amount of public sector research is not directed at

specific problems — that is, so-called basic research. For this type of research we would expect a weaker relationship between relative prices and research allocation than exists for the more applied type of research. Brozen [16] argues that nondirected research of universities and foundations accounts for many of the autonomous inventions that we observe. Also unexpected spin-offs coming from applied research on other problems or industries contribute to the error term.

Economies of Scale and Scale Bias

Economies of scale can be defined as a more efficient organization of traditional inputs stemming from an increase in the size of the firm or industry. And we have defined technical change as greater efficiency stemming from new inputs or quality improvements in traditional inputs. Although the two concepts at first glance may appear to be quite different, there is in fact considerable difficulty in separating the two, both conceptually and empirically, when technical progress is not neutral with respect to scale.

The problem occurs because new technology or new inputs may make it possible to realize scale economies that hitherto could not have been obtained. Poultry production provides a good example. Before the development of medicated feeds the difficulty of controlling disease generally made it uneconomical to keep a large number of birds in one location. By decentralizing production in smaller units a disease outbreak would affect a smaller number of birds and result in a smaller loss. A similar situation existed in hog production. More recently new technology in buildings, equipment, and machinery has probably contributed to the increase in the optimum size of farms. This hypothesis is supported by Ulveling and Fletcher's finding [157] of an increase in scale economies on Mexican farms using more capital-intensive technologies.

In economic terms we might say that technical progress is biased toward larger scale if the introduction of new technology or inputs increases the marginal productivities of traditional inputs at higher levels of output relative to their marginal productivities at lower levels. In such cases the effects of technical change and scale economies are inseparable.

Also, the distinction between scale bias and factor-saving bias is not clear-cut. For example, in the development of medicated poultry feeds, the technology biased toward larger scale probably increased the marginal productivity of capital relative to that of labor, thereby increasing the capital/labor at the same factor price ratio.

Supply Function Shifts and Technical Change

It is widely acknowledged that technical change by shifting the production function also shifts (increases) the supply function of the firm or industry.

Yet it should be kept in mind, at least in the case of agriculture, that supply function shifts are not limited to changes in agricultural technology alone. Reductions in input prices also shift the supply function of agricultural products to the right. These price reductions may stem from a number of sources including technical change, economies of scale, reductions in monopoly power, and an easing of import restrictions in the farm supply sector. It should be borne in mind that we are dealing here with price reductions of inputs of a given quality. An increase in the quality of an input more than an increase in its price also shifts the supply function to the right. We have labeled the latter phenomenon technical change.

Perhaps the most important example of this phenomenon in agriculture is the reduction in the real price of fertilizer (plant nutrients) over the past twenty years. In terms of a unit of plant food, quality has not increased but price per unit, particularly nitrogen, has declined substantially. As a source of this decline we can point to the adoption of new cost-reducing technology in the production of fertilizers, particularly the fixation of nitrogen, and in cheaper modes of transportation (Sahota [126, 127]).

Measurement of Technical Change

In keeping with the two ways of viewing technical change mentioned earlier, the magnitude of technical change can be measured either in terms of a change in the ratio of output to conventional inputs (usually an index when aggregation is necessary) or a shift in the production function consisting of conventional inputs. We first present a brief review of the various partial and total productivity indices that have been used to measure technical change in agriculture with their drawbacks and biases. Then we present alternative regression techniques for measuring technical change. In short, this section reviews what Tolley [31] refers to as the "no-quality-change approach."

Index Approach

Productivity is sometimes expressed in terms of output per unit of a particular input. Output per unit of a single input is a partial measure of productivity in the sense that it does not account for the effects of other factor inputs. However, a partial productivity measure can provide useful information on economic progress. For example, labor productivity is known to be a major determinant of farm income and wages and has often been used as a measure of economic progress. Land productivity is also a pertinent measure of agricultural productivity or, more broadly, agricultural development in most Asian countries where land is the limiting factor and farmers are primarily motivated to raise output per unit of cultivated land area.

These partial productivity indices are, in general, biased measures of tech-

nical progress because they include the effects of factor substitution together with the effects of advances in production techniques. In searching for the strategic factors in economic development economists have attempted to evaluate the influences of technical change and factor substitution independently. From their efforts total factor productivity measures have been developed. According to Ruttan [123], the total factor productivity approach was originally suggested by Copeland and Martin [23].

Total factor productivity is defined as the ratio of output to the aggregate of all factor inputs. Two major approaches have been developed to obtain a measure of total factor productivity. One uses a linear aggregation of various inputs with market factor prices as weights, and the other uses geometric aggregation with factor shares as weights.² Conceptually, the former assumes a linear form of aggregate production function and the latter a Cobb-Douglas form. However, a linear aggregation of inputs as utilized by the Laspeyres and Paasche indexes implies an elasticity of substitution between inputs of infinity. Aggregation in the Cobb-Douglas form implies an elasticity of substitution between inputs of one. In most situations we would expect the latter to fit reality more closely than the former.

Solow [145], one of the first to apply geometric aggregation to the construction of the productivity index, identified the index with technical change by explicitly introducing the concept of the aggregate production function. In order to permit identification of the index with technical change, the effects of factors other than technical change must be evaluated and allowed for. Such phenomena as scale economies and biased (nonneutral) technical progress have come to receive a good deal of attention as discussed in the previous section.

Both the linear and the geometric (linear in terms of growth rates) indices are inevitably subject to the well-known "index number problem." The index formulas commonly used are the Laspeyres formula, which uses the base-year weights, and the Paasche formula, which uses the end-year weights. As Ruttan [124] points out, the former tends to underestimate technical progress while the latter has the effect of biasing upward the measure of output per unit of input. The Divisia index, defined as the linear aggregate of growth rates using the base-year weights, is in effect a chain-linked index of Laspeyres indexes and may be recommended on the grounds that it is less vulnerable to systematic bias (see Jorgenson and Griliches [83]). However, on the bases of Jorgenson and Griliches's results, it appears that productivity growth as measured by the ordinary Laspeyres index is not appreciably different from what is obtained with the Divisia index. They report that during the period 1945-65 conventional inputs account for 52.4 percent of growth in total United States output using the Laspeyres index and 54.3 percent using the Divisia index.

With the use of either linear or geometric aggregation output over the aggregate of inputs can be identified as a shift in the aggregate production function under the following assumptions: (1) the economy is operating at the long-run equilibrium under perfect competition, and all factors are rewarded equal to their marginal value productivities, and (2) technical progress is a multiplicative factor of the aggregate production function (implying neutral technical progress). Mundlak and Razin [113] remind us that as a measure of technical change the productivity index is biased to the extent that these assumptions deviate from reality.

Regression Analysis with a Time Variable

For agricultural economists primarily interested in obtaining accurate estimates of production or supply parameters, technical change which shifts the production and the supply functions in a systematic fashion is a type of the disturbance that should be taken account of in the regressions.

A major statistical problem in the estimation of production and supply parameters in the presence of technical change is specification bias (Griliches [57]). Statistical estimates of regression parameters may be biased when such influential factors as technology are misspecified either by omitting these variables or by approximating them inadequately.

Another difficulty, which may be less serious, is the bias due to the application of single-equation least squares to the estimation of production functions on nonexperimental data. Originally, Marschak and Andrews [107] pointed out that input-output observations from cross-sectional or time-series samples are (we hope) generated as the result of producers' profit-maximizing behavior and, hence, factor inputs are not independent of the errors in the equation. This problem becomes more serious when differences in the levels of technology among sample observations are included in the error term.

These difficulties can be avoided if observations are such that they can be grouped into homogeneous subgroups. In this case unbiased estimates can be obtained for the respective groups, and the difference in the estimated parameters between the subgroups can be interpreted as an indicator of technical change. This method is admittedly ad hoc since homogeneous observations are not always available in sufficient number.

In time-series analysis it is common to represent technical progress by a smooth time trend. This convention fails when technical progress is in fact discrete or cannot be approximated by a statistically manageable function of time. Should technical progress represent a discrete shift of the production or supply function, covariance analysis or dummy variables may be utilized. Methods of measuring supply shifts from time-series data are presented by Cassels [17] and Cochrane [20, 21].

Covariance analysis is effective especially when data are cross-tabulated in two directions – for example, in terms of both region and time (Kaneda [85]). When at least two homogeneous observations exist in each cell of the two-way cross-tabulation, it is possible to obtain unbiased estimates of production parameters and, also, to estimate technical change or differences in technical efficiency. The usefulness of this technique in the measurement of technical change tends to be limited by the availability of adequate data, however.

Use of Partial Production Functions

Studies of partial production functions (for example, fertilizer response curves) by the use of experimental data constitute a well-established field of agricultural production economics (Heady and Dillon [71]). Partial production parameters from experimental data (which more closely satisfy the conditions for single-equation production function estimation) can provide a useful approximation of farm technology. Comparison of the partial production parameters estimated on experimental data over time could be a promising approach to the measurement of technical change. Surprisingly little has been done along this line, however. Usually interdisciplinary collaboration is required to compile an adequate time series of such parameter estimates for comparison.

The comprehensive study by Heady and Auer [70], in which they identify and measure the sources of yield changes in United States field crop production, represents an example of the use of partial production functions fitted to secondary data. In this study the authors measure the contribution of fertilizer, variety improvement, production location, and other crop yield variables to yield changes of field crops in the United States from 1939 to 1960. Herdt and Mellor [74] also demonstrate the usefulness of partial production functions in making interregional comparisons of production parameters in the United States and India.

Farrell's Index of Technical Efficiency

Farrell [41] attempts to measure the technical efficiencies of production units in terms of deviations from an isoquant representing the technological frontier. From a sample of observations on input per unit of output he constructs an isoquant by connecting the points which are not exceeded by the combinations of any other two points. Farrell's approach is useful in differentiating between technical efficiency (maximum output for a given combination of inputs) and price efficiency. As defined by Lau and Yotopoulos [97] economic efficiency includes both technical and price efficiency. The latter is defined as the ability of the firm to maximize profits by equating the value of

the marginal product of each variable input with its price. Utilizing a profit function as first introduced by McFadden [110], Lau and Yotopoulos [97] test for differences in economic efficiency between large and small (less than ten-acre) farms in India and find that small farms attain a higher level of economic efficiency. In a subsequent study Yotopoulos and Lau [163] extend the technique to measure separately the differences in technical and price efficiency between groups of farms. Here they find that both large and small farms are equally price efficient but that small farms are more efficient in a technical sense, although the authors acknowledge that a possible explanation for their finding could be an inverse relationship between farm size and soil fertility. Applying the Lau-Yotopoulos model to a sample of Indian wheat farms, Sidhu [143] finds that large and small farms exhibit equal economic efficiency in both the technical sense and the price sense.

Sources of Productivity Growth

We have argued that the basic source of technical change is the improvement in the quality of inputs. In the previous section we reviewed various conventional techniques used to measure technical change. In this section we consider the attempts to identify the sources of technical change (productivity growth) in United States agriculture and to account for the measured productivity growth by the sources identified.

Quality Changes and Productivity Growth

Increase in skills of farm people. This topic falls within the broad area of the economics of human resources. Although it is a relatively new area of study for economists, the output of literature in this area in recent years has been prolific. Even an attempt to survey the literature on the economics of education, a subitem under human resources, would carry us far beyond the scope of this paper and its space limitations (Schultz [135, 136]). Our modest objective here is to offer a brief sketch of the work relating specifically to the effect the education and skills of farm people have on agricultural output.

The idea that education is an investment in human capital which contributes to the output and income of people, of course, is not new. Marshall [108] argued that "the most valuable of all capital is that invested in human beings." Early in the postwar period Schultz [140] argued that differences in per-capita income between communities is much more a function of acquired abilities than of innate abilities. Also it is reasonable to believe that differences in acquired abilities exist because of differences in both quantity and quality of education. The effect of differences in quality of schooling on earnings of rural farm people is clearly documented by Welch [159].

But, we might ask, why should more years of schooling or higher quality of schooling increase an individual's output? Nelson and Phelps [116] suggest that "education enhances one's ability to receive, decode and understand information, and that information processing and interpretation [are] important for performing or learning to perform many jobs." Along this line Welch [160] offers the hypothesis that the productive value of education has its roots in (1) the worker effect and (2) the allocative effect. The first increases the marginal product of labor given the level of other inputs. The second enhances the worker's ability to acquire and interpret information about costs and new inputs. Welch further argues that the allocative effect is the more important of the two for agriculture. This may explain why education does not appear to have a high payoff in a traditional agriculture setting characterized by long-run equilibria in the factor and product markets (Choudri [19]). Welch also points out that production function studies which in effect hold other inputs constant result in a downward bias to the returns to education.

If the allocative effect of education is important, then we should observe the early adopters of new technology to have a higher level of skills (schooling) than those who lag in the adoption process. This observation is borne out by Kislav and Shchori-Bachrach [94] in their study of winter vegetable production technology in Israel. In their study of the "innovation cycle" they find that an innovation is first adopted by the more highly skilled entrepreneurs and then diffuses down the skills scale. As additional evidence, Huffman [76] finds the level of education of farmers to be a significant variable explaining the adoption of nitrogen fertilizer in the United States corn belt. The diffusion of new technology is discussed further elsewhere in this review.

Increase in quality of nonhuman capital. Casual observation leads one to believe that the quality of machinery, equipment, and buildings has increased greatly in the United States over the past century. It is important to bear in mind here that a large share of capital improvement is produced by private sector research and development. As such, its supply price is more likely to reflect quality differences than would be the case if the research and development were carried out in the public sector and the knowledge were made freely available. Of course, to the extent that more productive capital requires more labor and materials to produce, its supply price also will exceed that of less productive capital. The demand for higher-quality capital also can be expected to exceed that of less productive capital, resulting in a higher overall market price provided that the supply curve of nonhuman capital is upward sloping (as we would expect it to be, at least in the short run).

However, in order to use value as a measure of capital quality, it is necessary to separate the price increases due to quality improvements from the effects of a general rise in the price level due to inflation. The work of Court

[24] and Griliches [49] on hedonic price indexes for automobiles documents the positive relationship between quality components such as automatic transmissions and automobile prices. Fetting [42], also using this technique, finds a similar relationship for farm tractors with respect to horsepower and type of engine (gasoline or diesel).

But Griliches [51] argues that the official USDA prices-paid index grossly overstates the "true" quality-adjusted prices of inputs purchased by farmers by not taking quality improvements into account. For example, the purchase of automatic transmissions or factory air conditioning with automobiles shows up as an increase in the price of automobiles, according to the USDA index. As a result the USDA prices-paid index overstates the true rise in prices and therefore results in a downward bias to the real (quality-adjusted and price-adjusted) stock of capital on farms. This is illustrated by a 56 percent rise in the price of automobiles between 1947 and 1958 according to the USDA prices-paid index but a 34 percent increase according to the consumer price index.

Increase in quality of other inputs. Among the other inputs (besides labor and nonhuman capital) that would appear to be sources of productivity growth in agriculture, we can point to commercial fertilizers with improved nutrient content, new and improved crop varieties, more efficient breeds of livestock and poultry, and new and improved agricultural chemicals, mainly herbicides and insecticides.

Increase in quality of output. In comparison to the attention given to input quality change, relatively little has been said about output quality. In part, the explanation may be found in the homogeneous nature of farm products. With the exception of the high-lysine variety of corn, a bushel of corn is a bushel of corn whether it be produced in 1910 or 1972. The same is true for wheat and many other field crops. However, in the case of fruits and vegetables and some livestock products, there is some indication that quality has improved. As examples, one can point to new and improved varieties of fruits and vegetables that are less subject to attack by insects and disease, and dairy products that are lower in bacteria count. On the other hand, some have argued that current varieties of fruits and vegetables are less flavorful than those in years past. The same argument is made for poultry meat. It is not clear which has changed — the product flavor or the consumers' appreciation of flavor given the increased and prolonged consumption of these items.

Of course, any quality improvements in farm products should be reflected in higher prices for these products over what they would otherwise be. However, in order to construct a price-weighted aggregate output index of the Laspeyres type it is necessary to use constant base-year prices. Although this procedure is necessary for the purpose of aggregation and to remove the ef-

fect of changes in the general price level, it tends to remove quality-induced price increases. To the extent that quality improvements are lost by this procedure, we underestimate the growth in aggregate farm output. Of course, converting improved quality into increased quantity of output has the effect of increasing the unexplained residual, which in turn throws an even greater burden on input quality adjustment in accounting for the unexplained residual.

Schultz [137] reminds us of several additional problems of measuring farm output. A major omission from our commonly used output measures is the "improvements in the farm plant resulting from the farmers' own labor or from other labor and materials on the farm." As Schultz argues, the formation of home-produced farm capital in the form of cleared land, drainage, fences, and buildings surely was substantial during earlier decades and is still much too important to leave out.

Secondly, no allowance is made for the increased leisure time of farmers, which is in effect a component of farm output. Nor do we take into account the reduction in the drudgery of farm work. Spending ten hours in the air-conditioned cab of a modern combine is a good deal less physically demanding than spending ten hours pitching bundles in ninety-degree heat. Also the mechanization of many farm chores such as feeding, barn cleaning, and milking undoubtedly has helped make farming a more desirable occupation than it was at the turn of the century or even ten to twenty years ago. Both the unmeasured creation of farm capital and the improved working conditions of farmers (including more leisure) give rise to an underestimate of agricultural output.

Schultz mentions the depletion of natural resources as a negative adjustment to output. Soil erosion and fertility depletion together with the depletion of forests no doubt have been important, especially up to the end of World War II. For example, Bray and Watkins [13] argue that corn hybrids deplete the soil more rapidly than the open-pollinated varieties. Thus the yield increase of hybrids probably overstates their economic gains. Since the beginning of the 1960s more attention has been given to the social costs, or externalities, of agricultural production, mainly fertilizer runoff, odors, and farm pesticide residue. Failure to take these negative aspects of output into account might be regarded as overestimating the "true" output, although it is perhaps more common to regard such externalities as resulting in an underestimate of the true cost of production.

Economies of scale. We are well aware of the substantial increase in the size of the average farm unit in the United States. As Stigler [147, 148] points out, this is an indication that large firms are more efficient than small ones and that economies of scale exist. We argued in a previous section that it is

extremely difficult to separate pure scale economies (those resulting from more efficient combinations of traditional resources) from technical change. (See Griliches [57] for a discussion of specification bias and its effect on measured scale economies.)

Accounting for Productivity Growth

Now that we have identified what appear to be the major sources of the measured productivity growth, let us next review the attempts to account for the unexplained residual. Two general approaches have been used. One approach is to adjust inputs for quality, and the other is to measure the contribution of nonconventional inputs – research, education, and extension.

Adjustment for input quality. We have argued that changes in the quality of inputs represent the major sources of discrepancy between the growth in output and in inputs. If this be true, then adjusting inputs by an independent measure of quality should reduce the unexplained residual.

One procedure is to adjust inputs for quality changes before constructing a productivity index. An increase in the quality of an input is treated as equivalent to a larger quantity of that input. For example, labor should be measured in units of a given educational or skill level. An increase in skills then would be reflected as more units of labor of the previous skill level. In other words, a man-day of highly skilled labor is more labor than a man-day of unskilled labor. Similarly, a 100-horsepower tractor is more tractor than a 150-horsepower tractor, 100 pounds of 12-12-12 fertilizer is more fertilizer than 100 pounds of 10-10-10 fertilizer, and so on.

The usual assumptions in the construction of total productivity indexes using quality-adjusted data are (1) linear homogeneous production functions and (2) competitive equilibrium in the factor markets (Jorgenson and Griliches [83]). Of course, input quality adjustments should be made on the basis of independent information rather than on the assignment of greater weight to higher-quality inputs by some arbitrary formula or rule. For labor, a convenient weight is years of schooling. One can “inflate” labor by either a simple index of education or by first adjusting the education index by an earnings index based on the earnings of people with various years of schooling (Griliches [51, 55, 56]). Griliches reports that for the United States rural farm population the index of education weighted by income is almost proportional to mean school years completed.

Capital poses a more difficult problem. Ideally we would like to measure its service flow, but in reality we usually are provided with information on its depreciated or market value. A good proxy for the service flow of capital would be the rental value of capital. The higher the quality of a capital item (the higher its productivity), the higher its rental value in a perfect rental mar-

ket. Unfortunately, in agriculture the rental market for capital, particularly machines and buildings, is not well developed.

As mentioned earlier, the current market value of a capital item should reflect its quality or productivity. However, Griliches [51, 56] points out, the current market value of capital represents the market's estimation of the present value of all its present and future services. Hence, as a machine or building ages its market price declines, not necessarily because its current service flow declines but because it has fewer years of useful life remaining. Thus the current or market value would seem to underestimate its current annual service flow. An exception would be an increase in capital quality due to an increase in the durability or life of the machine. Here market value could increase without necessarily affecting the annual service flow.

Griliches [56] also points out that official USDA statistics on farm machinery reflect a depreciation pattern that reduces current value to about one-half of purchase price after the fourth year of use. But it is hard to imagine that the service flow of this equipment declines by a like amount. Thus the failure to take quality improvements into account in the prices-paid index, which understates the true stock of capital, and the practice of using the depreciated value of capital as a proxy for its annual service flow both result in an underestimate of the true service flow of farm capital. Hence Griliches argues that original purchase price or some constant fraction thereof provides a more accurate measure of the true service flow of equipment than the depreciated or current market value does. In effect, this procedure assumes that the annual service flow remains constant over the life of the machine. The fact that older machines tend to require more repairs in order to provide the same service flow as new equipment should be reflected by an increase in "other inputs" and labor.

Although the assumption of a constant service flow throughout the life of a machine probably is not too unrealistic in approximating the service flow of machines, Yotopoulos [162] argues that this is not likely to be the case for biological assets such as breeding stock, draft animals, and trees. For these assets the service flows are likely to increase during their early years, reach a peak, and then decline with age. To take account of this phenomenon Yotopoulos estimates the annual service flow of this type of asset by the expression $R_{it} = rV_t - (V_{it+1} - V_{it})$, where R_{it} is the service flow of asset i in year t , r is the rate of discount, and V_{it+1} and V_{it} are its values in years $t+1$ and t , respectively. From the empirical results obtained it would appear that specification of production functions can be much improved by utilizing this simple technique. The technique would seem particularly useful for production function estimation in developing countries where biological assets make up a relatively large share of capital in agriculture.

From the standpoint of other inputs in agriculture, commercial fertilizer can be measured at a constant quality by measuring plant nutrients (N, P, and K weighted by their respective prices) as opposed to measuring units of total fertilizer materials including filler.

Nonconventional inputs as separate variables. Given that quality improvements of inputs are not free gifts of nature, there must be activities which produce these quality changes. In agriculture we can point to research, education, and extension as activities which produce or transmit knowledge that in turn produces quality improvements in agricultural inputs or gives rise to entirely new inputs.³ If all quality improvements were the result of these activities, then we should be able to insert these variables directly into the production function instead of adjusting the traditional inputs for quality changes. On the other hand, G. L. Johnson [80] argues that management ability should not be included as a factor of production because it is already reflected in the quantities of other inputs used.

A major advantage of this approach is that it provides direct estimates of the marginal products of the activities engaged in improving inputs. As we have noted, these activities use up resources and therefore the really important question is whether or not it pays for society to invest in these input-improving activities.

Griliches appears to have been among the first to apply this approach by introducing the education of rural farm people as a separate variable in a cross-regional agricultural production function in the United States [48, 56], later including both education and public agricultural research and extension as separate variables [55]. Tang's study [150], which used time-series data for Japan, represents another pioneering effort in the use of this approach. Other authors using education, research, or extension as separate variables include Gisser [45], Kislev [93], Latimer and Paarlberg [96], Peterson [118], Evenson [37], Yotopoulos [161], Welch [160], and Fishelson [44] for the United States; Herdt [72] for India; Akino and Hayami [3] for Japan; and inter-country comparative studies by Hayami [60] and Hayami and Ruttan [62].

It is of course possible that these variables may not explain or take account of all the quality improvement in the traditional inputs. For example, an increase in the percentage of plant food in 100 pounds of commercial fertilizer is more likely to be the result of technical change and changing price relationships in the fertilizer industry than of public research and extension in agriculture. Also a substantial share (probably over one-half) of total agricultural research and extension is conducted in the private sector. Because of the lack of data on this research it may be necessary to adjust inputs affected by such research for quality change, even though public research is included in the

production function. Private research and development would seem to bear heavily on the machinery, farm structures, and chemical inputs.

The inclusion of public agricultural research as a separate variable in an agricultural production function fitted to state-level cross-section data presents an estimation problem in that the results of the research carried out in a particular experiment station may be utilized in a larger area than just the state in question. This expected pervasiveness of research results prompted Latimer and Paarlberg [96] to argue that one should not be able to observe a relationship between agricultural research and farm output. However, it should be noted that the other authors mentioned above who utilized research as a separate variable obtained a statistically significant coefficient on this variable when including it in an aggregate agricultural production function fitted to cross-section data.

In this section we have attempted to review the methods of accounting for productivity growth in agriculture by various sources. Ideally, we would like to summarize these findings by stating what fraction of the unexplained residual is explained by each source. About the closest we can come to such a summary is that provided by Griliches for United States agriculture. On the basis of his studies [55, 56] he concludes that up to the early 1960s the residual can be attributed to three major sources, each contributing about one-third of the total: input quality change, economies of scale, and investment in research and extension. The last category can be looked upon as one of the ultimate sources of input quality change and possibly of scale economies. Hence, the three sources are not mutually exclusive.

The Production of New Technology

We can be quite certain that technical change in agriculture has not taken place by chance, nor has it been the result of "manna from heaven." The evidence strongly supports the hypothesis that technical change — that is, unexplained output — is the result of quality improvements in inputs which have not been fully reflected in the input measures and that these quality improvements are the result of knowledge-producing activities that require real resources. Our objective in this section is to survey the literature that has attempted to assess the costs and returns to knowledge-producing activities in agriculture and to analyze resource allocation in the production of knowledge.

Costs and Returns of Agricultural Research

In order to assess the economic returns to investment in agricultural research we must assume that research is a production activity. Inputs in this

activity consist of labor (man-hours of scientists and supporting personnel), capital (laboratories, offices, computers, test plots), and other intermediate inputs (supplies, fuel, electricity), and output consists of new knowledge. The new knowledge itself becomes an intermediate input in the production of more productive, higher-quality inputs for agricultural production. The knowledge may be embodied in capital or in intermediate inputs such as pesticides, or it may be applied directly by farmers.

At the same time we should recognize that the research production function is likely to exhibit a sizable stochastic element. It is helpful to compare research with oil exploration. For every ten holes drilled, about eight are likely to be dry with only two yielding a portion of nature's bounty. In research, there are likely to be several projects that turn out to be "dry holes" yielding no new knowledge for every one that is able to add something to what we already know. Of course, the probability depends on the skill of the research worker just as it does for the oil explorer. It seems likely too that the probability of a significant contribution declines as one moves away from applied research to the more "basic" type of research. This does not mean that the expected return is lower for basic research than for applied research. But whatever the probability of success, it seems clear that little knowledge (output) will be gained unless resources (inputs) are allocated to its search.

VALUE OF INPUTS SAVED

We must credit Schultz [134] with the first attempt to quantify the benefits of agricultural research and extension. Using a total productivity index Schultz calculated the additional resources required to produce the 1950 level of output by 1910 techniques. The difference between this figure and the resources actually used to produce the 1950 output represents the value of inputs saved because of the increase in output per unit of input over the period. Schultz found that the savings in inputs for 1950 alone, \$9.6 billion, was larger than all the expenditures of the federal and state governments on agricultural research and extension from 1910 to 1950.

We might expect some upward bias in the returns vis-à-vis the costs with this procedure. First, it is likely that the increase in the educational level of farm people had some effect in raising output per unit of input over this period. Second, as Schultz mentions, part of the improvement in production techniques should be attributed to private research and extension. Schultz points out, however, that some public expenditure allocated to activities is not specifically aimed at producing and distributing new production techniques. As a result, these activities would not be reflected in the productivity ratio, thereby introducing a downward bias to the return side. Also, it is not

clear how activities which increase the quality of farm output are reflected in the productivity ratio.

Utilizing Schultz's technique and extending the data up to 1967, Peterson [119] finds that the *annual value* of inputs saved increases from about \$10 billion in 1950 to nearly \$26 billion in 1967 (constant 1957-59 prices). The more than doubling of annual resources saved in agriculture was the result of an increase in agricultural productivity (output per unit of input) and in the absolute value of agricultural output between 1950 and 1967. At the same time the annual cost of all research and extension (public and private) is estimated to have increased from \$390 million in 1950 to \$882 million in 1967. Thus the absolute difference between the annual value of inputs saved and the annual expenditure on research and extension appears to have increased substantially over time. Peterson also finds the *marginal* internal rate of return on agricultural research and extension in the early 1960s to be about double the long-run *average* rate, 42 percent versus 19 percent.

CONSUMER SURPLUS

In evaluating the returns to research with the inputs-saved technique we measure the reduction in resource cost of obtaining a given output by more efficient resources and techniques. In the consumer surplus approach we measure the extra value of output obtained from a given quantity of more efficient resources.

The consumer surplus approach was first used by Griliches [54] in his hybrid corn study. In this study Griliches obtains a measure of the area between the supply of corn using hybrid seed and the supply using open-pollinated seed bounded on the top (or the right) by the demand for corn. The increase in yields of hybrid corn (assumed to be 15 percent in this study) has the effect of shifting the supply of corn to the right of where it would be if open-pollinated varieties were used. (In the interest of obtaining a lower boundary to the estimated returns, or value of consumer surplus, Griliches measures the decrease in the supply of corn that would occur should hybrid seed disappear rather than the increase that occurs because of the availability of hybrid varieties.) Using a cash-flow technique with annual research costs as outflows and the annual value of consumer surplus as inflow, Griliches computes the widely quoted 743 percent rate of return to investment in hybrid corn research. We will discuss the meaning of this rate of return later in this section.

A major difficulty in such a study is to decide on and obtain the relevant research expenditure data. Griliches's expenditure data include both private and public research but only that research applying rather directly to hybrid corn. As such the data should not be interpreted as including all corn research

520 WILLIS PETERSON AND YUJIRO HAYAMI

during the period in question. Also, how much, if any, of the basic research on hybridization should have been included remains an open question. For example, Nelson [115] argues that George Harrison Shull, a geneticist, made the most significant breakthrough in hybrid corn development while working on genetic experiments with corn plants. Such research is not included in Griliches's measure.

Peterson's poultry study [118] applies in part the consumer surplus approach to a somewhat broader area. In this study a major problem was to obtain a measure of poultry productivity that reflected to a large extent the effect of new inputs stemming from poultry research. Improvements in feed efficiency and the decline in poultry output price relative to input prices are utilized as productivity measures to indicate the shift in the poultry supply function. The results turned up an average internal rate of return of about 20 percent on poultry research in the United States. Although at first glance this figure may appear modest in comparison with the 743 percent hybrid corn return, we will see shortly that the two figures are not comparable.

Schmitz and Seckler [130] utilize a similar technique to estimate the social returns to the development of the mechanical tomato harvester. In this case the authors use the reduction in harvesting costs to obtain a measure of the shift in the tomato supply function. Matching the social returns with the research costs, the authors obtain estimates of the rate of return in the range of 929 to 1282 percent. The procedure used to compute the rates of return is comparable to that used by Griliches in the hybrid corn study. However, because of the social costs involved (mainly displaced human tomato pickers), the authors question the desirability of the investment.

MARGINAL PRODUCT OF RESEARCH

As we have noted, Griliches, Peterson, Latimer and Paarlberg, and Evenson have included research as a separate variable in an agricultural production function using cross-section data. This approach has two major advantages: (1) it amounts to a rigorous test of the influence of agricultural research on agricultural output, and (2) the marginal product of research can be computed directly from the production function. Since decisions to invest or not to invest in agricultural research must be made continually, the relevant criterion is a marginal return rather than an average return.

In general, it appears that the marginal returns to investment in agricultural research are substantially larger than the overall average returns. Griliches [55] reports a \$13 marginal product on public agricultural research and extension. Peterson [118] and Evenson [37] obtain estimates of a comparable degree of magnitude. We should caution, however, against interpreting these marginal products as marginal rates of return. To do so would require that the

Table 1. A Summary of Studies Estimating Average and Marginal Internal Rates of Return to Agricultural Research and Extension in the United States

Author and Type of Study	Average Return (percentage)	Marginal Return (percentage)
1. Evenson, linear regression on residuals, time-series data [36]	--	48
2. Griliches, aggregate production function, cross-section data [55]	--	53
3. Griliches, hybrid corn study [54]	37	--
4. Peterson, poultry study [118]	18	50
5. Schultz, inputs-saved technique extended to 1967 [119, 134]	19	42

Source: Peterson [119].

returns be forthcoming in the same year the investment is made. Yet from our knowledge of the research process it seems unlikely that such would be the case. In fact, Evenson's work [36] reveals that the lag between the research input and the bulk of its output appears to be in the range of six to seven years. A marginal product can be converted to a marginal internal rate of return by finding that interest rate which makes the discounted present value of the marginal product of \$1 of research forthcoming in year $t + 6$ equal to \$1 in the year t (assuming a six-year lag). A marginal product of \$6.50 (the Griliches figure reduced by one-half to take account of private research) converts to about a 53 percent internal rate of return with a six-year lag. Of course, a 53 percent rate of return still is extremely attractive by any standard.

RATES OF RETURN

We have seen that it is not correct to interpret a marginal product figure as a marginal rate of return if there is a substantial lag between research input and output. It is important also to distinguish between an internal rate of return and a so-called external rate. The latter figure is derived by first computing a benefit/cost ratio and then converting the numerator (the discounted stock of benefits) to an annual flow by multiplying it by the discount rate used. The external rate is equal to the annual flow of returns expressed as a percent of the accumulated costs (a stock). The 743 percent return obtained by Griliches in his hybrid corn study is such a figure.

The internal rate of return is defined as that rate of interest which makes the accumulated costs equal to the discounted benefits at any point. In other words, it is equal to the rate of interest that results in a benefit/cost ratio of one. The internal rate computed from the stream of costs and returns in the Griliches hybrid corn study is equal to 37 percent, which is quite different from 743 percent (see table 1). The large divergence between the external and

internal rates is due to the long gestation period during which research was being done but no returns were forthcoming. The internal rate is quite sensitive to the length of the gestation period, especially if the rate of return is relatively high.

As a further precaution, one should distinguish between a long-run average rate of return on agricultural research and a marginal rate of return on additional investment. Although it may be interesting to know that the average return on all agricultural research has been high, a knowledge of the marginal return is necessary for making decisions on additional investment. The summary of rates of return presented in table 1 reveals that the marginal rate of return is substantially greater than the average rate.

The available evidence also suggests that the rates of return to investment in agricultural research in other countries are of a comparable order of magnitude. Ardito-Barletta's estimate [5] of the *average* internal rate of return to wheat research in Mexico (1943 to 1963) is about 75 percent. Ayer and Schuh [6] obtain a 90 percent average internal rate of return to cotton research in Brazil; Akino and Hayami [2] report an average internal rate in the range of 18 to 75 percent to rice-breeding research in Japan (1893 to 1950), and Evenson and Kislev [40] report substantial returns to investment in wheat and maize research based on cross-country observations.

The Allocation of Research

We know that the average or marginal rate of return to agricultural research in the aggregate is in part a function of the efficiency with which the research is allocated. For a given total expenditure the maximum return is obtained only if the marginal return is equalized among all possible research establishments and projects.

Although the allocation problem may be straightforward theoretically, empirically it is a great deal more complex. Until the late 1960s we had virtually no information on the actual allocation of agricultural research, let alone what the allocation should be. Peterson [117] employs a simple head count to determine the allocation of research, teaching, and extension activities by departments in United States colleges of agriculture from 1930 to 1967. Also in the 1960s a detailed and comprehensive inventory of agricultural research became available from the USDA [155].

Decisions bearing on the allocation of research funds both within and between experiment stations and other research agencies must, of course, be made regardless of the amount of information available. We might ask, however, what factors, if any, appear to influence these decisions. Federal funds are allocated by a formula which is based largely on a state's rural and farm population [153]. Regarding nonfederal (mainly state) funds, Schultz [132]

argues and presents evidence to show that differences in total income between states is an important variable explaining differences in nonfederal and total funds available. Heady [68] also argues that appropriations to experiment stations are greatest in the large industrial states and tend to be smaller the larger the proportion of state income represented by agriculture. (For additional discussion on the funding of experiment station research, see Dalrymple [27, 28] and Latimer [95].)

The results of an econometric investigation by Peterson [117] support the Schultz and Heady hypothesis. Moreover, Peterson finds that within experiment stations departments such as agronomy and animal science bear a relatively close relationship to farm income while others such as horticulture and agricultural economics are more closely tied to nonfarm income.

The observed relationship between state income and the allocation of research funds, of course, says nothing about the efficiency of the allocation. It merely reports, "what is," not "what should be." The study entitled *A National Program of Research for Agriculture* [156], prepared jointly by the USDA and the Association of State Universities and Land-Grant Colleges, is an attempt to provide estimates of "socially desirable" levels of publicly funded research in 1972 and 1977 in each of ninety-one problem areas. Although eight criteria are used to weigh each problem area, the man-year recommendation contained in the report reflects in large part the subjective evaluation of the committee preparing the report. We still have no assurance that the proposed allocation would provide a higher overall rate of return than the actual allocation.

Griliches's hybrid corn study [54] reveals that the absolute size of the related output is an important factor influencing the rate of return to a given research expenditure. Comparing hybrid sorghum, also assumed to increase yields by 15 percent, with hybrid corn, Griliches obtains a rate of return to hybrid sorghum research of about one-half that to hybrid corn research even though the sorghum research expenditure is considerably less than the hybrid corn research figure. We might conclude, therefore, that given the probability of success, the expected return to research will be greater the larger the value of related output. Hence the observed practice of allocating the larger portion of the research budget to the most important output in each state might be defended as a fairly good rule.

An account of a number of decision-making experiments at the USDA and at the state levels are contained in the University of Minnesota symposium report, *Resource Allocation in Agricultural Research* (see Meyer [111], Puterbaugh [120], Mahlstedt [101], and Fishel [43].) By and large, these efforts deal with the identification of goals along with the collection and summarization of information that may help research administrators to attain the goals.

Of course, the efficiency criterion is not the only consideration that bears upon the allocation of agricultural research. The distributional effects of agricultural research were brought to our attention long ago by Heady [65, 66, 69] and Schultz [138] and more recently by Schmitz and Seckler [130], Ayer and Schuh [6], and Akino and Hayami [2], and the environmentalists have reminded us of the possible social costs of our new technology on farms, mainly chemical inputs. The welfare aspects of agricultural research and technical change will be considered more thoroughly later in this paper.

*The Diffusion of Technology*⁴

It is evident that society cannot benefit from investment in research unless the results are made available and are adopted by producers. Here we review the literature on the process of interfarm and interregional diffusion within the United States and the process of international diffusion.

Interfarm and Interregional Diffusion

The process of diffusion of new technology among farms traditionally has been the domain of rural sociologists and geographers (see, for example, Beal and Bohlen [9]). The main focus of their studies has been on the impact of communication (or interaction) and sociocultural resistance to innovation on the pattern of diffusion over time and across space. There has been particular concern with understanding how the different sociocultural characteristics of adopters create a spectrum ranging from innovators to laggards and the resulting S-shaped diffusion curve. In general, these studies attempt to provide information on how such characteristics determine the means of communication that are most effective in accelerating the diffusion process.

In contrast, the main focus of economists in their approach to the diffusion of technology has been on how economic variables such as the profitability of innovation and the asset position of firms influence the rate of diffusion (for example, Mansfield [103, 104, 105, 106]). The study of hybrid corn diffusion by Griliches [50] and the subsequent exchange with sociologists bring out the contrast between the economic and sociological approaches as well as the role of economic and sociocultural factors in the diffusion process.

Griliches summarizes the diffusion path for each hybrid corn maturity area by fitting a logistic trend function to data on the percentage of corn area planted with hybrid seed. The logistic function is described by three parameters — an origin, a slope, and a ceiling. By observing differences in the slope (which measures the rate of acceptance) and the ceiling (which measures the level of acceptance at which use of hybrid seed tended to stabilize) of the S-

shaped logistic curve, Griliches attempts to measure changes in the demand for hybrid seed. He finds that both the slope and the ceiling in the heart of the corn belt exceeded those of the marginal corn areas. A similar finding is reported by Martinez [109] regarding the adoption of hybrid corn in Argentina. He interpreted his results as indicating that differences among regions in the rate (slope) and the level (ceiling) of acceptance are both functions of the profitability of a shift from open-pollinated corn to hybrid corn. Maier's study [102] of the adoption of the mechanical cotton picker also reveals that the rate of acceptance of this machine was closely related to its profitability.

Griliches's study was criticized by a number of sociologists. Brander and Straus [12], citing as an example the case of hybrid sorghum adoption in Kansas, argued that familiarity (congruence) with a technique or an input is the critical factor explaining the rate of adoption. Havens and Rogers [59] argued that communication or interaction between people is the important factor. In reply Griliches [46, 53] argues that even if congruence and interaction are important, there is no reason to exclude profitability as a factor explaining the rate of adoption. Indeed, as Griliches points out, the "profitability" approach can be broadened by allowing for differences in information, risk preference, and so on, thus bringing it as close to the "sociological" approach as one would want to.

The work of Nelson and Phelps [116], Welch [160], Kislev and Shchori-Bachrach [94], and Huffman [76] mentioned earlier provides a basis for broadening the profitability approach to include the education or skill distribution of potential adopters.

Griliches also finds that differences in the origin (defined as the date an area began to plant 10 percent of its "ceiling" area in hybrid corn) can be explained largely by differences in the size and density of the hybrid seed market as measured by the size and density of corn production. As Hayami and Ruttan [61] note, this finding has an important implication for the induced innovation hypothesis in that it supports the idea that developers of hybrid seed, both private seed companies and public research institutions, are motivated by the potential returns from hybrid corn. In the case of private companies, the motivation is provided by the potential profits from the production and sale of hybrid seed. In the case of public research institutions, the desire to maximize social returns to the region and ensure its competitive position forms the basis for their actions. As Griliches [50] observes, "the contribution of the various experiment stations is strongly related to the importance of corn in the area. In the 'good' corn areas the stations did a lot of work on hybrids and in the marginal areas, less." This observation is consistent with the public sector induced innovation hypothesis advanced by Hayami and Ruttan.

526 WILLIS PETERSON AND YUJIRO HAYAMI

This finding by Griliches also points out the critical role of adaptive research for the diffusion of agricultural technology among ecologically heterogeneous regions. Agricultural technology is typically location-specific or constrained by the local ecology. Techniques developed in a region often are not transferable to other regions without further adaptive research. Traditionally most of the diffusion models have been designed to describe or analyze diffusion among farms within a particular area over time. The attributes of technology and of potential adopters often are taken as given. Nevertheless, such models are not very helpful in explaining or predicting the diffusion of technology among heterogeneous regions, particularly among countries located in different climatic zones.

International Diffusion

The transfer of advanced technology existing in the developed countries to the less developed countries has been considered as the major means for promoting agricultural growth in the less developed countries. However, efforts to achieve rapid agricultural growth by the direct transfer of foreign technology have not been very successful. Modern agricultural technology has evolved largely in the developed countries of the temperate zone and is primarily adapted to their ecology and factor endowments. Inadequate recognition of the location-specific character of agricultural technology would seem to be a major reason for the lack of effectiveness of much of the efforts directed at international technology transfer. Also it seems that this perspective has resulted from the erroneous application of sociological interfarm diffusion models to the process of international technology transfer, in which local adaptation is essential.

We have argued that one of the merits of the Griliches model is that it incorporates the mechanism of local adaptation in the interregional diffusion of hybrid corn technology. This mechanism is based on the behavior of public research institutions and private agricultural supply firms. Modification of the model is needed, however, for the study of international technology transfer.

In the United States there exists a large stock of scientific and technical manpower, a well-structured federal and state experiment station network, and vigorous competition and entrepreneurship in the farm supply industry. When these conditions are not present, even if the potential profitability from the transfer of a particular technology is high, the required adaptive research may not be supplied. The problem of facilitating international technology transfer as an instrument of agricultural development is, therefore, how to institutionalize a system of adaptive research and development which is responsive to the opportunities of technology transfer that are profitable to society.

Based on the role of adaptive research in the process of diffusion, Hayami and Ruttan [61] distinguish three phases of international technology transfer: (1) material transfer, (2) design transfer, and (3) capacity transfer. The first phase is characterized by the simple transfer or import of new materials such as seeds, plants, animals, and techniques associated with these materials. Local adaptation is not conducted in an orderly and systematic fashion. The naturalization of plants and animals occurs primarily as a result of trial and error by farmers, usually involving a long gestation period.

In the second phase the transfer of technology is primarily through the transfer of certain designs (blueprints, formula books, and so on). During this period exotic plant materials and foreign equipment are imported for use in the development of new plant breeds and equipment designs, rather than for use in direct production. New plants and animals are subjected to orderly tests and are propagated through systematic multiplication.

In the third phase, the transfer of technology is made through the transfer of scientific knowledge and capacity which enable the production of locally adaptable technology, following the prototype technology which exists abroad. Increasingly, plant and animal varieties are bred locally to adapt them to local ecological conditions. The imported machinery designs are modified in order to meet climatic and social requirements and factor endowments of the economy. An important element in the process of capacity transfer is the migration of agricultural scientists, which is often of critical importance because scientific and technical manpower is in short supply in the less developed countries.

In support of their three-phase international technology transfer hypotheses Hayami and Ruttan point to the international diffusion of sugarcane varieties (Evenson, Houck, and Ruttan [39]) and to the transfer of tractors from the United States to the USSR (Dalrymple [25, 26]). Furthermore they argue that the dramatic appearance and diffusion of the higher-yielding varieties (HYV) of staple cereals in the tropics since the late 1960s (the widely heralded "Green Revolution") represents a case of capacity transfer: ". . . the development of the HYV's represents a process of agricultural technology transfer from the temperate zone to tropical and subtropical zones through the transfer of scientific knowledge and capacity. . . . These new HYV's adaptable to tropical ecologies were initially developed . . . by international teams of scientists drawing on the principles that emerged in the process of developing HYV's that had been introduced earlier in Japan, the United States and other temperate zone developed countries" (Hayami and Ruttan [61]). In their view this process also represents an institutional innovation: the adaptive research that led to the development of higher-yielding varieties was primarily conducted at a new set of international agricultural research centers which

528 WILLIS PETERSON AND YUJIRO HAYAMI

typically were supported by large United States foundations. The centers are staffed by international teams of scientists of various agricultural science disciplines assisted by in-service trainees and coordinated by a common orientation to produce major breakthroughs in yield potentials of certain staple cereals. The establishment of these research and training centers can be considered as an institutional innovation facilitating the transfer of an "ecology-bound" location-specific agricultural technology from temperate zone developed countries to tropical zone developing countries (Hayami and Ruttan [61]). They conclude that the success of agricultural development via international technology transfer hinges on the ability to institutionalize the effective supply of adaptive research in the developing countries, given their limited endowment of research personnel. The importance of adaptive research in obtaining productivity gains in wheat, maize, rice, and cereal grains production is further documented by Evenson [38] and Evenson and Kislev [40].

Technical Change and Welfare

In recent years the long-accepted goal of promoting technical change in agriculture and thereby increasing its productive capacity has come under increasing scrutiny, at least in the United States. There can be little doubt that the mass exodus of people from farms and rural areas to cities is in large part the result of technical change in agriculture.

Moreover, it seems likely that this migration has contributed to the problems of congestion and pollution now troubling the nation, especially its cities. But it is equally certain that without a more productive agriculture the per-capita real output of goods and services would be considerably smaller than it is today. Nations that must devote a large share of their resources to the production of food generally are those with the lowest per-capita income. If a society must use the bulk of its resources to produce food, it cannot produce the other things that make for a high standard of living.⁵ In this section we attempt to examine some of these issues, paying particular attention to the distinction between the output effects and the distributional effects of technical change.

Output Effects

Technical change is the name we have given to a phenomenon that provides an increase in output for a given level of conventional inputs. And we have already argued that the additional "unexplained" output is largely the result of unmeasured quality improvements in inputs or totally new inputs not accounted for on the input side. It is also evident that real resources are required to produce input quality improvements or new inputs. Thus we can

treat the production of technical change as an investment which uses resources and yields a stream of returns over time in the form of increased output. In this sense the production of technical change is no different than any other investment. (Much of the discussion in an earlier section dealt with attempts to measure the returns to this investment.)

From all indications it appears that the rate of return on investment in agricultural research has been and is as high or higher than the rate of return on alternative investments. Thus we can infer that the total output of goods and services available to society is higher than if the resources devoted to agricultural research had been instead devoted to other investment alternatives. Since most societies prefer more to less, it is difficult to criticize the decision to allocate resources to agricultural research strictly on the basis of its output effect. Nor is it wrong on this basis to advocate continued investment in agricultural research in view of its relatively high marginal return.

Distribution Effects

With respect to the distribution effects of agricultural research we should consider its effects on both the personal and functional distribution of income in agriculture as well as in the total economy. It long has been argued that technical change resulting from agricultural research may result in greater inequality in the personal distribution of income among farmers and between farmers and nonfarmers (Heady [65, 66, 69]). Schultz [138] recognizing that farm progress leads to a relative decline in the price of farm products and a resulting decline to labor earnings in agriculture, argues that a high marginal return to agricultural research should be a signal to allocate more resources to research only if there is some way of "reckoning and reconciling" all gains and losses. Unfortunately a procedure for redistributing the specific gains and losses from technical change in agriculture has not been implemented.

It is clear that technical progress has benefited some farmers and harmed others. Those farmers whose labor is a complement to new and improved inputs, mainly the skilled farmers, no doubt have experienced an increase in their marginal products and consequently have enjoyed an increase in real income. On the other hand, farmers whose labor is a substitute for new inputs, mainly the unskilled farmers, have experienced a declining demand for their services and therefore have suffered a reduction in net income. Day's study [30] of sharecroppers in Mississippi provides an excellent account of the latter case. According to Day's estimates, the annual requirement for unskilled labor in the Mississippi delta declined from 170.2 million man-hours in 1940 to 13.7 million man-hours in 1957 while the annual requirement for skilled labor increased from 0.69 to 1.19 million man-hours during this period. Schmitz and Seckler [130] estimate that the mechanical tomato harvester

will displace over 19 million man-hours per year after 1973 in the United States.

Unfortunately we have very little information on the effect of new technology on marginal productivity and the wages of labor retained in agriculture — that is, the labor to operate the cotton pickers, the tomato harvesters, and the like. Studies of the effect of research and development on the *total* agricultural labor market by Wallace and Hoover [158] and Bauer [8] reveal that, *ceteris paribus*, the demand for all farm labor is increased by agricultural research and development. When farm prices are allowed to adjust (decline) as a result of new technology, however, Bauer finds that a 10 percent increase in “technology” decreases the quantity of labor required in agriculture by 4.9 percent.

We should keep separate the income distribution effects of farm programs designed to increase all farm income from the distributional effects of technical change itself. We have strong evidence that past and current farm programs have benefited large, high-income farms to a much greater extent than their small, low-income counterparts (Schultz [139] and Schultze [142]). Surely the current personal distribution of income among farmers would be more equal if government payments to farmers would have been negatively correlated with farm income rather than positively correlated.

Kendrick [87] argues that technical change reduces income inequality because of the tendency for wage income to increase relative to property income, the latter being more important for higher-income people. And because low-income people tend to spend a larger fraction of their income on food than high-income people, it follows that lower food prices (relative to what they would otherwise be) resulting from agricultural research benefit low-income people to a proportionately greater extent than their higher-income counterparts. This fact is well documented by Tweeten [151]. Although the effect does not show up in the income distribution statistics, its net result is in essence similar to a shift to greater equality of income for a given price of food.

It also can be argued that income distribution will be affected by the kind of technology developed. For example, labor-saving technology can be expected to reduce the demand for labor and to displace more farm workers than neutral or labor-using technology. Also we might expect that mechanical innovations would more likely be labor saving than biological or chemical technology. Thus it appears that a greater allocation of agricultural research toward the biological and chemical spheres could have reduced the wholesale migration of farm people during the 1950s and 1960s.

Direct public control of agricultural research allocation is limited to the research conducted by agricultural experiment stations and the USDA (about

one-half of the total agricultural research during the 1950s and 1960s). Moreover, the major share of public agricultural research was already allocated to the biological area and, to a lesser extent, the chemical area, with the major share of mechanical research and development conducted in the private sector. Thus it is not at all certain that even a complete abandonment of mechanical research in the public sector would have had much of an impact on the personal distribution of income in agriculture.

In regard to scale economies, we argued earlier that technical change probably has been biased toward large-scale farms. But here again we might expect mechanical technology to have had the major impact. Although we know relatively little about the ultimate sources of scale economies, we should also consider the effect of increasing nonfarm per-capita incomes. As nonfarm earnings increase, farm size (in terms of output) tends to increase in order to provide farmers with somewhat comparable incomes. In economic terms we might say that as the opportunity cost of farm labor increases, unit labor costs increase on small farms relative to those on larger farms, hence scale economies appear and average farm size increases. Granted, agricultural research no doubt contributes to general economic growth and to rising per-capita nonfarm incomes, but this link between agricultural research and scale economies in agriculture is rather tenuous, to say the least.

The impact of technical change on the functional distribution of income between labor and capital (including land) in agriculture also is an important question. Herdt and Cochrane [73] argue that technical change benefits the landowner as opposed to the farm operator and manager. Their argument is that technical change shifts cost curves downward, resulting in pure profits. And as firms attempt to expand because of the new intersection between output price and marginal cost, the price of land is bid up. They estimate that a one-point rise in the total productivity index increases land price by an average of \$1.59 per acre.

An important assumption in this analysis is that of a constant output price, for economic theory suggests that a reduction in marginal cost leads to a reduction in output price and in the demand for inputs, *ceteris paribus*. Whether there is a net reduction in the demand for land in total depends on whether each particular parcel of land is a complement or a substitute to the new inputs adopted by farmers. At any rate it is not clear whether the observed distribution effects in the Herdt-Cochrane study are the result of technical change or of the particular characteristics of the farm income support programs which have prevented output prices from declining, at least initially, in response to new technology.

Further in regard to the functional distribution of income between capital and labor in agriculture, Ruttan and Stout [125] report that labor's share of

532 WILLIS PETERSON AND YUJIRO HAYAMI

agricultural income declined between 1946 and 1957. This is in contrast to D. G. Johnson's previous finding that labor's share had increased slightly from 1910 to 1946 [79]. One might infer from the Ruttan-Stout results that technical change in agriculture has been of a labor-saving variety. Ruttan and Stout also report a convergence of relative factor shares between regions. They attribute this phenomenon in part to an increase in current expenses, particularly the cost of fertilizer which serves as a land substitute and thus reduces in importance the native land endowment of each region.

Externalities and Adjustment Costs

Generally we define an externality or social cost as a cost borne by society or individuals over and above the cost of resources directly utilized to carry on a production activity. In the case of agricultural research (public and private) the adjustment cost borne by farm people who have decided to leave agriculture because of declining farm prices and incomes brought on by technical change can be considered a social cost. These adjustment costs might be categorized as both pecuniary (reduction in income before and during the change in occupation plus moving costs) and nonpecuniary (the uncertainty and anxiety of leaving relatives, friends, and familiar surroundings).

The seriousness of these adjustment costs depends somewhat on the length of run considered. In the short run it cannot be denied that these costs are important for displaced farm people. (See Day [30] and Schmitz and Seckler [130].) In the long run, however, it is hard to deny that most displaced farmers have been able to increase their real incomes in nonagricultural jobs over what they could have earned in agriculture if technical change had not occurred.

Other social costs arising from technical change in agriculture might include the pollution caused by the increased use of farm chemicals, mainly pesticides and commercial fertilizer. However, the allegations of the environmentalists and the counterallegations of industry spokesmen provide little hard evidence to date on the magnitude of this problem. Also it seems necessary to consider the increased pollution that resulted from the acreage restriction characteristic of the farm income support programs. We would expect that the use of farm chemicals has been stimulated as farmers have searched for land substitutes because of acreage restrictions. To the extent that land is a complement to farm labor, one might argue as well that acreage restrictions have reduced the demand for farm labor and have hastened off-farm migration.

A somewhat different kind of social cost to technical change could occur if it brought about an agricultural industry made up of a few firms with ex-

tensive monopoly power. However, the spatial characteristics of agricultural production force us to dismiss this possibility at least in the foreseeable future.

Notes

1. The function they estimated was

$$V = [(E_1 L)^{-\epsilon} + (E_k K)^{-\epsilon}]^{-\frac{1}{\epsilon}}$$

where V is value added and E_1 and E_k represent levels of efficiency of labor and capital, respectively.

2. It is common to call the ratio of output to the linear aggregate of inputs the index of total factor productivity and the ratio of output to the geometrical aggregate of inputs the index of technical change, though they are aimed at measuring the same thing. Empirical studies in United States agriculture using the arithmetic index have been carried out by Barton and Cooper [7], Kendrick [88], Loomis and Barton [100], Ruttan [121, 122], and Schultz [134, 138]. Studies using the geometric index have been conducted by Chandler [18] and Lave [98].

3. Strictly speaking, one can define an input of improved quality as a new input. For example, the farmer who learns that higher yields can be obtained by planting corn at an earlier date is in a sense a different person than before.

4. This section draws heavily on Hayami and Ruttan [61, pp. 169-190].

5. An exception to this rule occurs if a nation is able to export a large share of its agricultural output to other nations and buy other goods and services in return. Denmark and New Zealand, however, are about the only nations that have been able to do this on a relatively large scale. See Tweeten and Hines [152] for an attempt to measure the contribution of agricultural productivity and the resulting decline in the farm population to overall economic growth.

References

- [1] Abramovitz, M. "Resource and Output Trends in the United States since 1870." *Am. Econ. Rev.* 46: 5-23, May 1956.
- [2] Akino, M., and Y. Hayami. "Efficiency and Equity in Public Research; Rice Breeding in Japan's Economic Development." SAP Rep. 5, Tokyo Metropolitan University, 1973.
- [3] ———. "Sources of Agricultural Growth in Japan, 1880-1965." *Quart. J. Econ.* 88: 454-479, August 1974.
- [4] Amano, A. "Biased Technical Progress and a Neo-Classical Theory of Economic Growth." *Quart. J. Econ.* 78: 129-138, February 1964.
- [5] Ardito-Barletta, N. "Costs and Social Returns of Agricultural Research in Mexico." Unpublished Ph.D. dissertation, University of Chicago, 1970.
- [6] Ayer, W. A., and G. E. Schuh. "Social Rates of Returns and Other Aspects of Agricultural Research: The Case of Cotton Research in Sao Paulo, Brazil." *Am. J. Agr. Econ.* 54: 557-569, November 1972.

534 WILLIS PETERSON AND YUJIRO HAYAMI

- [7] Barton, G. T., and M. R. Cooper. "Relation of Agricultural Production to Inputs." *Rev. Econ. Stat.* 30:117-126, May 1948.
- [8] Bauer, L. L. "The Effect of Technology on the Farm Labor Market." *Am. J. Agr. Econ.* 51:605-618, August 1969.
- [9] Beal, G. M., and J. M. Bohlen. *The Diffusion Process*. Iowa State Agr. Exp. Sta. Spec. Rep. 18, 1957.
- [10] Berglas, E. "Investment and Technological Change." *J. Pol. Econ.* 73:173-180, April 1965.
- [11] Binswanger, H. P. "The Measurement of Biased Efficiency Gains in U.S. and Japanese Agriculture to Test the Induced Innovation Hypothesis." Unpublished Ph.D. dissertation, North Carolina State University, 1973.
- [12] Brander, L., and M. Straus. "Congruence versus Profitability in the Diffusion of Hybrid Sorghums." *Rural Sociology* 24:381-383, December 1959.
- [13] Bray, J. O., and P. Watkins. "Technical Change in Corn Production in the United States, 1870-1960." *J. Farm Econ.* 46:751-765, November 1964.
- [14] Brown, M. *On the Theory and Measurement of Technical Change*. Cambridge: At the University Press, 1966.
- [15] Brown, M., and J. Popkin. "A Measure of Technological Change and Returns to Scale." *Rev. Econ. Stat.* 44:402-412, November 1962.
- [16] Brozen, Y. "Determinants of the Direction of Technological Change." *Am. Econ. Rev.* (supplement) 43:288-302, May 1953.
- [17] Cässels, J. M. "The Nature of Statistical Cost Curves." *J. Farm Econ.* 15:378-383, April 1933.
- [18] Chandler, C. "The Relative Contribution of Capital Intensity and Productivity to Changes in Output and Income." *J. Farm Econ.* 44:335-348, May 1962.
- [19] Choudri, D. P. "Education and Agricultural Productivity in India." Unpublished Ph.D. dissertation, University of Delhi, 1968.
- [20] Cochrane, W. W. "Conceptualizing the Supply Relation in Agriculture." *J. Farm Econ.* 37:1161-1176, December 1955.
- [21] ———. "Farm Price Gyration — An Aggregative Hypothesis." *J. Farm Econ.* 29:383-408, May 1947.
- [22] ———. "Professor Schultz Discovers the Weather." *J. Farm Econ.* 35:281-283, May 1953.
- [23] Copeland, M. A., and E. M. Martin. "The Correction of Wealth and Income Estimates for Price Changes." In *Studies in Income and Wealth*. National Bureau of Economic Research, vol. 2, 1938.
- [24] Court, A. T. "Hedonic Price Indexes with Automotive Examples." In *The Dynamics of Automobile Demand*. General Motors Corporation, 1939.
- [25] Dalrymple, D. "American Technology and Soviet Agricultural Development." *Agr. Hist.* 40:187-206, July 1966.
- [26] ———. "The American Tractor Comes to Soviet Agriculture: The Transfer of a Technology." *Technology and Culture* 5:191-214, Spring 1964.
- [27] ———. "Comments on Public Purpose in Agricultural Research and Education." *J. Farm Econ.* 44:444-453, May 1962.
- [28] ———. "Public Investment in Agricultural Research and Education: Some Comments." *J. Farm Econ.* 47:1020-1022, November 1965.
- [29] David, P. A., and T. Van de Klundert. "Biased Efficiency Growth and Capital Labor Substitution in the U.S., 1899-1960." *Am. Econ. Rev.* 55:357-394, June 1965.

- [30] Day, R. H. "The Economics of Technological Change and the Demise of the Share Cropper." *Am. Econ. Rev.* 57:427-449, June 1967.
- [31] Denison, E. F. "Measurement of Labor Input: Some Questions of Definition and the Adequacy of Data" and discussion by G. Tolley. In *Output, Input and Productivity Measurement*. National Bureau of Economic Research, vol. 25. Princeton: Princeton University Press, 1961.
- [32] ———. "Some Major Issues in Productivity Analysis: An Examination of Estimates by Jorgenson and Griliches." *Survey of Current Business*, vol. 49, part II, pp. 1-27, May 1969. (Also included in *Survey of Current Business*, vol. 52, part II, pp. 37-63, May 1972.)
- [33] ———. "Theoretical Aspects of Quality Change, Capital Consumption, and Net Capital Formation." In *Problems of Capital Formation*. National Bureau of Economic Research Conference on Income and Wealth, vol. 19, 1957.
- [34] ———. "The Unimportance of the Embodiment Question." *Am. Econ. Rev.* 54:90-93, March 1964.
- [35] Domar, E. "On the Measurement of Technological Change." *Econ. J.* 71:709-729, December 1961.
- [36] Evenson, R. E. "The Contribution of Agricultural Research and Extension to Agricultural Production." Unpublished Ph.D. dissertation, University of Chicago, 1968.
- [37] ———. "The Contribution of Agricultural Research to Production." *J. Farm Econ.* 49:1415-1425, December 1967.
- [38] ———. "The 'Green Revolution' in Recent Development Experience." *Am. J. Agr. Econ.* 56:357-394, May 1974.
- [39] Evenson, R. E., J. P. Houck, and V. W. Ruttan. "Technical Change and Agricultural Trade: Three Examples—Sugarcane, Bananas, and Rice." In *The Technology Factor in International Trade*, R. Vernon, ed. New York: Columbia University Press, 1970.
- [40] Evenson, R. E., and Y. Kislev. "Research and Productivity in Wheat and Maize." *J. Pol. Econ.* 81:1309-1329, November/December 1973.
- [41] Farrell, M. J. "The Measurement of Productive Efficiency" and discussion by M. G. Kendall. *J. Royal Stat. Soc.* 120:253-287 (series A, part 3), 1957.
- [42] Fettig, L. P. "Adjusting Farm Tractor Prices for Quality Changes." *J. Farm Econ.* 45:599-611, August 1963.
- [43] Fishel, W. L. "The Minnesota Agricultural Research Resource Allocation Information System and Experiment." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.
- [44] Fishelson, G. "Return to Human and Research Capital and the Non-South Agricultural Sector of the United States, 1949-1964." *Am. J. Agr. Econ.* 53:129-131, February 1971.
- [45] Gisser, M. "Schooling and the Agricultural Labor Force." Unpublished Ph.D. dissertation, University of Chicago, 1962.
- [46] Griliches, Z. "Congruence *versus* Profitability: A False Dichotomy." *Rural Sociology* 25:354-356, September 1960.
- [47] ———. "The Demand for Fertilizer: An Economic Interpretation of Technical Change." *J. Farm Econ.* 40:591-606, August 1958.
- [48] ———. "Estimates of the Aggregate Agricultural Production Function from Cross-Section Data." *J. Farm Econ.* 45:419-428, May 1963.
- [49] ———. "Hedonic Price Indexes for Automobiles: An Econometric Analysis of

536 WILLIS PETERSON AND YUJIRO HAYAMI

Quality Change." In *Hearings on Government Price Statistics*. Joint Economic Committee, 87th Congress, 1st Session, 1961.

[50] ———. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25:501-522, October 1957.

[51] ———. "Measuring Inputs in Agriculture: A Critical Survey." *J. Farm Econ.* 42:1411-1433, December 1960.

[52] ———. "Production Functions in Manufacturing: Some Preliminary Results." In *The Theory and Empirical Analysis of Production*. National Bureau of Economic Research, vol. 31, 1967.

[53] ———. "Profitability versus Interaction: Another False Dichotomy." *Rural Sociology* 27:327-330, September 1962.

[54] ———. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." *J. Pol. Econ.* 66:419-431, October 1958.

[55] ———. "Research Expenditures, Education, and the Aggregate Agricultural Production Function." *Am. Econ. Rev.* 54:961-974, December 1964.

[56] ———. "The Sources of Measured Productivity Growth: United States Agriculture, 1940-1960." *J. Pol. Econ.* 71:331-346, August 1963.

[57] ———. "Specification Bias in Estimates of Production Functions." *J. Farm Econ.* 39:8-20, February 1957.

[58] Harrod, R. *Towards a Dynamic Economics*. London: Macmillan, 1948.

[59] Havens, A. E., and E. M. Rogers. "Adoption of Hybrid Corn: Profitability and the Interaction Effect." *Rural Sociology* 26:409-414, December 1961.

[60] Hayami, Y. "Sources of Agricultural Productivity Gap among Selected Countries." *Am. J. Agr. Econ.* 51:564-575, August 1969.

[61] Hayami, Y., and V. W. Ruttan. *Agricultural Development: An International Perspective*. Baltimore: Johns Hopkins University Press, 1971.

[62] ———. "Agricultural Productivity Differences between Countries." *Am. Econ. Rev.* 60:895-911, December 1970.

[63] ———. "Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880-1960." *J. Pol. Econ.* 78:1115-1141, September/October 1970.

[64] ———. "Professor Rosenberg and the Direction of Technical Change." *Economic Development and Cultural Change* 21:352-355, January 1973.

[65] Heady, E. O. "Economic and Welfare Aspects of Farm Technological Advance." *J. Farm Econ.* 31:293-316, May 1949.

[66] ———. *Economics of Agricultural Production and Resource Use*. Englewood Cliffs, N.J.: Prentice-Hall, 1952.

[67] ———. "Output in Relation to Input for the Agricultural Industry." *J. Farm Econ.* 40:393-405, May 1958.

[68] ———. "Public Purpose in Agricultural Research and Education." *J. Farm Econ.* 43:566-581, August 1961.

[69] ———. "Welfare Implications of Agricultural Research." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.

[70] Heady, E. O., and L. Auer. "Imputation of Production to Technologies." *J. Farm Econ.* 48:309-322, May 1966.

[71] Heady, E. O., and J. Dillon. *Agricultural Production Functions*. Ames: Iowa State University Press, 1963.

- [72] Herdt, R. W. "Resources Productivity in Indian Agriculture." *Am. J. Agr. Econ.* 53:517-521, August 1971.
- [73] Herdt, R. W., and W. W. Cochrane. "Farm Land Prices and Farm Technological Advance." *J. Farm Econ.* 48:243-263, May 1966.
- [74] Herdt, R. W., and J. W. Mellor. "The Contrasting Response of Rice to Nitrogen: India and the United States." *J. Farm Econ.* 46:150-160, February 1964.
- [75] Hicks, J. *The Theory of Wages*. London: Macmillan, 1932.
- [76] Huffman, W. E. "Decision Making: The Role of Education." *Am. J. Agr. Econ.* 56:85-97, February 1974.
- [77] Intriligator, M. D. "Embodied Technical Change and Productivity in the United States, 1924-1958." *Rev. Econ. Stat.* 47:61-70, February 1965.
- [78] John, M. E. "The Impact of Technology on Rural Values." *J. Farm Econ.* 40:1636-1645, December 1958.
- [79] Johnson, D. G. "Allocation of Agricultural Income." *J. Farm Econ.* 30:724-745, November 1948.
- [80] Johnson, G. L. "A Note on Non-Conventional Inputs and Conventional Production Functions." In *Agriculture in Economic Development*, C. K. Eicher and L. W. Witt, eds. New York: McGraw-Hill, 1964.
- [81] Johnson, R. W. M. "Efficiency Growth in New Zealand Agriculture: A Review." *Economic Record* 48:76-91, March 1972.
- [82] Jorgenson, D. W. "The Embodiment Hypothesis." *J. Pol. Econ.* 74:1-17, February 1966.
- [83] Jorgenson, D. W., and Z. Griliches. "The Explanation of Productivity Change." *Rev. Econ. Studies* 34:249-283, July 1967.
- [84] ———. "Issues in Growth Accounting: A Reply to Edward F. Denison." *Survey of Current Business*, vol. 52, part II, pp. 65-94, May 1972.
- [85] Kaneda, H. "Regional Patterns of Technical Change in U.S. Agriculture, 1950-1963." *J. Farm Econ.* 49:99-212, February 1967.
- [86] Kendall, M. G. "The Geographical Distribution of Crop Productivity." *J. Royal Stat. Soc.* 52:21-48, 1939.
- [87] Kendrick, J. W. "The Gains and Losses from Technological Change." *J. Farm Econ.* 46:1065-1072, December 1964.
- [88] ———. *Productivity Trends in the United States*. National Bureau of Economic Research. Princeton: Princeton University Press, 1961.
- [89] Kennedy, C. "The Character of Improvements and of Technical Progress." *Econ. J.* 72:899-911, December 1962.
- [90] ———. "Harrod on Neutrality." *Econ. J.* 72:249, March 1962.
- [91] ———. "Induced Bias in Innovation and the Theory of Distribution." *Econ. J.* 74:541-547, September 1964.
- [92] Kennedy, C., and A. P. Thirlwall. "Technical Progress: A Survey." *Econ. J.* 82:11-72, March 1972.
- [93] Kislev, Y. "Estimating a Production Function from U.S. Census of Agriculture Data." Unpublished Ph.D. dissertation, University of Chicago, 1965.
- [94] Kislev, Y., and N. Shchori-Bachrach. "The Process of an Innovation Cycle." *Am. J. Agr. Econ.* 55:28-37, February 1973.
- [95] Latimer, R. G. "Some Economic Aspects of Agricultural Research and Education in the United States." Unpublished Ph.D. dissertation, Purdue University, 1964.

538 WILLIS PETERSON AND YUJIRO HAYAMI

- [96] Latimer, R. G., and D. Paarlberg. "Geographic Distribution of Research Costs and Benefits." *J. Farm Econ.* 47:234-241, May 1965.
- [97] Lau, L. J., and P. A. Yotopoulos. "A Test for Relative Efficiency and Application to Indian Agriculture." *Am. Econ. Rev.* 61: 94-109, March 1971.
- [98] Lave, L. B. "Technological Change in U.S. Agriculture: The Aggregation Problem." *J. Farm Econ.* 46:200-217, February 1964.
- [99] Loomis, R. A. "Empirical Estimates of Technological Change in American Agriculture, 1850-1958." *J. Farm Econ.* 44:941-952, November 1962.
- [100] Loomis, R. A., and G. T. Barton. *Productivity of Agriculture, United States, 1870-1958*. USDA Tech. Bul. 1238, 1961.
- [101] Mahlstedte, J. P. "Long-Range Planning at the Iowa Agricultural and Home Economics Experiment Station." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.
- [102] Maier, F. "An Economic Analysis of the Adoption of the Mechanical Cotton Picker." Unpublished Ph.D. dissertation, University of Chicago, 1969.
- [103] Mansfield, E. "Intrafirm Rates of Diffusion of an Innovation." *Rev. Econ. Stat.* 45:348-359, November 1963.
- [104] ———. "Size of Firm, Market Structure, and Innovation." *J. Pol. Econ.* 71: 556-576, December 1963.
- [105] ———. "The Speed of Response of Firms to New Techniques." *Quart. J. Econ.* 77:290-311, May 1963.
- [106] ———. "Technical Change and the Rate of Imitation." *Econometrica* 29: 741-766, October 1961.
- [107] Marschak, J., and W. H. Andrews. "Random Simultaneous Equations and the Theory of Production." *Econometrica* 12:143-205, July/October 1944.
- [108] Marshall, A. *Principles of Economics*. 8th ed. London: Macmillan, 1936.
- [109] Martinez, J. C. "Economics of Technological Change: The Case of Hybrid Corn in Argentina." Unpublished Ph.D. dissertation, Iowa State University, 1972.
- [110] McFadden, D. L. "Cost, Revenue, and Profit Functions." In *The Econometric Approach to Production Theory*, D. L. McFadden, ed. Amsterdam: North Holland, 1972.
- [111] Meyer, J. H. "The California Academic-Responsive Budget System." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.
- [112] Mulleady, T. "Feasibility of Adopting Modern Technology in Corn Production in Argentina." Unpublished Ph.D. dissertation, Iowa State University, 1973.
- [113] Mundlak, Y., and A. Razin. "Aggregation, Index Numbers and the Measurement of Technical Change." *Rev. Econ. Stat.* 51:166-175, May 1969.
- [114] Nadiri, M. I. "Some Approaches to the Theory and Measurement of Total Factor Productivity: A Survey." *J. Econ. Lit.* 8:1137-1177, December 1970.
- [115] Nelson, R. R. "The Simple Economics of Basic Scientific Research." *J. Pol. Econ.* 67:297-306, June 1959.
- [116] Nelson, R. R., and E. S. Phelps. "Investment in Humans, Technological Diffusion, and Economic Growth." *Am. Econ. Rev.* 56:69-75, May 1966.
- [117] Peterson, W. L. "The Allocation of Research, Teaching and Extension Personnel in U.S. Colleges of Agriculture." *Am. J. Agr. Econ.* 51:41-56, February 1969.
- [118] ———. "Return to Poultry Research in the United States." *J. Farm Econ.* 49: 656-669, August 1967.
- [119] ———. "The Returns to Investment in Agricultural Research in the United

States." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.

[120] Puterbaugh, H. L. "An Application of P.P.B. in the Agricultural Research Service." In *Resource Allocation in Agricultural Research*, W. L. Fishel, ed. Minneapolis: University of Minnesota Press, 1971.

[121] Ruttan, V. W. "Agricultural and Nonagricultural Growth in Output per Unit of Input." *J. Farm Econ.* 39:1566-1575, December 1957.

[122] ———. "The Contribution of Technological Progress to Farm Output: 1950-75." *Rev. Econ. Stat.* 38:61-69, February 1956.

[123] ———. "Research on the Economics of Technological Change in American Agriculture." *J. Farm Econ.* 42:735-754, November 1960.

[124] ———. *Technological Progress in the Meat Packing Industry*. USDA Marketing Res. Rep. 59, 1954.

[125] Ruttan, V. W., and T. Stout. "Regional Differences of Technical Change in American Agriculture." *J. Farm Econ.* 42:52-68, February 1960.

[126] Sahota, G. S. *Fertilizer and Economic Development*. New York: Praeger, 1967.

[127] ———. "The Sources of Measured Productivity Growth: United States Fertilizer Mineral Industries, 1936-1960." *Rev. Econ. Stat.* 48:193-204, May 1966.

[128] Salter, W. E. G. *Productivity and Technical Change*. Cambridge: At the University Press, 1960.

[129] Sawada, S. "Technological Change in Japanese Agriculture: A Long-Term Analysis." In *Agriculture and Economic Growth: Japan's Experience*, K. Ohkawa, B. F. Johnston, and H. Kaneda, eds. Tokyo: University of Tokyo Press, 1969.

[130] Schmitz, A., and D. Seckler. "Mechanized Agriculture and Social Welfare: The Case of the Tomato Harvester." *Am. J. Agr. Econ.* 52:569-577, November 1970.

[131] Schmookler, J. *Invention and Economic Growth*. Cambridge: Harvard University Press, 1966.

[132] Schultz, T. W. "Agriculture and the Appreciation of Knowledge." In *A Look to the Future*. W. K. Kellogg Foundation Conference Proceedings. Battle Creek, Michigan, 1956.

[133] ———. "The Declining Economic Importance of Agricultural Land." *Econ. J.* 61:725-740, December 1951.

[134] ———. *Economic Organization of Agriculture*. New York: McGraw-Hill, 1953.

[135] ———. *The Economic Value of Education*. New York: Columbia University Press, 1963.

[136] ———. *Investment in Human Capital*. New York: Free Press, 1971.

[137] ———. "Output-Input Relationships Revisited." *J. Farm Econ.* 40:924-932, November 1958.

[138] ———. "A Policy to Redistribute Losses from Farm Progress." *J. Farm Econ.* 43:554-565, August 1961.

[139] ———. "Public Approaches to Minimize Poverty." In *Poverty amid Affluence*, L. Fishman, ed. New Haven: Yale University Press, 1966.

[140] ———. "Reflections on Poverty within Agriculture." *J. Pol. Econ.* 58:1-15, February 1950.

[141] ———. "Reflections on Agricultural Production, Output and Supply." *J. Farm Econ.* 38:748-762, August 1956.

[142] Schultze, C. L. "The Distribution of Farm Subsidies: Who Gets the Benefits?" Brookings Institution Staff Paper. Washington, D.C., 1971.

540 WILLIS PETERSON AND YUJIRO HAYAMI

- [143] Sidhu, S. S. "Relative Efficiency in Wheat Production in the Indian Punjab." *Am. Econ. Rev.* 64:742-751, September 1974.
- [144] Solow, R. M. "Investment and Technical Progress." In *Mathematical Methods in the Social Sciences*, K. Arrow, S. Karlin, and P. Suppes, eds. Stanford: Stanford University Press, 1959.
- [145] ———. "Technical Change and the Aggregate Production Function." *Rev. Econ. Stat.* 39:312-320, August 1957.
- [146] ———. "Technical Progress, Capital Formation and Economic Growth." *Am. Econ. Rev.* 52:76-86, May 1962.
- [147] Stigler, G. "Economic Problems in Measuring Changes in Productivity." In *Output, Input and Productivity Measurement*, J. W. Kendrick, ed. Princeton: Princeton University Press, 1961.
- [148] ———. *The Theory of Price*. New York: Macmillan, 1952.
- [149] Stout, T., and V. W. Ruttan. "Regional Patterns of Technological Change in American Agriculture." *J. Farm Econ.* 40:196-207, May 1958.
- [150] Tang, A. M. "Research and Education in Japanese Agriculture Development." *Econ. Studies Quart.* 13:27-41, 91-95, February/May 1963.
- [151] Tweeten, L. G. "Distribution of Benefits and Costs of Agricultural Research and Education." *Oklahoma Current Farm Economics* 46:3-7, October 1973.
- [152] Tweeten, L. G., and F. K. Hines. "Contributions of Agricultural Productivity to National Economic Growth." *Agricultural Science Review*, vol. 3, no. 2, Spring 1965.
- [153] United States Department of Agriculture. *State Agricultural Experiment Stations: A History of Research Policy and Procedure*. Misc. Pub. 904, 1962.
- [154] ———. *Changes in Farm Production and Efficiency*. Published annually.
- [155] ———. *An Inventory of Agricultural Research*. Compiled by Science and Education Staff. Washington, D.C., 1970.
- [156] United States Department of Agriculture and Association of State Universities and Land-Grant Colleges. *A National Program of Research for Agriculture*. 1966.
- [157] Ulveling, E. F., and L. B. Fletcher. "A Cobb-Douglas Production Function with Variable Returns to Scale." *Am. J. Agr. Econ.* 52:322-326, May 1970.
- [158] Wallace, T. D., and D. M. Hoover. "Income Effects of Innovation: The Case of Labor in Agriculture." *J. Farm Econ.* 48:325-338, May 1966.
- [159] Welch, F. "The Determinants of the Return to Schooling in Rural Farm Areas, 1959." Unpublished Ph.D. dissertation, University of Chicago, 1966.
- [160] ———. "Education in Production." *J. Pol. Econ.* 78:35-59, January/February 1970.
- [161] Yotopoulos, P. A. "On Efficiency of Resource Utilization in Subsistence Agriculture." *Food Research Institute Studies in Agricultural Economics, Trade, and Development*, vol. 8, no. 2, 1968.
- [162] ———. "From Stock to Flow Capital Inputs for Agricultural Production Functions: A Microanalytic Approach." *J. Farm Econ.* 49:476-491, May 1967.
- [163] Yotopoulos, P. A., and L. J. Lau. "A Test for Relative Economic Efficiency: Some Further Results." *Am. Econ. Rev.* 63:214-223, March 1973.

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