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TECHNICAL CHANGE IN AGRICULTURE

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I. Introduction

The main purpose of this paper is to present the major theoretical and empirical developments in the area of technical change in agriculture over the past 25 years. Although the paper is in large part a literature review, we will 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 hope to present what seems to be areas of agreement or 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 are replaced by more urgent questions.

In order to keep the paper a reasonable length, we must limit our coverage to a certain degree. The paper is concerned mainly with U.S. agriculture. We will not mention empirical studies of technical change in the non-agriculture 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.^{1/}

The plan of the paper is to first present in section II the major theoretical developments relating to the concept of technical change. Here we will draw heavily, although not exclusively, on the general economics literature. Section III will be concerned with the various techniques that have been employed to measure productivity growth. In section IV, attention is turned to identifying the sources of technical change in agriculture. Section V is devoted mainly to a survey of the literature that has attempted to measure the costs and return to agricultural research and extension. Section VI is concerned with the diffusion of technology among farms, among regions, and among countries. In section VII we consider the welfare implications of technical change in agriculture including both its output increasing and distributional effects.

II. The Concept of Technical Change

It seems safe to say that during the past 25 years 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. As one such source, indeed a major source, technical change 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. As a result, 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. As a consequence economists have increasingly turned to technical change as their major "engine of growth."

One should also bear in mind that agriculture was the only sector of the U.S. economy where the official statistical reporting agency collected and published input and output data and total productivity indexes.^{2/} Efforts to sort out and interpret these data, beginning with Griliches' seminal work "Measuring Inputs in Agricultural: A Critical Survey" (48), no doubt contributed to the interest and research in the area of technical change.

1. Technical change defined. 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 (121) definition 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 (119) 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, i.e., $L^\alpha K^\beta$. Conversely, the popular arithmetic productivity indexes such as the Laspeyres and Paasch type indexes imply an underlying linear arithmetic production function. We will have more to say about productivity indexes and production functions in section III.

It is important to recognize that in order to have changes in output per unit of input, or 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.^{3/} 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 (135) argues that the ideal input-output formula is one in which the ratio stays close to one. But Heady (65) 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 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 (133) reply 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 that we ought to know the costs of and returns to producing new technology. Without knowing how much quality improvements in inputs 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 that the mere fact 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 Abramavitz (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, i.e., 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 seems to be two distinct approaches to the analysis of technical change: (a) The "no-quality change approach" and (b) The "explain everything" approach. For example, Denison (31,33) argues that adjusting for input quality changes obscures the changes that productivity indexes are designed to measure. However, if input quality adjustments are made, then Denison argues that 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.

The difference between the "explain-everything" and the "partial-quality-change" approach comes to a head in the Jorgenson-Griliches versus Denison debate of the late 1960's and early 1970's.^{4/} 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 (81) are able to reduce the unexplained portion of total real output growth from 1.60 to .10 percent per year in the U.S. economy. In response to Denison's (34) criticism, mainly in regard to the capital utilization adjustment, Jorgenson and Griliches (80) revise the unexplained portion of output growth upwards 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 fully account for output growth by input quality adjustments, or to measure indexes of total factor productivity and attribute the increase in output per unit input to an increase in knowledge we still face the basic question raised by T. W. 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 will consider attempts to measure the return to this investment later in the paper).

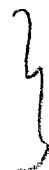
The phenomena of input quality improvements or an increase in knowledge leading to an increase in output per unit of input is commonly referred to either as "technical change" or "technological change". The two terms often are used interchangeably. Schmookler (128), however, preferred to use the term 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 arts would be technological change, whereas a change in actual production techniques would be technical change. In this paper we will be concerned with both phenomena, but in the interest of a brief and simple title we use only the term "technical change."^{5/}

2. 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. Robert Solow (141, 143) 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.^{6/} Solow 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.

To test this 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 percent improvement in capital goods from the previous year. Allowing λ to vary from zero to .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 explained 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) upwards from a 3 percent annual 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 (49) 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 (32) 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 trifle, and other requires much investment. Jorgenson (79), in an attempt to distinguish between embodied and disembodied technical change, argues there is no way of distinguishing between the two if the assumption of a constant exponential rate of technical change is dropped. Solow (143) assumes that embodied technical change takes place at a constant exponential rate.

But why should we be concerned with the embodiment hypothesis? Is it little more than an academic question? Jorgenson (79) 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 criticizes Schultz (131, pp. 119-122) 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. Here Cochrane argues 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 (74), 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 due to "manna 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, herbicides, etc.^{7/}

3. Factor-saving bias.^{8/}

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 (73, pp. 121-122) definition, technical change is neutral if the marginal rate of substitution between inputs is not affected. Non-neutral 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.

Harrod (56, p. 23) defines technical progress as capital saving, neutral, or labor saving according to whether the 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 (86, 88) argues the two are equivalent when technical change only takes place in the sector producing consumer goods.^{9/}

We know that in U. S. 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 (146) argue that technical change in U. S. agriculture has not been neutral because it seems unlikely that the rapid decline in farm employment from 1925-1955 can be accounted for entirely by the increase in the price of labor relative to other inputs.

In regard to the total U. S. 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.^{10/} 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 U.S. and Japanese agriculture since the turn of the century. In the United States there is evidence of a strong fertilizer and machinery using bias during the 1912-1968 period. Technical change appears to be neutral with respect to labor until the 1930's 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 U. S. 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 U. S. agriculture, although after the 1920's fertilizer appears neutral with respect to technical change. Also in contrast to the positive machinery bias in the U. S., Japanese agriculture exhibits an overall negative bias with respect to this input. Technical change is reported to be labor using until 1928 and then is labor saving, while land exhibits an overall negative bias over the 1893-1962 period.

The David-Klundert technique also was applied to Japanese agriculture by Sawada (126); and to New Zealand agriculture by R. W. M. Johnson (78). Sawada reports that technical change in Japanese agriculture was biased towards the land-saving direction for the period before World War II, but the bias for the post-war period turned towards the labor-saving direction. The Johnson study indicates that the bias in technical progress in New Zealand agriculture was always towards labor saving during the 1921-1967 period.

4. Induced Innovation

Although it may be interesting to know whether technical change has progressed in either a capital or 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 (73, pp. 121-122) in 1932, its 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" (73, p. 120). 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 towards using labor in prewar Japanese agriculture in which labor was more abundant (hence cheap) relative to land and capital, whereas it was biased towards 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 for the postwar period due to rapid absorption of labor by expanding industry the direction of technical progress began to bias towards 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, 59, pp. 111-135) also are consistent with the Hicks theory. In addition Binswanger's (11) study comparing U. S. 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, W. E. G. Salter, (125, pp. 43-44) denies that relative factor prices influence the nature of invention. He argues,

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 (87) 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 are essential for a theory of induced innovation.

Hayami and Ruttan (59, p. 55) 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 there has been no theory of induced innovation in 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 influences 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. They argue,

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 (59, p. 57).

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, i.e., 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 the non-directed research of universities and foundations account 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."

5. Economies of scale and scale bias in technical change

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. Also the new technology in buildings, equipment, and machinery has likely contributed to the increase in the optimum size of farms.^{11/}

In economic terms, we might say that technical progress is biased towards 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 towards larger scale probably increased the

marginal productivity of capital relative to that of labor, thereby increasing the capital/labor ratio at the same factor price ratio.

6. 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.^{12/}

Perhaps the most important example of this phenomenon in agriculture is the reduction in the real price of fertilizer (plant nutrients) over the past 20 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 cheaper modes of transportation.^{13/}

III. Measurement of Technical Change

In keeping with the two ways of viewing technical change, mentioned in section II, its magnitude 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 will 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. Secondly we will present alternative regression techniques for measuring technical change. In short this section reviews what Tolley (31) refers to as the "no quality change approach."

1. 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 a 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 technical progress because they include the effects of factor substitution together with the effects of advances in production techniques. 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.^{14/}

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.^{15/} 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 Paasch 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 (142), 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.^{16/} 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 (non-neutral) 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 Paasch formula which uses the end year weights. As Ruttan (120) points out, the former tends to underestimate technical progress while the latter has the affect biasing the measure

of output per unit of inputs upwards. 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 indices and may be recommended on the grounds that it is less vulnerable to systematic bias (see Jorgenson and Griliches (81)). However, on the bases of the Jorgenson-Griliches results, it appears that productivity growth was measured by the ordinary Laspeyres index is not appreciably different than what is obtained with the Divisia index. They report that during the 1945-65 period, conventional inputs account for 52.4 percent of growth in total U.S. output using the Laspeyres index and 54.3 percent using the Divisia index.

Using 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: (a) the economy is operating at the long-run equilibrium under perfect competition, and all factors are rewarded equal to their marginal value productivities, and (b) technical progress is a multiplicative factor of the aggregate production function (implying neutral technical progress). Mundlak and Razin (109) remind us that as a measure of technical change, the productivity index is biased to the extent that these assumptions deviate from reality.

2. Other approaches

Approaches to the conventional measurement of technical change, other than the index approach include:

A. 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 eliminated from the observations.

A major statistical difficulty in the estimation of production and supply parameters in the presence of technical change is specification bias (Griliches (53)). 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 non-experimental data. Originally, Marshak and Andrews (104) 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 sub-groups. In this case unbiased estimates can be obtained for the respective groups, and the difference in the estimated parameters between those sub-groups can be interpreted as an indicator of technical change. This method is admittedly ad hoc, since homogeneous observations are not always available in a 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.^{17/} Should technical progress represent a discrete shift of the production or supply function, covariance analysis or dummy variables may be utilized.

Covariance analysis is effective especially when data are cross-tabulated in two directions, e.g., in terms of both region and time.^{18/} 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. Usefulness of this technique in the measurement of technical change tends to be limited by the availability of adequate data, however.

B. Use of partial production functions

Studies of partial production functions, e.g., fertilizer response curves, by the use of experimental data constitute a well established field of agricultural production economics.^{19/} 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 (68) in which they identify and measure the sources of yield changes in U.S. 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 (72) also demonstrate the usefulness of partial production functions in making interregional comparisons of production parameters in their U.S.-India comparative study.

C. Farrell's index of technical efficiency

Farrell (39) 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 (94) economic efficiency includes both technical and price efficiency. They define the latter 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 (107), Lau and Yotopoulos (94) test for differences in economic efficiency between large and small (less than 10 acre) farms in India, and find that small farms attain a higher level of economic efficiency. In a subsequent study Yotopoulos and Lau (159) extend the technique to separately measure 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.^{20/} Applying the Lau-Yotopoulos model to a sample of Indian wheat farms, Sidhu (140) finds, however, that large and small farms exhibit equal economic efficiency in both the technical and price sense.

IV. 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 will consider the attempts (a) to identify the sources of technical change (productivity growth) in the U. S. agriculture, and (b) to account for the measured productivity growth by the sources identified.

1. Quality changes as the sources of productivity growth

A. Increase in skills of farm people

This topic falls within the broad area of the economics of human resources.^{21/} 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 sub-item under human resources, would carry us far beyond the scope of this paper and its space limitations.^{22/} Our modest objective here is to offer a brief sketch of the work relating specifically to the effect of education and skills of farm people on agricultural output.

The idea that education is an investment in human capital which contributes to output and income of people, of course, is not new. Marshall (105, pp. 560-563) argued that "the most valuable of all capital is that invested in human beings ..." Early in the post-war period,

T. W. Schultz (136) 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 (156).

But we might ask, why should more years of schooling or higher quality schooling increase an individual's output? Nelson and Phelps (113) suggest that "education enhances one's ability to receive, decode and understand information, and that information processing and interpretation is important for performing or learning to perform many jobs." Along this line, Welch (155) offers the hypothesis that the productive value of education has its roots in (a) the worker effect, and (b) 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 pay-off in a traditional agriculture setting characterized by long-run equilibria in the factor and product markets.^{23/} 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 Kislev and Shchori-Bachrach (91) in their study of winter vegetable production technology in Israel. In their study of the "innovation cycle", they found that an innovation is first adopted by the more highly skilled entrepreneurs and then "diffuses" down the skills scale. We will say more about the diffusion of new technology later in the paper.

B. 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 100 years. 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 R & D 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.^{24/} The demand (VMP) for higher quality capital also can be expected to exceed that of less productive capital, resulting in a higher overall market price providing the supply curve of nonhuman capital is upward sloping which we would expect 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 (46) on hedonic price indexes for

automobiles documents the positive relationship between quality components such as automatic transmissions and automobile prices. Fetting (40) also using this technique finds a similar relationship for farm tractors with respect to horsepower and type of engine (gasoline or diesel).

But Griliches (48) 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 and price adjusted) stock of capital on farms.^{25/}

C. 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 an improved nutrient content of commercial fertilizer, new and improved crop varieties, more efficient breeds of livestock and poultry, and new and improved agricultural chemicals, mainly herbicides and insecticides.

D. 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, 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 less infected by insects and disease, and more wholesome dairy products 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. However it is not clear which has changed: product flavor or the consumers' appreciation of flavor because of 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 effect 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.^{26/} 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 (133) reminds us of several additional problems of measuring farm output. A major omission from our commonly used output measures is

"improvements in the farm plant resulting from the farmers' own labor or from other labor and materials on the farm." As Schultz argues, the formulation of home produced farm capital such as land clearance, drainage, fences, buildings, etc. surely was substantial during earlier decades and is still much too important to leave out.

Secondly, no allowance is made for the increased leisure of time of farmers which is in effect a component of farm output. Nor do we take into account the reduction drudgery of farm work. Spending 10 hours in the airconditioned cab of a modern combine is a good deal less physically demanding than 10 hours of pitching bundles in 90 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 10 to 20 years ago.^{27/} 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.^{28/}

Schultz also mentions the depletion of natural resources as a negative adjustment to output. Soil erosion and fertility depletion together with a depletion of forests no doubt were important especially up to the end of World War II. For example, Bray and Watkins (13) argue that corn hybrids depleted the soil more rapidly than the open pollinated varieties. Thus the yield increase of hybrids likely overstated their economic gains. In the decade of the sixties 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.

E. 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 (145, p. 144) points out, this is an indication that large firms are more efficient than small ones, i.e., economies of scale exist. We argued in a previous section that it is extremely difficult to separate pure scale economies, i.e., a more efficient combination of traditional resources, from technical change.^{29/} Nevertheless, we should not neglect the effect of scale economies in U. S. agriculture.

2. Accounting for productivity growth

Now that we have identified what appears to be the major sources of the measured productivity growth, let us next review the attempts to account for the unexplained residual.

A. Input quality adjustment

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 100 horsepower tractor is more tractor than one of 50 horsepower, 100 pounds of 12-12-12 is more fertilizer than 100 pounds of 10-10-10, etc.

The usual assumptions in the construction of a total productivity indexes using quality-adjusted data are: (a) linear homogeneous production functions and (b) competitive equilibrium in the factor markets (Jorgenson and Griliches (81)). Of course, input quality adjustments should be made on the basis of independent information rather than just assigning a larger 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 48, 52, 55).^{30/}

Capital poses a more difficult problem. Ideally we would like to measure its service flow while in reality we usually are provided with information on its depreciated or market value. A good proxy for capital's service flow would be its rental value. The higher the quality of a capital item, i.e., the higher its productivity, the higher would be its rental value in a perfect rental market. Unfortunately, in agriculture the rental market for capital, particularly machines and buildings, is not well developed.

As mentioned previously the current market value of a capital item should reflect its quality or productivity. However, as Griliches (48, 55) 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. As a result, current or market value would seem to seriously underestimate its current annual service flow. An exception would be an increase in capital quality due to an increase in durability or life of the machine. Here market value could increase without necessarily affecting annual service flow.

Griliches (55) 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 (mentioned earlier) which understates the true stock of capital, and the practice of using capital's depreciated value as a proxy for its annual service flow both result in a underestimate of the true service flow of farm capital. As a result 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. In effect this procedure assumes that the annual service flow remains constant over the life of the machine.^{31/}

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 (157) 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. This 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.

B. 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 (a) research, (b) education, and (c) extension,

as activities which produce or transmit knowledge that in turn produce quality improvements in agricultural inputs, or give rise to entirely new inputs.^{32/} 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.^{33/}

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

Griliches appears to be among the first to use 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 (55, 45) and later including both education, and public agricultural research and extension as separate variables (52). Tang's study (147) using 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 (43), Kislev (90), Latimer and Paarlberg (93), Peterson (114), Evenson (37), Yotopoulos (158), Welch (155), and Fishelson (42), for the United States; Herdt (70) for India; Akino and Hayami (3) for Japan; and inter-country comparative studies by Hayami (58) and Hayami and Ruttan (60).

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 percent of plant food in 100 pounds of commercial fertilizer is more likely to be due to technical change and changing price relationships in the fertilizer industry than public research and extension in agriculture. Also a substantial share of total agricultural research and extension is conducted in the private sector.^{34/} Because of a lack of data on this research it may be necessary to adjust inputs affected by this 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 larger area than just the state in question. This expected pervasiveness of research results prompted Latimer and Paarlberg (93) 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.

C. Summary

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 U.S. agriculture. On the basis of his studies (55, 52), he concludes that the "residual" (up to the early 1960's) can be attributed to three major sources, each contributing about one third of the total. These are: input quality change, economies of scale, and investment in research and extension. The latter 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.

V. 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, i.e., unexplained output, is the result of quality improvements in inputs which has 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 (a) to assess the costs and returns to knowledge producing activities in agriculture, and (b) to analyze resource allocation in the production of knowledge.

1. Cost and returns of agricultural research

In order to assess the economic returns to investment in agricultural research, it must be assumed that research is a production activity. Inputs in this activity consist of labor (manhours of scientists and

supporting personnel), capital (laboratories, offices, computers, test plots, etc.) and other intermediate inputs (supplies, fuel, electricity, etc.), 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 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. A helpful analogy is to compare research with oil exploration. For every 10 holes drilled, about 8 are likely to be dry with only 2 yielding a portion of nature's bounty. In research, there is likely to be several projects that turn out to be "dry holes," i.e., yield no new knowledge for every one that is able to add something to what we already know. Of course, the probability will depend 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 the strictly applied to the more "basic" type of research. This does not mean that the expected return is lower for "basic" 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.

A. Value of inputs saved

We must credit T. W. Schultz (131, pp. 119-122) with the first attempt to quantify the benefits of agricultural research and extension. Using

a total productivity index, Schultz calculates 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 1950 output represents the value of inputs saved because of the increase in output per unit of input over the period. Schultz finds that the savings in inputs for 1950 alone, \$9.6 billion, is 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-a-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. On the other hand, Schultz points out that some public expenditure is allocated to activities 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 quality of farm output are reflected in the productivity ratio.

Utilizing Schultz's technique and extending the data up to 1967, Peterson (116) finds that the annual value of inputs saved increases from about \$10 billion in 1950 to nearly \$26 billion in 1967 (constant 1957-1959 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 annual value of inputs saved and 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 1960's to be about double the long run average rate, 42 versus 19 percent.

B. 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 latter technique was first used by Griliches (51) 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 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 bound to the estimated returns (value of consumer surplus) Griliches measures the shift in supply to the left that would occur should hybrid seed disappear, rather than the shift to the right because of the availability of hybrid varieties).

Using a cash-flow technique with annual research costs as outflows and annual value of consumer surplus as inflows, 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' expenditure data includes both private and public research but only that research applying rather directly to hybrid corn. As such it should not be interpreted as including all corn research during the period in question. Also it remains an open question as to how much, if any, of the basic research on hybridization should have been included.^{35/}

Peterson's (114) poultry study 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 in large part 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 to the 743 percent hybrid corn return, we will see shortly that the two figures are not comparable.

Schmitz and Seckler (127) 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. We will discuss the problem of social costs in more detail in section VII.

C. Marginal product of research

As mentioned, several authors including 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: (a) it amounts to a rigorous test of the influence of agricultural research on agricultural output, and (b) 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 rather than an average return.

In general it appears that the marginal returns to investment in agricultural research is substantially larger than the overall average returns. Griliches (52) reports a \$13 marginal product on public agricultural research and extension. Peterson (114) and Evenson (36) 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 returns are forthcoming 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 (36) work reveals that the lag between the research input and the bulk of its output appears to be the range of 6 to 7 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 one dollar of research forthcoming in year $t + 6$ equal to one dollar in year t . (Assuming a 6 year lag). A \$6.50 marginal product (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 6 year lag. Of course, a 53 percent rate of return still is extremely attractive by any standard.

D. 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 time. 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 where 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 on additional investment. Although it may be interesting to know that the average returns 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's (5) estimate 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, while 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).

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

	Average return (percent)	Marginal return (percent)
1. Schultz, inputs saved technique extended to 1967	19	42
2. Griliches, aggregate production function, cross section data	--	53
3. Evenson, linear regression on residuals, time series data	--	48
4. Griliches, hybrid corn study	37	--
5. Peterson, poultry study	18	50

Source: Peterson (116)

2. 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 1960's, we had virtually no information on the actual allocation of agricultural research to say nothing of what the allocation should be. Peterson (115) employs a simple head count to determine the allocation of research, teaching, and extension activities by departments in U. S. colleges of

agriculture from 1930 to 1967. Also in the 1960's a detailed and comprehensive inventory of agricultural research became available from the U. S. Department of Agriculture (149).

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 formula which is based largely on the state's rural and farm population.^{36/} Regarding nonfederal (mainly state) funds, Schultz (130) 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 (66) also argues that appropriations to experiment stations are greatest in the large industrial states and tend to be smaller, the larger is the proportion of state income represented by agriculture.^{37/}

The results of an econometric investigation by Peterson (115) support the Schultz and Heady hypotheses. Moreover, Peterson finds that within experiment stations, certain 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" rather than "what should be."

The report, A National Program of Research for Agriculture (152) 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 91 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' hybrid corn study (51) 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 15 percent, with hybrid corn, Griliches obtains a rate of return to hybrid sorghum research of about one-half that of 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 the state levels are contained in the University of Minnesota symposium report, Resource Allocation in Agricultural Research (see

Meyer (108), Puterbaugh (117), Mahlstedt (98) and Fishel (41)). By and large these efforts deal with the identification of goals along with the collection and summarization of information that may be helpful to 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 (63, 64, 67) and Shultz (129) and more recently by Schmitz and Seckler (127), Ayer and Shuh (6) and Akino and Hayami (2). Also the environmentalists have reminded us of the possible social costs of new technology on farms, mainly chemical inputs. We will consider the welfare aspects of agricultural research and technical change more thoroughly in section VII.

VI. Diffusion of Technology^{38/}

It is evident that society cannot benefit from investment in research unless the results become available and are adopted by producers. Here we review literature on the process of diffusion of agricultural technology. First we review studies on the inter-farm and inter-regional diffusion within the United States, and then we discuss the process of international diffusion.

1. Inter-farm and inter-regional diffusion

The process of diffusion of new technology among farms traditionally has been the domain of rural sociologists (and geographers).^{39/} The main focus of their studies has been on the impact of communication

(or interaction) and socio-cultural resistance to innovation on the pattern of diffusion over time and across space. There has been particular concern with understanding how the different socio-cultural characteristics of adopters create a spectrum ranging from innovators to laggards and the resulting S-shaped diffusion curve. By and large these studies attempt to provide insights 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 (e.g., Mansfield (100, 101, 102, 103)). The study of hybrid corn diffusion by Griliches (47) and the subsequent exchange with sociologists bring out the contrast between the economic and sociological approaches as well as the role of economic and socio-cultural 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. Griliches finds that both the slope and the ceiling in the heart

of the corn belt exceeded those of the marginal corn areas.^{40/} 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 to hybrid corn. Maier's (99) study of the adoption of the mechanical cotton picker also reveals that the rate of acceptance of this machine was closely related to its profitability.

However, Griliches' 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 input is the critical factor explaining the rate of adoption. Havens and Rogers (57) argued that communication or interaction between people is the important factor. In reply Griliches (44, 50) 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, etc., and thus bring it as close to the "sociological" approach as one would want to.

The work of Nelson and Phelps (113), Welch (155), and Kislev and Shchori - Bachrach (91) 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 (59, p. 173) point out, this finding has an important implication for the induced innovation hypothesis. For it supports the idea that developers of hybrid seed, both private seed companies and public research institutions, were 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 insure its competitive position formed the basis for their actions. As Griliches (47, p. 511) 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.

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 transferrable 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 that of potential adopters often are taken as given. However, 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.

2. 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 inter-farm 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 inter-regional 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-state experiment station network, and vigorous competition and entrepreneurship in the farm supply industry. When these conditions are not met, 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 (59, pp. 174-182) distinguish three phases of international technology transfer: (a) material transfer, (b) design transfer, and (c) 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 (blue prints, formula books, etc.). During this period the imports of exotic plant materials and foreign equipment are made in order to obtain new plant breeding materials or to copy equipment designs, rather than for their own use in direct production. New plants and animals are subject to orderly tests and 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 "proto-type" 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 to ease the constraint of the short supply of scientific and technical manpower in the less developed countries.

In support of their three-phase international technology transfer hypotheses, Hayami and Ruttan point to the international diffusion of sugar cane varieties (Evenson, Houck and Ruttan (38) and to the transfer of tractors from the United States to the USSR (Dalrymple (25, 28). Furthermore they argue that the dramatic appearance and diffusion of the higher yielding varieties (HYV) of staple cereals in the tropics since the late 1960's i.e. 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 of 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 temperature zone developed countries" (Hayami and Ruttan (59, pp. 183-184)). In their view this process also represents an institutional innovation: The adaptive research that led to the development of HYV's was primarily conducted at a new set of international agricultural research centers which typically were supported by large U. S. Foundations. They are staffed by international teams of scientists of various agricultural science disciplines and by in-service trainees and coordinated by a common orientation to produce major breakthroughs in yield potentials of certain staple cereals. Establishments of these research-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, (59, pp. 184-185)). They conclude that the success of agricultural development via the international transfer hinges on how to institutionalize the effective supply of adaptive research within the scarce endowment of local research manpower in developing countries.

VII. 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, pollution, and social instability 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.^{41/}

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.

1. 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 argued previously 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 our discussion in section V 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 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.

2. Distribution effects. With respect to the distribution effects of agricultural research we should consider its effects both on the personal and on the 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 (63, 64, 67)), Schultz (129), 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 benefitted some farmers and harmed others. Those farmers whose labor is a complement to new and

improved inputs, mainly the skilled, no doubt have experienced an increase in their VMP and consequently have enjoyed an increase in real incomes. On the other hand, farmers whose labor is a substitute for new inputs, mainly the unskilled, have experienced a declining demand for their services and therefore have suffered a reduction in income.

Day's study (30) of the sharecropper in Mississippi provides an excellent account of the latter case. According to Day's estimates, annual unskilled labor "requirements" in the Mississippi delta declined from 170.2 million man hours in 1940 to 13.7 million in 1957 while the annual skilled labor "requirement" increased from .69 to 1.19 million man hours during this period. Schmitz and Seckler (127) in their study of the mechanical tomato harvester estimate that the 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 VMP and wages of labor retained in agriculture, i.e. the labor to man the cotton pickers, the tomato harvesters, and the like. Studies of the effect of R & D on the total agricultural labor market by Wallace and Hoover (154) and by Bauer (8) reveal that ceteris paribus the demand for all farm labor is increased by agricultural R & D. However, when farm prices are allowed to adjust (decline) as a result of new technology, Bauer finds that a 10 percent increase in "technology" decreases quantity of labor demanded in agriculture by 4.9 percent.

We should also 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 benefitted large, high income farmers to a much greater extent than their small, low income counterparts (Schultz (134) and Schultz (139)). 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.

Indeed Kendrick (85) 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. Also 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. Although this 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 holding the price of food constant.

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 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 towards the biological and chemical spheres could have reduced the wholesale migration of farm people during

the 1950's and 60's.

However, direct public control of agricultural research allocation is limited to the research conducted by agricultural experiment stations and the USDA (about one-half of total agricultural research during those two decades). Moreover, the major share of public agricultural research was already allocated to the biological and to a lesser extent chemical areas, with the major share of mechanical R & D conducted by the private sector. Thus it is not at all clear that even a complete abandonment of mechanical research by 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 in the paper that technical change probably has been biased towards larger 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, one should also consider the affect of increasing nonfarm per capita incomes. As nonfarm earnings increase, farm size (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 contributed to general economic growth and 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 (71) argue that technical change benefits the land owner 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/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 (122) report that labor's share of agricultural income declined between 1946 and 1957. This is in contrast to D. Gale Johnson's (76) previous finding that labor's share had increased slightly from 1910-1914 to 1945-1946. 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 phenomena in part to an increase in current expenses, particularly for fertilizer which serves as a land substitute, thus reducing in importance the native land endowment of each region.

3. 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 from 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 (127)). However in the long run, it is hard to deny that most displaced farmers have been able to increase their real incomes in non-agricultural 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 counter allegations of industry spokesmen

provide little hard evidence to date on the magnitude of this problem. Also it seems necessary to consider the chemical pollution impact of the acreage restriction characteristic of the farm income support programs. Here we would expect that the use of farm chemicals has been stimulated as farmers have searched for land substitutes because of acreage restrictions. Also to the extent that land is a complement to farm labor, one might argue that acreage restrictions have reduced the demand for farm labor and 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 extensive monopoly power. However, the spatial characteristics of agricultural production forces us to dismiss this possibility at least in the foreseeable future.

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Footnotes

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1/

For a survey of the general economics literature on technical change, see Kennedy and Thirlwall (89) and Nadiri (111).

2/

See U. S. Dept. of Agriculture, "Changes in Farm Production and Efficiency," published annually, (150).

3/

Some difficulty arises as to how to treat economies of scale. We will consider this problem in some detail later in this section.

4/

The entire exchange is contained in the Survey of Current Business, May 1972, Vol. 52, Number 5, Part II.

5/

For a number of other commonly used expressions synonymous for technical change see Domar (28).

6/

Salter (125, p. 63) also emphasized the importance of embodied technical change at about this time.

7/

Again let us defer a discussion of economies of scale as a source of the residual until later in this section.

8/

For a more thorough discussion of the neutral and nonneutral characteristics of technical change see Murray Brown (14)

9/

See Amano (4) and Kennedy (86,88) for a recent exchange over this question.

10/

The function they estimated was $V = \left[(E_1 L)^{-e} + (E_k K)^{-e} \right]^{-\frac{1}{e}}$
where V is value added and E_1 and E_k represent levels of efficiency of labor and capital respectively.

11/

Ulveling and Fletcher (153) found evidence of an increase in scale economies on Mexican farms using more capital intensive technologies.

12/

Here we are dealing with price reductions of inputs of a given quality. An increase in the quality of an input more than an increase in its price has the same effect on the supply function. However, we have labeled this latter phenomenon technical change.

13/

See Sahota (123, 124) for an analysis of the sources of cost reductions in the fertilizer industry.

14/

According to Ruttan (119), the total factor productivity approach was originally suggested by Copeland and Martin (23, p. 127). An early empirical study on agriculture is presented by Barton and Cooper (7).

15/

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 both of them are aimed at measuring the same thing. Empirical studies in U. S. agriculture using the arithmetic index have been carried out by Barton and Cooper (7), Kendrick (84, pp. 133-188), Loomis and Barton (97), Ruttan (118, 121), and Schultz (131, pp. 99-124, 135). Those using the geometric index have been carried out by Chandler (18) and Lave (95).

16/

It is interesting to observe that Solow after developing this approach which assumes neutral technical change changes his thinking rather abruptly a few years later when advocating the embodiment hypothesis which implies non-neutral technical change.

17/

Ways in which agricultural production and supply change are characterized in Cassels (17) and Cochrane (20,21).

18/

For example, see Kaneda (82).

19/

See Heady and Dillion (69) for some examples and a comprehensive bibliography of partial production function studies.

20/

The authors acknowledge that a possible explanation for their findings could be an inverse relationship between farm size and soil fertility.

21/

We include the economics of education, health, poverty, migration, discrimination, etc., under the broad heading of human resources.

22/

For a comprehensive review of the literature in this area up to the early 1960's, see T.W. Schultz (138). Also see Schultz (132) for a more recent account.

23/

See D.P. Choudri (14) for further discussion of the role of education in agricultural production.

24/

There is also the possibility of technical change in the capital goods industry which would have the effect of reducing the supply price of capital of a given quality. We discuss this phenomenon in a following paragraph.

25/

This is illustrated by a 56 percent rise in the price of automobiles between 1947-49 and 1958 according to the USDA prices paid Index and a 34 percent increase according to the Consumers Price Index.

26/

This problem, of course, is not unique to agricultural products.

27/

The reduction in drudgery of farm work is mentioned also by John (75).

28/

The increase in leisure time of farm and nonfarm people has the effect of understating current GNP compared to GNP 4 to 5 decades ago.

29/

For a discussion of specifications bias and its effect on measured scale economies, see Griliches (53). Also see Stigler (144) for additional discussion of the problems of measuring scale economies.

30/

Griliches notes that for the U.S. rural farm population the index of education weighted by income is almost proportional to mean school years completed.

31/

The fact that older machines tend to require more maintenance and repairs to provide the same service flow as new equipment should be reflected in an increase in "other inputs" and labor.

32/

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.

33/

A dissenting view is given by Glenn Johnson (77) who argues that management ability should not be included as a factor of production since it already is reflected in the quantities of other inputs used.

34/

Our best guess is that at the present something over one-half of all agriculturally related research in the United States is carried on by private firms.

35/

For example, Richard Nelson (112) argues that George Harrison Shull, a geneticist made the most significant breakthrough in hybrid corn development while working with corn plants on genetic experiments. Such basic research is not included in the Griliches study.

36/

See U.S. Department of Agriculture publication (151, p. 232) for a detailed explanation of the formula.

37/

For additional discussion see Dalrymple (26,27) and Latimer (92).

38/

This section draws heavily on Hayami and Ruttan (59, pp. 169-190).

39/

See Beal and Bohlen (9).

40/

A similar finding is reported by Martinez (106) who applies the Griliches model to the adoption of hybrid corn in Argentina. Also see Mulleady (110) for a comparison of the profitability of various corn production technologies in Argentina.

41/

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 (148) for an attempt to measure the contribution of agricultural productivity and the resulting decline in the farm population to overall economic growth.