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THE CENTER FOR AGRICULTURAL ECONOMIC RESEARCH

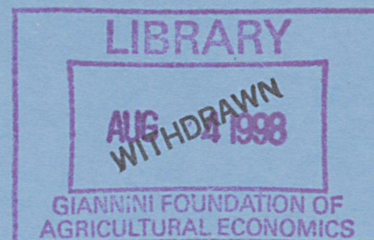
Hebrew University.

Working Paper No. 9807

PRODUCTION AND SUPPLY

by

Yair Mundlak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PRODUCTION AND SUPPLY

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THE CENTER FOR AGRICULTURAL ECONOMIC RESEARCH
P.O. Box 12, Rehovot

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Comments are welcome

PRODUCTION AND SUPPLY

Handbook of Agricultural Economics, Vol 1

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Technology along with the competitive conditions constitute the core of the supply side of the economy. There is hardly a subject in economics that can be discussed with production sitting in the balcony rather than playing center stage. To mention the main favorable subjects in agricultural economics research: product supply, factor demand, technical change, income distribution, the relationships between factor prices and product prices, the competitive position of agriculture, returns to scale, the size distribution of firms, and capital accumulation. The nature of the relationships and the conclusions derived in any particular analysis depends on the order of magnitude of the parameters in question. Hence, whether we want it or not, the empirical analysis of technology and its changes is of cardinal importance, and measurement problems are pertinent even if on the surface it seems that the subject matter is 'not technical'.

In this review, we deal with the various aspects of the analysis. As it will become clear, much of the discussion in the literature is methodology driven, often unaccompanied by substantive applications. In as much as methodological innovations are desirable, the question is how do they help us to think of, or deal with, specific issues of interest. This is a question that the reader should try to answer for himself, depending on his particular interest. To assist in this endeavor, we summarize here the empirical findings that bear on the main parameters of interest and address some important methodological issues pertinent to the interpretation of empirical studies and to future research. In many cases, the empirical results display a wide

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[1] I am indebted to Rita Butzer for comments and for editorial assistance.

range and as such highlight the need for an appropriate framework for their evaluation. The choice of subjects and the discussion are carried out with the purpose of constructing a uniform framework to meet the purpose. This is built on the cumulative experience and contributions provided by numerous studies and on the evolution of the thinking that is so valuable in the reading and the interpretation of the data. To emphasize this aspect, the subjects are introduced largely in an order that highlights this evolution.

There are two fairly distinct periods in the study of agricultural production functions, before and after duality. The change of guards was in the early 1970s, although a few studies employing direct estimation continue also to appear after 1970. The appearance of duality changed not only the method of estimation but also the questions asked to the extent that there is little continuity in the subjects of interest. This can be accounted for by the fact that much of the work is methodology driven rather than as an indication that the old questions had been adequately answered or of any explicit agenda.

PRIMAL ESTIMATES OR THE COBB-DOUGLAS CULTURE

The setting of the agenda

It seems that the empirical work on agricultural production functions originated in a methodological paper by Tintner (1944) and an application by Tintner and Brownlee (1944), which appeared as a short paper in the Notes section of the *Journal of Farm Economics* and was followed by a full size paper by Heady (1944). This work was influenced by the work of Cobb and Douglas (1928).[1] It thus took about fifteen years to adopt the work of Douglas in agricultural economics application.

These studies used data from a random sample of Iowa farms for 1939. The data were classified by area of the state, type, and also size of farm. The inputs included were land, labor, equipment, livestock and feed, and miscellaneous operating expense, a classification that is still valid today. Interestingly, this early work anticipated some of the more difficult subjects in the empirical work of production functions. Management was recognized as an

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[1] A regression equation linear in the logarithms "[is] similar to the production function employed by Paul Douglas in his empirical studies." (Tintner and Brownlee, 1944, p. 567).

input, but "[t]he productive agent management has been excluded since there is no satisfactory index of inputs for this factor." (Tintner and Brownlee, 1944, p. 566). Allusions were also made to the importance of input quality.[2] Heady expressed similar concerns about the quality issue and the omission of management.[3] Also, based on the criticism of the Cobb-Douglas work that appeared at that time by Reder (1943), Bronfenbrenner (1944), and Marshack and Andrews (1944), Heady noted that "[t]he functions which have been derived ... are of the interfirm rather than intrafarm variety. ... it can be expected that a multitude of functions exists ... because the varying combinations of techniques employed and commodities produced." (Heady, 1944, p. 999). This is a recognition of the problems caused by aggregation over techniques. Similarly, Smith (1945) observed that firms in cross section may employ different techniques, particularly due to fixed plants inherited from the past, and the long-run production functions so derived may represent "mongrels" or hybrids. Aside from the question of input quality, Douglas and Bronfenbrenner (1944) raised the point that capital and labor are not on the same footing because labor is a flow ("quantity used"), whereas capital is a stock (represents the "available quantity"). This can be interpreted as an early recognition of the conceptual problem of the evaluation of the productivity of durable inputs.

These studies were concerned with the contribution of inputs to output variations and with a comparison of the factor productivity on different farm types and the relationship to their returns. The estimated production elasticities reported by Tintner and Brownlee (1944) for the sample as a whole are: land 0.34, labor 0.24, and other assets and variable inputs, 0.41. The sum is 0.99. Heady used a larger sample and a somewhat different classification of inputs to obtain for the sample as a whole: land 0.23, labor 0.03, and other assets and variable

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[2] "Using the number of acres in the farms as a measure of inputs of land ignores variations in the quality of land. Measuring inputs of labor in terms of months of labor also ignores variations in the quality and intensity of labor, particularly that of operator and his family." (Ibid).

[3] At the time the issue of management bias was unrecognized, therefore they both speculated that had management been included, the sum of the elasticities, as a measure of returns to scale, would have increased (Tintner and Brownlee, 1944, p. 569; Heady, 1944, p. 995). However, Heady also indicates that the sum of the elasticities might have decreased due to the introduction of management (Op. cit., p. 997).

inputs 0.59. The sum is 0.85.

Several points are of interest. First, these studies were prompted by a methodological innovation introduced by Douglas. Yet, their orientation is applicative in nature, and they address substantive issues related to the efficient use of inputs. Second, sampling from the same data source yields different elasticities. The sum of the elasticities of labor and land vary between 0.58 and 0.25 in the two studies respectively. This difference suggests sensitivity of the estimates to output composition and perhaps differences in the physical environment. Third, the sum of the elasticities is smaller than one.

The approach formulated by the foregoing studies served as a framework for the production function estimation for more than two decades, where attention was focused on the following issues: the contribution of the various factors to the explanation of output variations in the cross section or over time, the production elasticities and their significance, the robustness of the estimates, the role of economies of scale, as judged by the sum of the elasticities, the importance of the quality of inputs, the treatment of management and its relations to the properties of the estimates, the functional forms, and the role of technical change. The data base of these studies varied from observations on individual farms to cross-country comparisons.

The question of efficient use of inputs is the objective of many studies.[4] Lack of robustness of empirical results was raised by Hildebrand (1960) who found that annual cross-section regressions are not robust and any hypothesis can be supported by some results. Lack of robustness is also evident in some other studies that present more than one set of results. Heady and Dillon (1961, Chapter 17) review and summarize 32 studies in various countries based on farm data. The mean elasticities and their coefficient of variation (in parentheses) are: land 0.38 (0.58), labor 0.21 (0.80), and "other services" 0.39 (0.59). In all these studies the sum of all the elasticities is near one. The magnitude of the coefficient of variation indicates a wide spread in the results among the studies. They compare their results with

[4] See for instance, Hopper (1965), Chennareddy (1967), Sahota (1968), and Herdt (1971) for India, Yotopoulos (1967b) for Greece, Huang (1971) for Malaya, andHeadley (1968) for the US.

those obtained in the pioneering cross-country study by Bhattacharjee (1955) and with assumptions made in the literature.[5] All of this indicates an effort to get a definitive substantive solution. But as this target was realized to be elusive, they concluded that "[s]till, the variations shown among the elasticities of Table 17.14 bears witness to the dangers associated with the use of any such global production function." (Heady and Dillon, 1961, p. 633).[6] The discussion is then shifted to the examination of the efficiency of the resource use. For instance, their Table 17.17 presents a ratio of the marginal productivity of labor to its opportunity cost with values varying between 2.84 observed in Taiwan to negative values obtained in dairy farming in Sweden. The median value of this ratio is 0.67. They present similar calculations for land and capital services, but these are more problematic for conceptual reasons which need not be discussed at this point. Table 1 summarizes the results obtained in some country studies.

In 1944 Marschak and Andrews pointed out that the inputs are endogenous, and therefore OLS estimates of the production function are biased. Their paper extended the scope of the analysis by introducing issues related to the statistical properties of the estimates. Their work and Haavelmo's (1947) work on the consumption function were early examples of the problems of simultaneity in economic analysis and thus revived the question that had been asked by Working (1927) about the meaning of statistical demand equations. That opened up a route of work centered on methodological issues with a life of its own.[7]

The simultaneity problem in the estimation of production functions was overcome by the factor share estimator proposed by Klein (1953) and applied by Wolfson (1958). This estimator is based on the assumption that firms always employ *all* their inputs so as to satisfy

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[5] Bhattacharjee (1955, regression 4) reports elasticities of 0.36 and 0.3 for land and labor respectively.

[6] Clark (1973) assembles many results of factor shares in an informal framework but with good international coverage. It is very clear that the estimates depend on the economic environment which is a major theme of our discussion.

[7] The early work on production functions, up to the early 1960s, is surveyed by Walters (1963).

the first order conditions for profit maximization given the *current ex post* prices (italics by YM). As such, the factor share estimator is subject to a major conceptual difficulty in that it can not answer the original question of Cobb and Douglas about the empirical relevance of the competitive conditions because they are imposed in the derivation of the estimator.[8] Although this is seldom explicitly recognized, or acknowledged, all the estimators that use the first order conditions for profit maximization - and to be sure, these include the estimators based on duality as well as nonparametric estimators - use the very same property and as such are subject to the same limitation.

A different line of attack on the simultaneity problem was taken by Mundlak (1961) and Hoch (1962) through the use of covariance analysis.[9] Applying this method to a sample of family farms in Israel gave lower estimates for the elasticities compared to OLS without allowance for firm effect, and their sum declined from roughly one to roughly 0.8. Mundlak (1961) interpreted the difference between one and the sum of the elasticities as the factor share of management.[10] The method was also used to estimate the managerial capacity and its empirical distribution in Mundlak (1964a). Another substantive result of that study is an

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[8] I found the following statement by Clark (1957, fn 8, p. 21) to be interesting: "Douglas told me that when the function was first prepared in the 1920s, he was expecting it to show that wages then actually received by labour were considerably below its true marginal product; and was surprised to find that they were in fact extremely close to the level predicted by the function."

[9] Hoch (1958) examined a solution to the simultaneity problem based on identification through the second moments of the equations disturbances. There is no reference in the literature to an empirical application of this method, perhaps for a good reason because, as indicated by Mundlak and Hoch (1965), it is very sensitive to the specification and in the case of a likely specification error can have an unbounded bias. In another paper, Hoch (1955) suggested the use of covariance analysis. However, the method was not discussed in connection with the simultaneity problem. This is probably the reason that covariance analysis was not mentioned in Hoch (1958) which deals head on with that problem. It is only in Hoch (1962) that the covariance analysis is seen as a solution to the simultaneity problem.

[10] Other sources of farm-specific effects are differences in land quality, micro-climate, and so on. However, the emphasis has been placed on management. The firm effect is observed not only in production functions estimated from farm data; it is also a common phenomenon in cross-section analysis of manufacturing data. Thus, it seems that differences due to farming environment are not the main reason for the firm effects.

elasticity of land near zero. The farms in the sample are very small, and on the surface one would have expected a higher elasticity for land. However, a low elasticity for land is indicative of low profitability of agriculture. This interpretation is supported by the fact that a negligible elasticity for land in Israel was also obtained for a sample of large farms (kibbutzim) in Sadan (1968) so the result is unrelated to farm size.

The observations made so far are:

O.1 The estimates are not robust.

O.2 Often, results show a gap between marginal productivity and real factor prices.

O.3 Specifically, there is a difference between inter and intrafarm estimates.

O.4 Firms use different techniques.

O.5 Input quality is not addressed.

O.6 Should stock and flow variables be treated differently?

O.7 Inputs are endogenous, and therefore OLS estimates are inconsistent.

O.8 It is possible to overcome the problem of inconsistency.

O.9 What is the role and scope of factor-share estimates?

A simple production model

The initial discussion can be conducted in terms of a single-input Cobb-Douglas production function

$$Y = AX^{\beta}e^{m_0 + u_0} \tag{1}$$

where m_0 is the firm effect, or management, a firm-specific factor known to the firm but not to the econometrician (private information), and u_0 is a random term whose value is not known at the time the production decisions are made. The conditional expectation of output, given the input, of firm i is[11]

[11] Note that $E(e^{u_0}) \cong (1 + \sigma_{00}^2/2)$; $\sigma_{00}^2 = E(u_0^2)$. This term is ignored in (2).

$$Y_i^e \equiv E(Y|_{X_i}) \cong AX_i^\beta e^{m_{0i}}. \tag{2}$$

At this stage we assume that the price is known, and the firm chooses the input so as to maximize the expected profit:

$$\max_{X_i} \pi^e(X|_{W,P,i}) = PY_i^e - WX_i \tag{3}$$

where P and W are the product and input prices respectively. The first order condition is met up to the stochastic terms m_1 and u_1

$$\beta AX^{\beta-1} = \frac{W}{P} e^{m_1 + u_1} \tag{4}$$

where m_1 is known to the firm but not to the econometrician, and u_1 is a transitory component. The term m_1 reflects the firm's expectation formation and its utility function. In what follows, we will deal with real prices, so that W is the wage in output units, and P is the product price in input units.

We write equations (2) and (4) in logarithms, with the variables measured as deviations from their overall mean, and introduce time notations:

$$y_{it} - x_{it}\,\beta = m_{0i} + u_{0it} \tag{5}$$

$$y_{it} - x_{it} = w_{it} + m_{1i} + u_{1it} + u_{0it} \tag{6}$$

When prices are exogenous the reduced form for x (note that $p = -w$) is

$$x_{it} = -c(p_{it} + u_{1it} + m_{1i} - m_{0i});\ \ c \equiv (1 - \beta)^{-1}. \tag{7}$$

The four error components are assumed to be IID with the following first two

moments:

$$u_{jit} \sim (0,\ \sigma_{jj});\quad m_{ji} \sim (\mu_j,\ \tau_{jj});\quad j = 0,1 \qquad \textbf{(8)}$$

where $\mu_0 = 0$ and μ_1 is unrestricted. The expected value of all cross products of the error components are zero.[12]

Several of the observations made above are related to the endogeneity of the input. Equation (7) shows that the input is a function of the firm effect, m_{0i}, which is also part of the production function shock, and therefore the input is not exogenous. The bias caused by this dependence contributes to the lack of robustness. Specifically, it contributes to the differences between intra and interfirms estimates (O.3). Also, when biased coefficients are used to test the efficiency of resource use, an erroneous conclusion of an inefficient use of resources (O.2) might be reached even when the firms use resources efficiently, or conversely.

Several approaches are offered to overcome the problem of input endogeneity (O.7). When the sample consists of panel data, covariance analysis transforms the variables to deviations from the firm mean, and thereby the firm effect is eliminated from equation (7). Let the sample average over the time observations be $x_{i.}$, then equation (7) is transformed to

$$x_{it} - x_{i.} = -c(p_{it} - p_{i.} + u_{1it} - u_{1i.}), \qquad (9)$$

and it is seen that the firm effect is disappeared. The estimator is referred to as a within estimator (because it is based on within-firm variations).

An alternative approach is to use the price as an instrumental variable for estimating equation (5). This is basically the dual approach to estimation to be discussed below. This estimator is likely to be less efficient than the covariance estimator because it does not use all the pertinent information (Mundlak, 1996a). This can be seen intuitively from equation (7). The variability of the input in the sample is generated by four components: p_{it}, u_{1it}, m_{1i}, and m_{0i}.

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[12] Shocks that affect all firms generate time effects that can be treated in the same way as the firm effect. The extension to include time effects is straightforward and need not be reviewed here (see Mundlak, 1963).

The last term causes the bias and should be eliminated, whereas the other three terms provide the information for the estimation. Hence, the most efficient procedure would be to use the first three components as instrumental variables. However, this can not be done directly because of the three variables, only p is observed. The within estimator uses the within-firm variations of p and u_1 as instruments, whereas the dual estimator uses as an instrumental variable the total variations of p but does not utilize the information in u_1. The point is that any variability of input, regardless of whether or not it is consistent with the first order condition for profit maximization, generates points on the production function and therefore helps to trace it, or more technically, helps to identify the production function.

The use of price as an instrument is subject to some limitations. If the sample consists of competitive firms, the between variability of the prices should be nil. If the sample consists of market (rather than micro) data, then the prices are not necessarily exogenous and therefore can not be used as instrumental variables. In any case, it is possible to combine the two estimators by using the within-input variable and the price as two instrumental variables. Other possible modifications are suggested in Mundlak (1996a). However all these have not been tried out. The empirical experience is limited to the within and the dual estimators. Some of the results with respect to the within estimator have been reviewed above, whereas the empirical experience with the dual estimator will be discussed below.

The factor-share estimator imposes the first order conditions for profit maximization in which case the factor share is equal to the production elasticity, β, up to a stochastic term. Using equation (6) it is easy to see that this estimator is inconsistent.

An important issue in the empirical investigation is whether the function displays constant returns to scale (CRT). If it does, in the case of the single-input function, β, is equal to one, and there is nothing to estimate. Thus the problem is more pertinent to the more realistic case with more than one input. To see this, assume now that there are k inputs. In this case, the model consists of equation (5) where x and β will be k-vectors and k-equations of the form of (6). Note that the difference of the first-order conditions for any two inputs, say 1 and 2, is free of m_0 and of u_0

$$x_2 - x_1 = w_2 - w_1 + u_2 - u_1 + m_2 - m_1 \tag{10}$$

Therefore, $x_2 - x_1$ can serve as an instrumental variable. Note that this variable contains all the information related to the two inputs. There are k-1 such instruments, and there is a need for one more instrument to complete the estimation of the system. The assumption of CRT is a good candidate. In this case, a Cobb-Douglas function where the variables are divided by one of the inputs is free of simultaneous-equations bias.

Productivity

To understand some of the subsequent literature we turn to another direction of inquiry, that of measuring factor productivity that was taking place at the same time. The most influential work in agriculture was that of T.W. Schultz (1953). He noted that in the period 1910-1950 agricultural production rose by about 75 percent due to a change in inputs and in technology. The change in inputs was instigated by price change, with labor becoming more expensive and therefore replaced by machines.[13] The importance of inputs is measured by their factor shares: "Land and labor are ... very important in farming, with labor representing 46 percent and agricultural land 24 percent of all inputs used in agriculture in 1910-1914." (Op. cit., p. 100).

He then goes on to discuss the aggregation of inputs and to derive a measure of the overall increase in productivity by comparing the relative changes in output and input. He notices that the results are sensitive to the price weights and the period of analysis. The rise in the annual average productivity for the period as a whole with end of period prices is 1.35 percent and with beginning of period prices is 0.8 percent.

Where does the technical change come from? Schultz (p. 110) considered three hypotheses: 1. Discoveries of new techniques are by-products of scientific curiosity and as such are unpredictable. 2. The level of scientific activity reflects cultural and institutional values rather than the value of its fruits, and as such, the development of new techniques is not

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[13] "Although new production techniques have been many and important, substitution among inputs is clearly evident and it is consistent with changes that have occurred in the relative prices of inputs. ... labor has been withdrawn while other, cheaper inputs have been added." (Op. cit., p. 103). "United States agriculture has become increasingly dependent on inputs which are acquired from the nonfarm sector." (Op. cit., p. 104).

induced by market conditions. 3. Science is supported by society because of its potential material contribution.

There is room for all three, but the gold medal is given to the last one. "Therefore, a new technique is simply a particular kind of input and the economies underlying the supply and use are in principle the same as that of any other type of input. We do not wish to imply that every human activity entering into the development of new techniques can be explained wholly by considerations of cost and revenue; our belief simply is that a large part of the modern process of technological research from "pure" science to successful practice can be explained by economic analysis." (Op. cit., p. 110-111). This is the notion of induced innovation. However, "[w]e need also to explain the rate at which farmers adopt new techniques. Clearly, the mere availability of such techniques is no assurance that they will be applied in farming. The process by which farmers take on new techniques, as one would expect, is strongly motivated by economic considerations and yet very little is known about this process." (Op. cit., p. 114). Although uncertainty about the new technique is important, he views the new technique as a new input and suggests that the standard economic analysis be applied in the analysis of its adoption. He also recognizes the importance of credit rationing for agricultural markets. This view of technological change is related to the notion of implementation of technology discussed below.

This discussion by Schultz amplifies themes already mentioned above and puts on the agenda new ones, particularly the use of factor shares to measure the relative importance of inputs, the need to differentiate between the change in productivity due to a change in inputs and the change in technology, that the change in inputs takes place in response to changes in factor prices, and that the changes in the quality of inputs has to be taken into account in measuring factor prices. To sum Schultz's additional observations,

O.10 Part of the change in technology is unpredictable.

O.11 Not all of what is known (in terms of technology) is actually implemented.

These are all key themes for understanding the subsequent work. To assist the

discussion on the measurement of productivity, we write the production function as

$$Y(t) = F[A_1(t)X_1(t),...,A_k(t)X_k(t), t] \tag{11}$$

where the As are factor-augmenting functions or, not independently, quality indexes. Differentiate the function logarithmically, using a generic notation, $d\ln x / dt = \hat{x}$,

$$\begin{aligned} \hat{Y}(t) &= [\omega_1(t)(\hat{A}_1(t) + \hat{X}_1(t)) + \dots + \omega_k(t)(\hat{A}_k(t) + \hat{X}_k(t))] + \tau(t) \\ &= [\text{aggregate input}] + \tau(t) \end{aligned} \tag{12}$$

where the ωs are weights and τ is the relative change in the total factor productivity or the 'residual'. In estimation, the As should be included as variables in the analysis to avoid specification error.

All productivity measures are based on a comparison of changes in aggregate output with changes in aggregate input. The change in the aggregate input should measure changes in quantity and in proper quality, that is changes in quality that take place under constant technology. This is not always the practice, and it requires a clarification. For instance, the work of children in ditch digging is not as productive as that of adults. Therefore, adjusting the labor input by assigning different coefficients by age or gender will give a more meaningful measure of the labor input. Another example is the measure of fertilizers by their nutrient content. But most of the quality adjustments are of a different nature. A good example is the adjustment of the labor input for education where a measure of schooling multiplies the physical labor input to yield quality-adjusted labor input, measured by the total years of schooling. What is the meaning of this adjustment? If the task is digging ditches, education, at best, should not make a difference. Where should education make a difference -- when there are different techniques which vary in productivity and in the scope for education in their implementation. An increase in the level of education, other things equal, is expected to increase the use of more advanced techniques. Thus, in this case technology is not held constant; education is a carrier of a technical change and as such should not be part of the

aggregate input. One implication of this distinction is that the measure of returns to scale should not include the effect of 'quality' variables that represent technology. We will return to this issue below.

The aggregation weights can be based on market values leading to factor shares, as done by Ruttan (1956) and Solow (1957), or by production elasticities derived from empirical production functions. Note that in the case of a Cobb-Douglas production function these elasticities are constant. Otherwise, they vary over the sample as do the factor shares, and the results vary accordingly.

Much of the work on measures of productivity change uses elasticities derived from empirical production functions. Griliches (1963a) deals directly with the effect of input quality on the measurement of productivity and, not independently, on the empirical production function. He argued for the use of the empirical production function to provide the weights for the aggregation of inputs. To this end, he fitted a Cobb-Douglas function to data for the 68 USDA regions in the US in 1949. The emphasis is on the role of education and economies of scale in accounting for productivity changes. He obtained a sum of elasticities of 1.36 from a regression without education and 1.35 with education included. Thus, the education was not the source for the sum of elasticities to exceed 1, which was taken as evidence of economies of scale. This result was incorporated in the analysis of sources of productivity growth, with the assertion that "... changes in output are attributable to changes in the quantities and *qualities* of inputs, and to *economies of scale*, rather than to "technical change"." (Griliches, 1963b, p. 332; italics by YM). "This procedure led to an almost complete accounting for the sources of output growth in the United States agriculture during 1940-60 leaving no "unexplained" residual to be identified with unidentified "Technical changes"." (Op. cit., p. 333). The essence of that discussion is the belief that if the analysis is carried out with care, there should be no unexplained residual left.[14]

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[14] This view was also repeated in Griliches (1964) where the empirical analysis was extended to cover 1954 and 1959. "[I]t is possible to account for all of the observed growth in agricultural output without invoking the unexplained concept of (residual) technical change." (p. 970).

There was some discomfort with the estimates, but, nevertheless, those were preferred to factor shares because, relying on Schultz, the agricultural sector was perceived to be in a continuous disequilibrium.[15] As the empirical results show, education is important, the elasticities differ from factor shares, and the sum of elasticities was larger than 1. Therefore, "[t]hese findings, particularly the last two, if accepted, will account for a substantial fraction of the conventionally measured productivity increases." (Op. cit., p. 336). In passing, one can question the meaning and the usefulness of the concept of equilibrium used to describe agriculture if it is thought to be in a continuous disequilibrium. Basically, it reflects an application of the concept of static equilibrium to a dynamic process. The two are not the same. We shall return to this below.

Aside from the question of the residual, can the above results be taken as indicative of economies of scale? There are two issues to be considered. First, internal economies of scale is a concept related to the cost structure of a firm and can not be measured from regional aggregates. There are many farms of different size, and hence there is nothing in the structure of agriculture that suggests economies of scale. The optimal size depends on the technology used and the level of management of the firm. Changes in technology affect the optimal size, but this change in size is the result of the technical change. Second, there is a statistical aspect. Note that the regressions that produce a sum of elasticities larger than one are strictly cross-section, and hence they are subject to a bias caused by the correlation between the unobserved regional productivity level and the inputs, similar to the management bias in the analysis based on firm data. This view was taken by Kislev (1966) who analyzed data of 3000 US districts for 1949 and 1959. To account for the unobserved regional productivity he introduced regional dummies (68 regions), and as a result the sum of elasticities declined from 1.167 to 1.05. Regional dummies do not capture the management effect, so a management bias is still present in these estimates. Very likely this is the reason that the sum of elasticities is still slightly above 1. Kislev and Peterson (1996) reexamine the evidence on economies of

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[15] In the spirit of positive economics, "[t]he most important test of the estimated production functions is not how well it fits the data it was derived from but rather whether and how well it can "predict" and interpret subsequent behavior." (Op. cit., p. 339).

scale with reference to empirical results of cross-state estimates of Cobb-Douglas functions for the US.[16] The sum of elasticities for each of the years 1978, 1982, and 1987 is 1.3. They do not take it as evidence of increasing returns to scale but rather as an indication of management bias. We return to this subject in the discussion of cross-country studies.

Griliches (1964) also introduces a measure for research and extension as a shifter of the production function, a practice that has been followed in other studies such as the studies based on cross-country data.

The productivity of capital

Durable inputs are entered into the production function and in productivity analysis as stocks. This procedure is sometimes questioned (O.6), and it is suggested that the stock variable should be replaced by a flow that represents the service provided by the stock. This suggestion is based on the assumption that there is a unique variable that represents the service. Unfortunately, this is not the case. By its very nature, a durable input is purchased if the discounted expected returns from this input over its lifetime covers its cost. Thus, the service from this input is the returns over its lifetime, and this is not easily transferable to a service in a given calendar period, say a year. To sharpen the point, note that the service of a combine in the winter, when there is no harvest, is zero. However, the service for the year is positive. In some years the service is greater than in other years, depending on the area harvested and the yield, and these are affected by stochastic variables. Ex post, the value of these variables is not the same as the expected values. However, the actual service in a given year is determined by the *expost* values. How are these determined? In a production function analysis, they are determined from the coefficients of the empirical equation. For instance, the coefficient of capital in a Cobb-Douglas function estimates the 'average' elasticity of capital for the sample. This can be used then to compute the marginal productivity of capital for each sample point. In some years, it may be lower than the rental cost, but this does not mean that

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[16] The respective results for cross-state regressions for 1978, 1982, and 1987 are: land 0.1, 0.11, 0.13; labor 0.27, 0.27, 0.22; machinery 0.23, 0.27, 0.15; fertilizers and chemicals 0.27, 0.21, 0.27; and other 0.43, 0.43, 0.52.

there was too much capital in that year. The apparent overcapacity is there to provide the service in times of higher demand.

Productivity and heterogeneous technology

The foregoing discussion provides sufficient empirical evidence to evaluate the most cardinal question related to production: what is the rate, and also the nature, of technical change? Aspects of this question were addressed in one form or another in almost every empirical study of time-series data. Equation (12) characterizes much of the literature which conveys the idea that there is a unique answer to this question, and if we work hard enough, we will find it or come close to it. Unfortunately, the matter is not that simple.

The available technology is defined as the set of all available techniques, and technical change is a change in this set. An appearance of a new technique implies a change in the available technology. In this sense, the available technology changes continuously; any new scientific publication may represent a change. However, this definition is too broad, and as such its usefulness is limited to serving as a reference point but has no operational value. The available technology contains a subset of techniques which are not implemented and as such are not observed, directly or indirectly. Therefore, there is no metric to measure the stock of the available technology nor its change. Any empirical inference about technical change is based on observations and as such, by definition, is restricted to the implemented, rather than the available, technology. This is the domain of the empirical analysis.

The distinction between the available and implemented technology is not trivial if there is more than one available technique. In this case, the choice of the implemented techniques can affect the calculation of the change in the total factor productivity (TFP). To illustrate the issue, we refer to Figure 1 which presents two production functions describing, say, traditional (f_1) and modern (f_2) techniques. The horizontal axis measures the input ratio, say capital-labor ratio, and correspondingly, the vertical axis measures the average labor productivity. Initially, only the traditional technique is available, and output is at point A with input ratio k_0. The response to the appearance of the modern technique may take various forms depending on the constraints to its implementation and the market conditions. If the sector is a price taker,

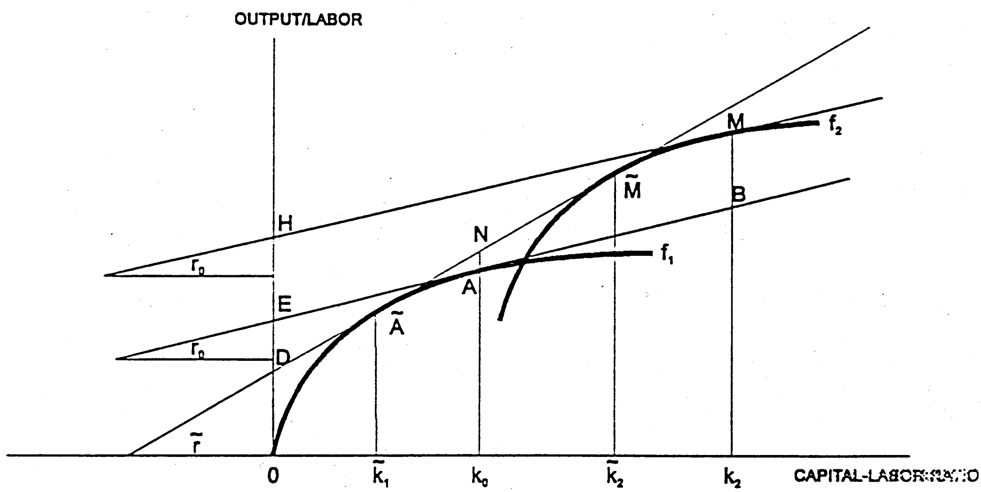

FIGURE 1 RESOURCE CONSTRAINT AND THE CHOICE OF TECHNIQUE

production changes from point A to point M with input ratio of k_2. The total change in output, Y_M/Y_A, is decomposed to the input effect, Y_B/Y_A, and the relative change in the TFP, Y_M/Y_B. The point Y_B is obtained by extending the line tangent to the production function at point A to point B with capital-labor ratio k_0. If the supply of capital is initially perfectly inelastic, the input ratio remains at k_0, and resources are allocated to the two techniques to produce the output given by point N. This movement generates a relative change in TFP of Y_N/Y_A. As more capital becomes available, the movement will be along the tangent line from N to $\tilde{M}$. This movement from point N on is explained exclusively by the input change and thus shows no change in the TFP. Consequently, the resulting TFP is different from that obtained in the case of perfectly elastic factor supply. The discussion abstracts from the question of time needed to travel on each path. Actual calculations are done for data collected for calendar time, say a year. The results will differ with the changes in the pace of the yearly movement. However, when the annual results are integrated, the final outcome will depend on the path followed by the economy. Obviously, the path taken under a resource constraint will give a smaller value to the TFP. In this sense, the difference in empirical calculation of the TFP is path dependent.

The reason for the difference between the two results to the same change in the available technology is related to the change in the factor prices, or marginal productivity. The appearance of a new technique which is both capital intensive and more productive increases the demand for capital. When the capital supply is not perfectly elastic, its price (or its rental rate) will increase so as to internalize all or part, depending on the supply elasticity, of the technical change. Specifically, when capital is fixed, the movement from N to $\tilde{M}$ is fully accounted for by the change in capital availability. Thus, in the first case the contribution of the input is obtained by using the same marginal productivity in the base and new technology, whereas in the second when the two techniques coexist, the marginal productivity of the scarce resource increases and that of the other resource declines. The resulting change of weights absorbs some of the technical change and assigns it to the inputs.

This is a remarkable result. The technical change might be of considerable magnitude and still may escape the measurement. This is the case where the bias of the technical change

is in the direction of a scarce input. This applies not only to physical capital but also to human capital, and specifically to the level of education. It is in this sense that we said before that education is a carrier of technology. The literature discusses the slowdown in productivity changes in the US economy during the 1970s. Such a phenomenon is consistent with the process analyzed above where there is a change in technology but it is not captured by the calculation of productivity. The discussion is also related to adjustments in quality done in the calculation of changes in the TFP. The importance of the quality is an outcome of the technical change, and if it is considered as a contribution of the inputs, it takes away from the TFP. Thus attempts to eliminate the residual technical change by such adjustments grossly underestimate the importance of technical change (see for instance Griliches and Jorgenson, 1966).

The implication of heterogeneous technology for empirical analysis was formulated in Mundlak (1988, 1993). It is outlined in the following section. The approach was applied empirically to time series studies (Mundlak, Cavallo, and Domenech, 1989; Coeymans and Mundlak, 1993). We will now use this framework to interpret the empirical analysis of cross-country data and report results from Mundlak, Larson, and Butzer (1997).

Heterogeneous technology

Let X be the vector of inputs and $F_h(X)$ be the production function associated with the hth technique, where F_h is concave and twice differentiable, and define the available technology, T, as the collection of all possible techniques, $T = \{F_h(X); h=1, \dots, H\}$. Firms choose the implemented techniques subject to their constraints and the environment within which they operate. We distinguish between constrained (K) and unconstrained (V) inputs, X = (V,K), and assume, without a loss of generality, that the constrained inputs have no alternative cost. The optimization problem calls for a choice of the level of inputs to be assigned to technique h so as to maximize profits. To simplify the presentation, we deal with a comparative statics framework and therefore omit a time index for the variables. The Lagrangian equation for this problem is

$$L = \sum_h P_h F_h(V_h, K_h) - \sum_h W V_h - \lambda(\sum_h K_h - K_0), \qquad (13)$$

subject to $F_h(.)\in T$; $V_h \geq 0$; $K_h \geq 0$,

where P_h is the price of the product produced by technique h, W is the price vector of the unconstrained inputs, and K is the available stock of the constrained inputs. The solution is characterized by the Kuhn-Tucker necessary conditions. Let s=(K,P,W,T) be the vector of state variables of this problem and write the solution as: $V_h^*(s)$, $K_h^*(s)$, $\lambda^*(s)$. The optimal inputs V_h^*, K_h^* determine the intensity at which the hth technique is implemented, where zero intensity means no implementation. The optimal output of technique h is $Y_h^* = F_h(V_h^*, K_h^*)$, and the implemented technology (*IT*) is defined by $IT(s) = \{F_h(V_h,K_h); F_h(V_h^*,K_h^*) \neq 0, F_h \in T\}$.

The essence of the analysis is that the implemented technology is endogenous and determined jointly with the level of the unconstrained inputs conditional on the state variables. This result can not be overemphasized, and it is essential for the interpretation of all the empirical results, regardless of specification. Of particular importance is the interpretation of the aggregate production function which expresses the aggregate of outputs, produced by a set of micro production functions, as a function of aggregate inputs. This function is not uniquely defined because the set of micro functions actually implemented, and over which the aggregation is performed, depends on the state variables and as such is endogenous. A change in the state variables causes a change in the implemented technology and in the use of inputs. It is in this sense that the function is endogenous and as such not identified. It can be identified if there are deviations from the first-order conditions. Given such deviations, we get an empirical function as F(X, s). This function has a second degree approximation which looks like a Cobb-Douglas function, but where the elasticities are functions of the state variables and possibly of the inputs:

$$\ln Y = \Gamma(s) + B(s,X)\ln X + u \qquad (14)$$

where Y is the value added per worker, B(s,X) and Γ(s) are the slope and intercept of the

function respectively, and u is a stochastic term. This expression is given below a more descriptive structure which leads to an approach in its estimation which requires the knowledge of factor shares. The factor shares needed for this approach were not available in the cross-country application reviewed below, and therefore we do not go into it.

Variations in the state variables affect $\Gamma(s)$ and $B(s,X)$ directly as well as indirectly through their effect on inputs:

$$\partial \ln Y/\partial s_h = \partial\Gamma(.)/\partial s_h + \ln X[\partial B(.)/\partial s_h] + B(.)[\partial \ln X/\partial s_h]. \qquad (15)$$

The last term shows the output response to a change in inputs under constant technology. The innovation in this formulation lies in the response of the implemented technology to the state variables as shown by the first two terms on the right hand side. The elasticities have a time index, which is suppressed here, indicating that they vary over the sample points. Because the state variables have a large spread across countries, the coefficients of the Cobb-Douglas function are expected to change accordingly. This is the reason for the lack of robustness in the results.

When the available technology consists of more than one technique, a change in the state variables may cause a change in the composition of techniques in addition to a change of inputs used in a given technique. In this case, the empirical function is a mixture of functions and as such may violate the concavity property of a production function. Consequently, the evaluation of empirical results should deal with the role of the state variables in production in addition to that of the inputs (or their prices in the case of dual functions). Some state variables are included in many of the studies without a reference to an explicit theory.

The state variables can be classified to the following groups: constraints, incentives, available technology, physical environment, and the political environment. There is no clear-cut separability between inputs and state variables. For instance, when capital is a constraint, its coefficient in the production function will reflect not only its productivity in a given technique but also its contribution to output through the change in the composition of the implemented techniques. A similar argument applies to the role of prices in the empirical dual

functions. It is conjectured that future progress in the empirical analysis of production will have to deal more explicitly with the role of the state variables within a coherent framework. In this review, we concentrate on the role of inputs and limit our discussion of the state variables to serve this end. As such, it is incomplete but still serves a starting point to stir thinking to the subject.

Cross-country studies

The considerable spread between countries in agricultural productivity, in resource use, and in the economic and physical environment provides an important source of information for testing our understanding of the factors that determine productivity. The cross-country analysis of Bhattacharjee (1955) had no follow up until the revival by Hayami (1969, 1970) and Hayami and Ruttan (1970). This revival added important variables that were missing in the original paper, namely measures of some capital components (livestock and machines) and of education.

The underlying assumption of these studies is that all countries use the same production function. But this assumption lacks empirical support. To get an idea of the prevailing heterogeneity, we can compare the elasticities obtained in the earlier cross-country studies (Table 2) with those obtained from country studies (Table 1). For an order of magnitude, we refer to the values Hayami and Ruttan used in their exercise for sources of growth differences between countries: labor 0.4, land 0.1, livestock 0.25, fertilizers 0.15, machinery 0.1, education 0.4, and research and extension 0.15. As to the sum of elasticities, in their analysis for 1960, the estimates were in the range of 0.95-0.98. The exercise attributes about two thirds of the output differences among countries to input differences and one third to differences in human capital. Subsequent studies updated and extended the analysis.

Nguyen (1979) updated Hayami-Ruttan results by computing regressions for 1970 and 1975. The results are similar to those obtained by Hayami and Ruttan with two exceptions:

the elasticity of machines increased with time,[17] and the elasticity of fertilizers declined and approached zero in 1975. He finds that when education is measured as a sum of primary and secondary education, it is not significant, but secondary education alone is significant. He takes the view that the secondary education has a causal effect on productivity. Alternatively, we can interpret this result as indicative that education is endogenous, and higher productivity increases the demand for education. The adjustment to a changing economic environment is at the margin, and this places the emphasis on secondary education.

Kawagoe and Hayami (1983) and Kawagoe, Hayami, and Ruttan (1985) further update the analysis to include 1980. Like Nguyen they test for a change of coefficients over time and state that the production elasticities of conventional and nonconventional inputs remained largely the same, although some pronounced changes occurred between 1960 and 1980: the elasticity of labor declined from 0.53 to 0.41, machinery increased from 0.04 to 0.12, fertilizer increased from 0.13 to 0.25, and land increased from 0.04 to 0.08. Thus, there is no evidence of land-saving technical change. It is hard to think of fertilizer share as being 0.25, which is also in direct contrast to the results obtained by Nguyen in which the fertilizer elasticities were approaching zero.

Another deviation from the earlier results of Hayami and Ruttan is a sum of elasticities for developing countries of about 1.3, which they take as evidence of increasing returns to scale. This magnitude affects the growth-accounting exercise because, as indicated by equation (12), an increase in the input weights used for calculating TFP increases the contribution of the aggregate input and reduces the TFP. This explains their conclusion that the cross-country differences in output are mainly due to differences in inputs with a very small role for the residual, under 7% and as low as -5.5%. This conclusion on negligible change in the TFP is similar to that reached by Griliches (1964). As we argue below, they both are the outcome of biased coefficients which exaggerates the relative importance of the inputs. This interpretation is supported by the results reported by Kislev and Peterson (1996) who computed the Hayami-Ruttan regressions with country dummies, and the sum of

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[17] Similar results were obtained by Shumway, Talpaz, and Beattie (1979) for the US.

elasticities declined from 1.32 to 1.077, with the latter not significantly different from one.

A search for variables that represent the shift in the productivity level in the context of cross-country studies led Evenson and Kislev (1975) to emphasize research and Antle (1983) to emphasize infrastructure. The problem with this group of variables is that some of them are unobservable, others are measured in some countries and not in others, and finally, because of multicollinearity, regressions do not support all of the variables that are actually used in the analysis.[18]

An implicit questioning of the assumption of uniform technology is detected in the work of Hayami and Ruttan when they divide the countries into two groups, developed and developing. This would imply that the technology changes with the level of development. However, this classification is not sufficiently informative because neither group is homogeneous. To introduce the impact of the level of development, it is more informative to include an income variable in the regression. This procedure opens up the door for extending the analysis to allow for heterogeneous technology. Mundlak and Hellinghausen (1982) removes the assumption that all countries *employ* the same production function. Instead, it is assumed that all countries have *access to the same technology* and they differ in the implementation of the technology, in line with O.11. The variables postulated to affect the choice of technology, referred to as state variables, were resource endowment and the physical environment. The resource constraint consists of physical and human capital. As no information was available on the individual components of this constraint, it is represented in the study by the per capita total output in the country. The results show a great spread in the estimates across countries and over time which is accounted for, in part, by differences in the physical and economic environment.

All these results provide clear evidence for the lack of robustness of the empirical

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[18] As Evenson and Kislev noted, "... with the inclusion of research variable, the fertilizer variable declines in size and significance, the same being true about the schooling coefficient ... These two variables, together with the technical education variable, served in the original Hayami and Ruttan analysis as proxies for human capital and research. These proxies are effectively replaced by genuine research variable ..." (Op. cit., p. 180). A somewhat similar result was obtained by Antle (1983) with an infrastructure variable.

results, which is consistent with O.1. One possible way to stabilize the results is to chose a more flexible functional form than the Cobb-Douglas. The major changes that were introduced were the constant elasticity of substitution (CES) function by Arrow et al. (1961) and the translog function by Christensen, Jorgenson, and Lau (1973).[19] The CES function generalized the Cobb-Douglas function by allowing a constant elasticity of substitution to differ from one. The translog function is an example of a flexible function, a function that allows a second degree approximation to a production function. The few experiments with the CES function in agricultural economics did not prove it to be significantly different from Cobb-Douglas, and therefore it was not widely applied. The situation is different with quadratic functions that have been widely used since the early 1970s, largely in connection with the dual approach, as reviewed below. From the vantage of the present discussion, we note that the main feature of a quadratic production function is to make the marginal productivities, or the production elasticities, depend on the input combination for which these coefficients are calculated. Thus, we can still postulate that all producers (or countries) use the same production function and their production elasticities vary with their choice of inputs.

Alternatively, it is possible that the producers do not use the same production function and the choice of the function is an economic decision. The variability in the state variables that exist in cross-country data offers an opportunity to gain an insight to the determinants of resource productivity. For instance, the available technology, common to all countries, varies over time. On the other hand, capital constraints and the physical environment are country specific. There are three processes which can be studied by decomposing the country-panel

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[19] Hayami (1970) tried several modifications to the cross-country analysis. He found that a Cobb-Douglas function is not rejected when the maintained hypothesis is a CES function and that Nerlove-type distributed lags as well as serial correlation correction as suggested by Griliches gave "implausible results." Heady and Dillon (1961) discuss various functional forms used in agricultural research, including the quadratic function. Fuss, McFadden, and Mundlak (1978) discuss functional forms used in economic analysis. For an interpretation of the literature on the elasticities of substitution at the time and their relationship to functional forms see Mundlak (1968).

data to three orthogonal components to yield the regression:[20]

$$y_{it} - y_{..} = (x_{it} - x_{i.} - x_{.t} + x_{..})w(it) + (x_{.t} - x_{..})b(t) + (x_{i.} - x_{..})b(i) + e_{it} \qquad (16)$$

where y is log output, x is log input (or a vector of inputs), a dot in the subscript indicates an average over the missing index, w(it), b(t), and b(i) are the regression coefficients of the within-country-time (or, simply, within), between-time, and between-country variables respectively.

The between-time process captures the impact of changes over time in the state variables common to all countries such as changes in the available technology (technical change). The between-country process captures the impact of the country-specific variables that take place when the available technology is held constant but other state variables differ across countries and contribute to the differences in the implemented technology. Finally, the within-country-time process represents the effect of changes in the outputs, inputs, and state variables when the available technology and the country-specific environment are held constant and as such comes closest to a production function representing what we refer to as the core technology.

This approach was used by Mundlak, Larson, and Butzer (1997) in the analysis of a sample of 37 countries for the period 1970-1990. The study differs from other studies in that it uses a new series of agricultural capital and in the state variables that were included. This choice of variables limited the sample to countries which had all the required information. We will concentrate here on the coefficients of the conventional inputs. The results are summarized in Table 3 which presents the estimated elasticities for the three regressions where the dependent variable is the log of agricultural GDP.

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[20] Regressions that use time and country dummies provide estimates of w(it), those that use only country dummies provide estimates of matrix-weighted averages of w(it) and b(t), those that use only time dummies provide estimates of matrix-weighted averages of w(it) and b(i), whereas regressions without time or country dummies provide estimates of matrix-weighted averages of all three coefficients in equation (16). It is in this sense that the three sets of coefficients in equation (16) constitute a canonical set.

A striking result is the relative importance of capital. The capital elasticity is 0.37 for the core technology and 0.34 in the between-country regression. This result is quite robust to various modifications of the model and to the disaggregation of capital. On the other hand, the capital elasticity in the between-time regression is 1.03. This represents the response common to all countries in the sample. It indicates that, on average for the sample, an increase in capital was accompanied with a proportional increase in output. This strong response is consistent with the view that physical capital has been a constraint to agricultural growth. This empirical proposition is well illustrated by McGuirk and Mundlak (1991) in the context of the green revolution.

The between-time regression shows that the shift to more productive techniques is associated with a decline in labor. The labor coefficient in the core technology is also relatively low, whereas that of the between-country regression is more in line with the other cross-country studies. The low labor elasticity obtained for the core technology and the between-time regressions is an indication of the labor-saving technical change in agriculture, which is consistent with the slight decline of labor over time. This is not news, but it is emphasized here because it comes out of an integral view of the process which separates between the core technology and the changes that took place over time and between countries. These results highlight the importance of capital in agricultural production, an attribute critical in the understanding of agricultural development and its dependence on the economic environment. This indicates that agricultural technology is cost-capital intensive compared to nonagriculture.[21]

This last conclusion is further reinforced by the magnitude of the land elasticity in the core technology and is at variance with the view that land is not an important factor of production in modern agriculture. This view is based on an incorrect reading of the data where no distinction is made between changes in the technology and the movement along a given production function. The sum of capital and land elasticities is around 0.8 in various formulations, making it clear that agriculture should be more sensitive than nonagriculture to

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[21] We say that a technology is cost-capital intensive with respect to a reference technology if its factor share of capital is larger than that of the reference technology.

changes in the cost of capital and less to that of labor (Mundlak, Cavallo, and Domenech, 1989). This value of the sum is a bit high compared to the literature. It is possible that a different choice of countries and time periods would lead to somewhat different results. However, a sum of 0.8 for land and capital elasticities leaves room for the conclusion on the importance of capital to remain intact.

The introduction of state variables to account for technology, prices, and physical environment resulted in a production function that displays constant returns to scale and thus avoided the pitfalls of previous studies and the misguided conclusions that followed. Using the within elasticities from Table 3 and the median growth rates for the sample, we obtain that aggregate input and total factor productivity residual technical change each accounts for about one half of the total output growth of 3.82 percent per year. This evaluation of the contribution of aggregate input is substantially smaller than the rate reported in the cross-country studies referred to above. These studies use the between-country estimates where the weight of fertilizers is high and that of land is low. The median growth rate of land in the sample was 0.12 percent and that of fertilizers was 3.04. The difference in the elasticities of these two variables accounts for much of the difference in the growth accounting. In addition, the studies that report increasing returns to scale overstate the role of inputs and understate the role of technical change.

The rate of technical change

As indicated above, all measures of technical change refer to changes in the implemented technology and as such report not only on the advances in knowledge but also on its implementation. Direct measures deal mainly with changes in the TFP and not with its bias. The latter is the subject of the studies based on duality to be discussed below. We summarize some results to give orders of magnitude to the changes in the TFP and its importance.

Ball (1985) calculates total factor productivity growth using constructed Tornqvist-Theil indexes of outputs and inputs for US agriculture for the period 1948-1979 based on data adjusted for quality variations. The inputs are labor, capital, and intermediate inputs, such as

energy, agricultural chemicals, feed and seed, and miscellaneous. The result is average annual growth of productivity of 1.75 percent as compared with 1.7 percent obtained from USDA data. Capalbo and Vo (1988) review the evidence on agricultural productivity and their result for 1950-1982 is TFP of 1.57 as compared to 1.95 as obtained by the USDA for the same period.[22] Ball et al. (1997) present the production accounts for the US agriculture for the period 1948-1994 and report growth rates for the period and subperiods, based on Fisher indexes. The average growth rates for the period as a whole are 1.88, -0.07, and 1.94 percent for production (including intermediate products), aggregate input, and TFP. A derived figure from their results for the change in the TFP during 1948-1979 is approximately 1.47 percent, which is lower than the figure reported in Ball (1985). It is important to note that the latter study reports a decline in the aggregate input so that the change in the TFP is larger than the change in production. This is an extreme difference from the studies based on cross-state data for the US which attributes most of the change in output to inputs rather than to productivity. The result obtained by Mundlak, Larson, and Butzer (1997) reported above for 37 countries for the period 1970-1990 show that the average growth in agricultural output (GDP) of 3.82 percent was attributed to aggregate input and TFP in equal shares. This gives a rate of 1.9 percent to TFP.

Jorgenson and Gollop (1992) compare the postwar productivity performance of US agriculture with sectors in the private nonfarm economy using the total price function. Productivity growth explains 82 percent of economic growth in agriculture, but only 13 percent in the private nonfarm economy. The average annual growth rate of TFP growth in agriculture during 1947-1985 was 1.58 percent, nearly four times larger than that of the rest

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[22] The cost shares were:

Year	Labor	equipment & livestock	land & structures	chemicals	energy	other
1960	0.24	0.25	0.16	0.04	0.04	0.26
1980	0.11	0.21	0.41	0.06	0.04	0.17

The average annual growth rates were: output 1.76, labor -1.32, family labor -3.09, equipment 2.04, animal capital 0.38, structures and land 0.1, fertilizer 5.01, pesticides 6.07, energy 1.58, other materials 1.2, and all inputs 0.17.

of the economy.

Rosegrant and Evenson (1992) examine total factor productivity growth and its sources in the crops sector in India, using districts panel data for the period 1956-1987. They first compute TFP and second explain its variations in terms of variables representing investments in research, extension, human capital, and infrastructure. The TFP in the Indian crops sector grew during 1957-1985 at an approximate average annual rate of 1 percent and accounted for about one third of total output growth in that sector. The growth rate for the same period was 0.78 in Bangladesh and 1.07 in Pakistan. Research, extension, domestic and foreign inventions, and adoption of modern varieties show statistically significant, positive impacts on TFP. The effect of the proportion of area irrigated on TFP is slightly negative, indicating that irrigation has no additional effects on productivity except through its contribution to total input levels.

Primal estimates - summary

The centerpiece in the primal estimation is the Cobb-Douglas function. This approach does not impose the competitive conditions but instead submits them to empirical testing. Such testing often shows a difference between the factor shares and the estimated production elasticities. This is not an absolute rejection of the prevalence of the competitive conditions but rather a conditional result, based on the model used and the statistical procedure. Still it is indicative of wide gaps when they exist.

Tables 1 and 2 present selected summary results of the studies reviewed as well as others with a similar message. It is noted that the elasticity of labor never exceeds 0.5, and in most cases it varies in the range of 0.25 to 0.45. This value is well below the elasticity of labor in nonagriculture.[23] Consider all nonlabor income as capital income, the result supports the position that agriculture is cost-capital-intensive and therefore is less susceptible to

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[23] In most studies on agriculture, output is measured as production, which includes raw materials, whereas production analysis in nonagriculture is conducted in terms of value added. Thus an exact comparison calls for applying the same output concept in both sectors. This was done in Mundlak, Cavallo, and Domenech (1989) for Argentina, where it was found that the factor share of labor in agriculture is indeed lower than that in nonagriculture.

increases in the wage rate than nonagriculture. Also, the labor elasticity declines with time, indicating that the technical change was labor saving.

In country studies, the elasticity of land varies between zero in some cases to about one third. We interpret this elasticity to be a measure of the competitive position of agriculture. From the point of view of farm income it is meaningful to look at the sum of labor and land elasticities, and this sum is fluctuating around 0.5.

The sum of elasticities of farm inputs (that is, inputs decided on by the farmer, in contrast to public inputs) is used as a measure of economies of scale. In some studies based on cross-sectional data this sum is larger than one; this was taken by the authors as evidence of increasing returns to scale. We attribute this result to statistical bias.

One justification for estimating production functions is to provide weights for the computation of technical change. However, this approach has not provided any substantive advantage as compared to the use of factor shares, even though they may not be the same as the production elasticities. The reason is that mistakes in specification and interpretation of statistical studies are often greater than the discrepancies between the factor shares and the true production elasticities. An example is the error involved in the finding of increasing returns to scale and its incorporation in the computation of total factor productivity that leads to the elimination of the residual in a comparison of growth over time or productivity differences across countries. It is tempting to speculate that such a procedure was motivated by the belief that all growth can be accounted for and therefore there should be no residual. As we take an opposite view, we do not feel that the loss of explanation involved in the reduction of the sum of elasticities to one causes any loss in insight; on the contrary, it directs our attention to search for an understanding of the process.

An important feature common to many of the studies is lack of robustness of the estimates and their dependence on the variables used and the sample coverage. This finding contributed to a search in three directions: 1. Overcoming the simultaneous-equations bias caused by the endogeneity of the inputs. As we shall see in the next section, dual estimates that were supposed to solve this problem do not produce more robust results. 2. Algebraic form of the production function. Indeed, the Cobb-Douglas function is restrictive, but natural

generalizations enriched, rather than shrank, the set of results. 3. Allowing for the endogeneity of the implemented technology. This approach utilizes the variability to improve our insight of the observed productivity differences over time and across countries.

THE DUALITY CULTURE

Quadratic production functions, by their nature, contain many variables that are correlated, and therefore the estimated parameters suffer from low precision (big confidence regions) to the extent that they often do not make sense. To overcome this problem, the common procedure is to estimate the production function parameters by fitting the factor shares, with or without the constraint of the production function itself. The implicit idea is that the variations observed in the factor shares in the sample can be attributed to differences in input ratios, or said differently, to different locations on the production function. Judging by the trend in the literature, the estimates of such functions, the most popular being the translog function, were not satisfying, and therefore a rescue was sought in the form of profit or cost functions. By this shift, the factor shares become functions of prices rather than of quantities. This shift is somewhat arbitrary in that it is not backed by any justification. We should note that the basic idea of duality is that each point on the production function corresponds uniquely to a vector of price ratios. The converse does not hold in general unless a strong assumption on the nature of the production function is imposed. Once this is imposed, then variations in prices cause, and therefore reflect, variations in quantities. This exhausts their information about technology. Hence, if regressing the shares on quantities was not satisfactory, why should prices do a better job? A plausible possibility is that the price variations cause not only movements along a given production function but also movements across production functions. This possibility is not part of the literature, but it is part of the more general framework of our discussion.

Under duality, the technology is summarized by profit, cost, or revenue functions, referred to as dual functions. The profit function is expressed in terms of factor and product prices, the cost function is expressed in terms of the factor prices and output, and the revenue function is expressed in terms of the product prices and inputs. In time-series analysis, each of

these functions include a measure of changes in technology, usually time trend. Also, the profit or cost functions are allowed to include some fixed inputs and as such are qualified as restricted or short run. Similarly, the revenue or profit functions can be restricted by the inclusion of a constraint on output (that is, a production quota).

Duality theory became a standard subject in economic analysis in the late 1960s.[24] It was adopted for empirical applications with some great hopes, but like with many innovations, the test of time has been less generous. There were several reasons for such hopes. For competitive firms, prices, unlike quantities, are exogenous and therefore when used as explanatory variables do not cause simultaneous-equations bias that is part of life in the primal estimation. This property is indeed valid but with a limited liability. First, it is not automatically applicable to data at the market or industry level. Second, it is unnecessary to estimate a dual function in order to utilize the exogeneity of prices, when this is indeed the case.

More profoundly, the econometric literature was initially motivated by the ease that duality offers to characterize the production structure.[25] Interestingly, this view paves the way to avoid duality rather than to use it. Heuristically speaking, duality means that by following some rules (optimization), one can move from a production function to dual functions (or behavioral functions, namely product supply and factor demand) and return to the original function. Thus knowing the production function, it is possible to move to the behavioral functions and vice versa. This is a simple journey under self-duality when both the technology

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[24] See McFadden (1978, p. 5) and Jorgenson (1986) for a brief review of the history of duality.

[25] "An alternative approach to production theory is to start directly from observed economic data -supplies, demands, prices, costs, and profits. The advantage of such an attack is that the theory can be formulated in terms of causal *economic* relationships that are presumed (underlining by YM) to hold, without intervening constructive steps required on the traditional theory. Because this approach is not bound by computational tractability in the step from production technology to economic observations, the prospect is opened for more satisfactory models of complex production problems." (Fuss and McFadden, 1978, p. vii). Similarly "[d]emand and supply can be generated as explicit functions of relative prices without imposing the arbitrary constraints on production patterns required in the traditional methodology." (Jorgenson, 1986, p. 1843).

and the dual functions have closed-form expressions. Examples are the Cobb-Douglas or the CES functions. The problem arises when self-duality does not exist as is the case with the more complicated functional forms such as the quadratic functions. However, the move to duality in this case shifts the weight from one foot to the other in that it makes the derivation of the behavioral functions direct, but it ignores the fact that questions asked about the production function itself require the exact indirect computations that were to be avoided by moving to the dual functions.

For instance, given the profit, or cost, function, what is the marginal productivity of an input, and how is it affected by the input ratios? The answer to the first question is simple because by construction the competitive conditions are imposed, and therefore the marginal productivity is equal to the real factor price. The dependence of the marginal productivity on the other inputs is a question that has only a complicated answer, except when the function is self-dual. The truth of the matter is that the empirical (econometric) literature on duality does not ask these questions. Thus it appears that duality is just a name, and the property is not fully exploited in the sense that the estimated behavioral functions are not used to answer questions related to relationships between inputs and outputs. However, the progress made in the ease of obtaining numerical solutions makes it possible to move from one system to the other; therefore this should cease to be an important consideration. The choice of whether to estimate a primal or a dual function should then be made on the basis of other criteria, such as statistical precision, and as argued in Mundlak (1996a) the dual approach to the study of the production structure is generally inferior to the direct approach. In this section we review a sample of the empirical work related to agriculture.[26]

The combination of duality and the use of quadratic functions has extended the analysis to cover topics related to the properties of the production structure and comparative statics that with some exceptions,[27] had not been part of the agenda of most studies at the time and thereby extended the area of inquiry. Of particular interest is the attempt to fit production

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[26] The survey by Jorgenson (1986) covers applications in other sectors.

[27] For instance, Mundlak (1964b) uses the second order conditions of optimization to rule out the Cobb-Douglas function as a legitimate multi-product function.

systems that are consistent with the assumptions of comparative statics. But this is done at the cost of ignoring the subjects covered in the eleven observations made above (with the exception of O.7 and O.8).

To fully describe all the properties of comparative statics, the single-output function with m inputs, or the corresponding dual function, should have at least (m+1)(m+2)/2 parameters (Hanoch, 1975). A quadratic function that maintains the symmetry conditions has exactly this many parameters, and as such it is considered flexible in the sense that it can provide a second order approximation to the unknown true production function. But since inputs tend to move together, it is statistically difficult to estimate the function directly with precision, and therefore the procedure has been to fit the factor shares to the data. It is in this respect that such procedures are basically an extension of the factor share estimator.

For the dual functions to describe a production system consistent with comparative statics, they have to maintain some properties that can be tested empirically, the less trivial ones are monotonicity and convexity (or concavity, as the case may be). When the estimation is of factor demand or product supply, the monotonicity imposes signs on the first derivatives of the dual functions, whereas the convexity imposes conditions on the second derivatives of the dual functions, or more to the point on the sign of the Hessian matrix. If these conditions are not met, the system is inconsistent with profit maximization. Besides these regularity properties, the dual form is used to test various hypotheses about the production structure such as separability, homotheticity, and the form of technical change.

A major shortcoming of the approach is the difficulty in achieving the regularity conditions in empirical analysis.[28] Although duality is a micro theory, many of the studies use

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[28] In a survey of studies of US agricultural productivity, based mostly on duality, it was observed that "...empirical results and theoretical consistency are sensitive to model specification. ... Many researchers found the translog to be ill-behaved over portions of the data set, that is, monotonicity and curvature properties hold only locally (Caves and Christensen, 1980). This was also evident in many of the models presented in this chapter. ...not all the econometric models satisfied locally the monotonicity conditions and the curvature conditions." (Capalbo, 1988, p. 184). And in another review: "The review exposed some of the limitations of existing research. For example, it is not clear what should be done with empirical models that violate theoretical properties." (Capalbo and Vo, 1988, p. 124). More recently, "... as most students of the existing

macro data. The studies vary in functional forms used, in the type of function used in the estimation, and in the questions asked. We will try to give the flavor of these studies in a capsule and summarize their results, with an orientation to our needs.

Early application of duality to the study of agricultural production were made by Lau and Yotopoulos (1972) and Yotopoulos, Lau, and Lin (1976). They used a Cobb-Douglas profit function. As Cobb-Douglas is a self-dual function, it was a straightforward matter to obtain from the profit function estimates of the production function elasticities and to compare them with direct estimates of the same parameters. This comparison reveals some substantive differences. However, such a numerical comparison of the dual and the primal estimates had no follow-up and has practically vanished from empirical analysis.

Studies based on cost functions

Define the restricted cost function

$$C(W,K,Y,t) = \min_{V} [WV;\ Y = F(V,K,t)] \tag{17}$$

where V is a vector of unrestricted (variable) inputs with prices denoted by W, K is a vector of constrained inputs which are assumed to have no alternative cost, Y is a vector of outputs, and t is a technology index. By the envelope theorem (Shephard's Lemma)

$$\frac{\partial \ln C(W,K,Y,t)}{\partial \ln W_j} \equiv S_j(W,K,Y,t)\ . \tag{18}$$

Various restrictions are imposed in empirical analysis; most of the studies assume that all inputs are unrestricted, in which case K is not part of the argument. In what follows, to

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empirical literature on agricultural supply response systems know, failure to satisfy convexity in estimated profit functions is not unique to this study." (Chambers and Pope, 1994, p. 110).

This result had been anticipated: "Some expansions, such as the translog function ... can never except in trivial cases satisfy monotonicity or convexity conditions over the entire positive orthant." (Fuss, McFadden, and Mundlak, 1978, p. 234). This reservation is related to the functional form. However, this is not all; the major difficulty comes from the fact that the implemented technology is not constant over the sample.

simplify the notation we will use this assumption unless indicated otherwise. The empirical results depend on the structure imposed on the function. Several properties are of interest:

Homotheticity: $C(W,Y,t) = \phi(Y)C(W,t)$; Hence, $S_j(W,Y,t) = S_j(W,t)$. (19)

Neutral technical change: $C(W,Y,t) = A(t)C(W,Y)$; Hence, $S_j(W,Y,t) = S_j(W,Y)$. (20)

Homotheticity and neutrality: $S_j(W,Y,t) = S_j(W)$. (21)

The cost function is expressed as a quadratic function in the variables or as a monotonic transformation of the variables, most commonly logarithmic, yielding the translog function. The share equations are then linear in the same variables. Unless indicated otherwise, the technology is represented by a time trend. The empirical analysis deals with the estimation of the factor share equation under one of the above restrictions, often not tested empirically. There is no single central issue in these studies; different studies emphasize different topics. The most important ones are related to the behavior of factor shares with respect to changes in factor prices, the trend in the shares (time as an index of technology), and the effect of output when homotheticity is not assumed. Some studies emphasize methodological aspects by testing the properties of the function needed to describe a production system consistent with comparative statics.

Binswanger (1974) estimates a translog homothetic cost function from a cross-states data set for the US for the period 1949-1964. Agriculture is assumed to be a price taker in all inputs, including land. He compares factor demand elasticities (evaluated at the mean) with those derived under the constraint of Cobb-Douglas. Except for land, the elasticities are near one. They are close to the Cobb-Douglas-based elasticities for machinery and fertilizer but much lower for land (-0.34 as compared to -0.85). This result can be attributed to the fact that the model assumes a perfectly elastic supply of land, but this is not the case in reality, and the estimates reflect the data that was generated by a fairly inelastic land supply.

The cross-derivatives of the cost function provide a measure of substitution. It is found that "[t]he best substitutes are land for fertilizer ... It was a surprise ... to find that machinery is better substitute for land than for labor." (Op. cit., p. 384). To explain the

result, note that in general shocks are both land expanding and land augmenting (Mundlak, 1997). Technical change in agriculture caused a decline in the product price and thereby suppressed its expansion effect, so that under the new technology less land was needed to produce the demanded output. The new techniques were more fertilizer-intensive and machine-intensive, resulting in the positive association between machines and fertilizers and the negative association of these two variables with land demand.

The technical change is labor saving and machine using; the labor share declined at the average annual rate of 5.5 percent, and that of machines increased at the rate of 2.5 percent. Regional dummies were significantly different from zero. The inclusion of regional dummies qualifies the estimates as within-region estimates. The fact that they are significantly different from zero indicates differences in regional productivity and that the explanatory variables need not be exogenous.

Ray (1982) uses a translog cost function with two outputs, livestock and crops, in estimating the technology of US agriculture in 1939-1977. He imposes Hicks-neutral technical change and finds decreasing returns to scale for aggregate output and as such the technology is nonhomothetic. The reason for the decreasing returns can be attributed to the fact that not all the inputs are included in the analysis, and as such, the estimates are of a short-run cost function. The average annual rate of the technical change is 1.8 percent. The own demand elasticities are less than 1. The substitution of hired labor for machines is much smaller than that between labor and fertilizers. Also, he finds substitution between labor and fertilizer in contrast to Binswanger (1974) who claims complementarity.

Kako (1978) uses a translog cost function to study rice production in Japan in 1953-1970. Constant returns to scale is imposed, and technical change is measured by time trend with different slopes for three subperiods. The average percentage change in factor use during the period was: labor 2.6, machinery 3.9, fertilizers 4.4, and the rice area did not change. Output grew at the rate of 2.7 percent. The input changes are decomposed to output effect, substitution (or price) effect, and technical change. The technical change was dominating for labor, whereas the output effect dominated the changes in fertilizers and machinery. Thus technical change was largely labor saving but had little effect on the other

inputs. What picture does this finding portray of rice production? If the rice area did not change, it is not clear what changes in output could prompt an increase in machines. Perhaps, part of the answer is related to the calculation of technical change. It is reported that 56 percent of the increase in output is attributed to technical change; thus, indirectly the use of machines is affected by technical change. We can think about these changes in terms of changes in the composition of techniques which became labor saving and machine and fertilizer using. Finally, the fact that land did not change during the period is consistent with the view that land supply is far from being perfectly elastic as implicitly assumed in the formulation. As such, the results are likely to be distorted.

Kuroda (1987) estimates a translog cost function using national averages data for Japan for the period 1952-1982 and concludes that "...the production process of postwar Japanese agriculture was characterized neither by Hicks neutrality nor homotheticity. Biases ... reduced labor relative to other factor inputs ..." (p. 335).

Lopez (1980) used a generalized Leontief cost function to study the structure of production of Canadian agriculture in 1946-1977. The paper emphasizes two subjects, tests for integrability and for homotheticity. A necessary condition for integrability is symmetry of the price coefficients in the derived demand equations. Integrability is not rejected, and it is concluded that there is a production function that can represent Canadian agriculture. The idea is that the cost function can be derived from this production function. This is the idea of duality, but things are not that simple. Below we question the validity of the assumption that market prices used in an analysis of macro data are exogenous and maintain the requirements underlying the derivation of a cost function. If the assumption is violated, the estimated coefficients of the cost function would be biased. Given that the integrability conditions are met, the fitted function may be integrated to an aggregate technology, but this is not the relevant one for Canadian agriculture.[29] By a way of analogy, a negatively sloped line fitted to price-quantity data need not represent a demand, nor supply, function, and it may be a combination of supply and demand functions.

The factor demand equations include output and time trend. The output coefficients

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[29] On this issue see Mundlak and Volcani (1973).

are significantly different from zero, indicating nonhomotheticity. The time coefficients were not significantly different from zero except for labor. This indicates neutral technical change with respect to all inputs except for labor. However, when homotheticity was imposed, the time coefficients became significantly different from zero, and the signs were consistent with factor augmenting technical change. This is another illustration of the tradeoff between the inclusion of output and time trend in the equations. We discuss this finding below. The own-factor-demand elasticities are less than one, cross-elasticities are all positive. Labor is a substitute for all inputs except for land.

Clark and Youngblood (1992) estimate a translog cost function for central Canadian agriculture (Ontario and Quebec) for 1935-1985 using a time-series approach instead of including a time trend as a technical change measure. They concur with Lopez (1980) that technical change is neutral but output is an important variable in the shares of land and fertilizers.

What is the message? [30]

Factor shares have undergone changes over time; particularly, the share of labor declined, that of machinery and purchased inputs increased. How much of these can be attributed to economic factors? The studies reviewed above indicate that some of these changes were associated with changes in factor prices. Still, the major part of the change is attributed to changes in output or reflects the time trend. There is a tradeoff between the role of homotheticity and neutrality of the technical change. When output was included in the equation, it tended to replace the role of the time variable.[31] This result is consistent with the

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[30] Issues related to the choice of the functional form are discussed by Chalfant (1984). He argues that the translog and the Generalized Leontief cost functions are less appropriate for modeling agricultural production since they do not result in negative own-demand elasticities of substitution for all inputs. However, the estimates resulting from the use of the Fourier flexible form also failed to satisfy the negative own elasticities for all of the factors. (p. 119). Lopez (1985a) discusses similar issues for profit functions.

[31] This is also consistent with the conclusion of a survey by Capalbo (1988, p. 184-185): "Nonhomothetic functions performed better than models that maintained neutral technical change or constant returns to scale, or both." Wide variations were obtained in the level and bias of

fact that the new techniques are more productive and use different factor ratios than the old techniques.

Two conceptual limitations to the empirical analysis of cost functions may distort the results. First, the cost function is derived for a price taker agent and as such does not apply to macro data where prices are determined by market supply and demand. The factor demand is derived from the cost function, and therefore it is affected by shocks affecting the cost function. These shocks are thereby translated to the factor prices. In short, factor prices need not be exogenous. This limitation applies to all studies that use market data - rather than firm data - including studies based on profit functions. This is not a trivial point because agriculture can not be assumed to be a price taker in the rural labor and capital markets and definitely not in the land market.

Second, a cost function is derived conditional on output, and this is interpreted erroneously in empirical analysis to mean that output is exogenous. In general, there is no reason to believe that the marginal cost, and therefore output, is independent of shocks to the cost function.[32] This problem is not shared by profit functions.

Studies based on profit functions

The profit function provides a compact form to summarize a multiproduct technology and an efficient way to introduce the properties imposed by theory on this system. This possibility is utilized in the empirical analysis, and thus there is no direct comparison with results obtained from the cost function with a single aggregate output. Also, the profit function facilitates the examination of whether the technology is that of joint production (Chambers and Just, 1989).

The restricted profit function of an individual producer is defined by

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technical change, although all the reported results indicate that the technical change was labor-saving and chemical and equipment-using, whereas the results with respect to land are ambiguous.

[32] An exception in nonagriculture is the interesting study by Nerlove (1963) of the power generating plants where the output is demand driven and as such is exogenous.

$$\pi(P,W,K,T) = \max_{Y,V} (PY - WV\colon Y,X\varepsilon T) \tag{22}$$

where Y is a vector of outputs, X is a vector of J inputs decomposed to variable, V, and fixed, K, components: $X = (V,K)$ with dimensions (J_v,J_k), $J_v + J_k = J$, T is the available technology set, P is the vector of product prices, and W is the vector of factor prices. It can be decomposed to conform to the decomposition of X. However, where ambiguity does not exist, such a decomposition is not made explicit. By the envelope theorem (Hotelling's Lemma) the product demand and factor supply functions are written:

$$Y_i(P,W,K,T) = \frac{\partial\pi}{\partial P_i}, \quad V_j(P,W,K,T) = -\frac{\partial\pi}{\partial W_j} . \tag{23}$$

The equations in (23) can be expressed also as shares. Like the cost function, the profit function is expressed as a quadratic function of a monotonic transformation of the variables. Then, equations (23) become linear in the same variables.

Lopez (1984) estimates a Generalized Leontief profit function for Canadian agriculture, using 1971 cross-section data. The Hessian matrix (the matrix of the second partial derivatives of Y_i and V_j) evaluated at the sample points has mostly the wrong sign, indicating that the profit function is not everywhere convex. The elasticities are generally low, particularly for supply (0.01 for crops and 0.472 for animal products). There is a gap between the variables used in the analysis and those assumed in the theoretical model. The paper suggests that there is sufficient variability across regions for a meaningful analysis, but this variability is in part spurious, reflecting quality variations; thus it is likely that the results reflect data problems.

Antle (1984) uses a single product translog profit function to estimate input demand and output supply functions for US agriculture for 1910-1978. Technical change is represented by time trend and time dummies for subperiods.[33] The findings lead to the acceptance of symmetry, convexity, and structural change in the postwar period and to the

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[33] "Without time dummy variables, very small D-W statistics were obtained, suggesting misspecification." (Op. cit., p. 417).

rejection of homotheticity, parameter stability, and neutral technical change. Also, he finds differences in the direction of the technology bias between the pre and postwar periods.[34] Scale effects are very important postwar and are not important prewar. "It shows that changes in factor use were more a function of technical change and a scale change in the postwar period than in the prewar period. Thus, input use in the postwar period was apparently less price responsive over time than in the prewar period." (p. 418). This conclusion is consistent with the world of heterogeneous technology as discussed above.

The low price elasticities are claimed to be consistent with those reported by Shumway (1983) and by Weaver (1983) and as such are considered to be acceptable. This result is also consistent with many other studies of supply response reporting low supply elasticity. In our discussion of the subject at a later stage, the low elasticity is attributed to inelastic factor supply. Antle also suggests that his results are in line with induced innovations.[35] However, his argumentation indicates that the pace of the technical change was related to the implementation rather than to the pace of changes in the available technology itself.

Shumway and Alexander (1988) fit a system of five outputs and four inputs to US regional data for the period 1951-1982. They had to impose price linear-homogeneity, symmetry, and convexity.[36] It is indicated that the great variability of the results "... clearly document the importance of considering regional differences in predicting the distributional effects of potential changes in economic conditions ..." (p. 160). Technical change was not Hicks-neutral. The own-price-demand elasticities varied from 0 to -1.42, and output elasticities varied from 0.01 to 1.22, with great variations across regions.

Shumway, Saez, and Gottret (1988) estimated a quadratic profit function with five

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[34] "The prewar is biased toward labor and mechanical technology and against land, whereas the postwar technology is biased against labor and toward machinery and chemicals." (Op. cit., p. 420).

[35] "Actual on-farm technology, therefore, lagged behind agricultural research, and estimates of the prewar technology should not be expected to show much evidence of technical change bias toward mechanical or chemical technology." (Antle, 1984, p. 420).

[36] "Convexity of the profit function was not maintained in the model exploration phase." (Op. cit., p. 155).

output groups and four input groups for the US for the period 1951-1982. Land and family labor are fixed; time trend represents technology. Like in the previous study, symmetry, linear homogeneity, and convexity in prices had to be imposed. Estimates were obtained for regional data under the assumption that regional prices are exogenous and for national data where the variable-factor prices were endogenized. The regional estimates are aggregated and compared with the national estimates. The output-supply and input-demand elasticities are low and become even lower when upward-sloping supply curves for the variable inputs were introduced. The low response is attributed to fixity of land and family labor.

Additional support for the proposition that techniques, outputs, and inputs are determined jointly is obtained from the fact that important properties of a production function are not maintained under aggregation over techniques: "A larger number of U.S. parameters are significant when derived from the regional estimates (53%) then when directly estimated (42%)." (Op. cit., p. 334).[37] More important, "[s]ymmetry of price parameters in the system of equations (1) and (2) was not preserved in the national aggregation." (p. 334, footnote 2). The findings also support the proposition that shocks affect land expansion and land augmentation in the same direction: "All five outputs increase as the quantity of real estates services increase. .... All variable inputs are complements to real estates. Half are complements to family labor, and third are complements to other variable inputs." (p. 334).

Huffman and Evenson (1989) fit a normalized quadratic restricted profit function with six outputs and three variable inputs to data for US cash grain farms during 1949-1974. They expand on previous duality-based studies by allowing the shares to depend on agricultural research, extension, and farmers' schooling in addition to time. The partial effect of research is in the direction of fertilizer using and labor and machine saving. As research was machine saving, the observed increased use of machines is attributed to declining prices. There is asymmetry in the explanation of the increased use of machines and the decline in the use of labor. This can be resolved by assuming that the change has been facilitated by a decline in

[37] The standard errors for the aggregated coefficients were obtained under the assumption of independence of the regional estimates and as such are an approximation. National shocks affect all regions, and therefore their coefficients are jointly affected and thereby correlated. This may be the reason for the difference in significance levels.

the cost of machines and that the new machines require less labor than the old machines. This explanation is consistent with the heterogeneous technology framework. The effect of extension was small. The shadow value of private crop research is near zero, but it is high for public research. The own-price elasticities at the sample means are: fertilizer -1.2, fuel -0.72, machinery -0.61, labor -0.51, soybean 1.3, wheat 0.97, and feed grains 0.016.

Bouchet, Orden, and Norton (1989) fit a normalized quadratic profit function to data for French agriculture in 1959-1984. This was a period of strong growth, mainly in cereals, a decline in labor, and an increase in labor cost. The analysis differentiates between short and long-run response. The supply is price responsive, but the elasticities are below one. "However, the response to price changes are estimated to be inelastic even in the long run when usage of quasi-fixed capital and family labor have fully adjusted to optimal levels." (Op. cit., p. 292). The estimates of the long-run response are obtained under the implicit assumption of perfectly elastic supply of quasi-fixed inputs. When in reality the supply functions were not perfectly elastic, the estimated responses are biased downward.

The findings show that both family labor and capital have a strong positive effect on the supply of cereals, milk, and animal products. This result raises two puzzles. First, cereals is not a labor-intensive product, and therefore it is not obvious why it should have a strong positive response to changes in family labor. Second, one would expect an opposite effect of labor and capital. This similarity of effects can be explained by a strong expansion effect that dominates the substitution effect. The expansion effect is prompted by the technical change that accounts for the observed growth. Putting it all together, the observed changes can be accounted for in terms of changes in the composition of techniques.

Ball et al. (1993) use restricted and unrestricted profit functions to evaluate the consequences of the Common Agricultural Policy (CAP). The main empirical result is that the response elasticities are low but in line with values that appear in the literature using other functional forms and less demanding models. Land and labor are taken as fixed in the evaluation, and this is the reason for obtaining low response elasticities.

Dual estimates - summary

In summarizing the foregoing findings it has to be kept in mind that the reviewed studies are mostly for the US, Canada, and Japan so the numerical values may not be fully representative. However, the main developments in the agriculture of these countries are shared by other countries. The postwar period is characterized by a strong technical change in agriculture, both in the level and in the direction of factor use. Yields increased together with improved varieties and the use of chemicals, while labor was replaced by machines. As such, the results have broad implications, and they facilitate the drawing of important methodological conclusions.

What distinguishes the dual approach from the primal is the appearance of prices in the empirical equation. Hence, in evaluating the performance of this approach we address the following questions:

- What has been the contribution of prices to the empirical equation?
- What additional information is obtained from the dual equations, and how can they be interpreted?
- Are the underlying assumptions of duality met?
- What are the statistical benefits of this approach?
- Where do we go from here?

The dual estimates are obtained by regressing factor shares on prices, time trend, and sometimes output. When the change in the use of inputs is decomposed to price, trend (a proxy for technology), and output effects, it is found that trend and output capture most of the changes, whereas the role of prices is the least important. Thus the contribution of prices to the explanation of inputs or output variations is rather limited.

The price elasticities of factor demand and product supply are usually obtained under the assumption that producers are price takers in the product and factor markets. On the whole, the own-price elasticities are less than one. There is no uniformity in the signs of the cross elasticities, but in general, most inputs appear to be substitutes. The strength of the own and cross elasticities reflect in part the fact that in reality factors' supply are not perfectly

elastic as the models assume, and therefore the results need not represent the demand-driven substitution as it is thought. This is the case with respect to elasticities related to labor, land, and capital. We further elaborate on this subject below.

With respect to other findings, interestingly, on the whole the studies based on duality do not show increasing returns to scale. Technical change, obtained by including a time trend in regressions of factor shares, is largely labor saving, capital using, and fertilizer using, with the results on land being somewhat ambiguous. This is reflective of the data, which means that whatever was the effect of prices, it was not sufficient to change conclusions that could be drawn from the raw data. This does not give a strong mark to the analysis in that the results are obvious without it.

Duality between technology and prices holds under well-defined conditions that can be tested empirically. In most studies these underlying conditions are not fully met; particularly the concavity of the cost function or the convexity of the profit function is violated. Therefore, the estimated technology is inconsistent with the basic premises of the model. In a way, this is the most disappointing result because duality theory is a very powerful theory, and the question is why it does not come through in the empirical analysis. There may be more than one reason, but probably the most important one is related to the changes in technology.

One of the expected virtues of duality has been related to its solution of the simultaneous-equations bias realized in some primal estimators. However, as shown above, in general dual estimators are inferior to primal estimators. Where do we go from here? We return to this at the end of the chapter.

SUPPLY ANALYSIS[38]

Background

Analytically, the supply function is the partial derivative of the profit function with respect to the product price. As we have seen above, it is one of the functions estimated in using duality to characterize the production structure. However, it has been considered as an entity by itself. The reason can be attributed to substance and history. The interest in supply analysis in agriculture had begun long before the work on the production function in agriculture and completely disconnected from it. From its very beginning, supply response analysis was very much concerned with policy issues rather than with the application or development of formal econometric analysis. This is revealed by the titles of some of the early work: "The Farmers' Response to Price" (Bean, 1929), "The Nature of Statistical Supply Curves" (Cassels, 1933), "Can Price Allocate Resources in American Agriculture?" (Brewster and Parsons, 1938), "The Maintenance of Agricultural Production During the Depression: The Explanations Reviewed" (Galbraith and Black, 1938). Some of this discussion was motivated by the fact that agricultural production did not contract during the Big Depression of the thirties when prices of agricultural products declined substantially. The explanation to this was provided by D. Gale Johnson (1950) by indicating that not only product prices decreased in the depression, factor prices decreased as well. This brings in the cyclical behavior of agriculture.

The central theme, the role of prices in determining output, has not changed much since. However, there are additional aspects high on the public agenda which are related to the ability to increase food supply to meet the growing demand. While the role of prices is related to the behavior under given supply conditions, the growth aspect is related to the shift in these conditions. This is a neat classification, which unfortunately does not apply to the data. Observations are determined by all the forces that affect supply, and it is therefore for the empirical analysis to sort out the role of the various factors.

Empirical supply functions regress output on prices and other variables with the purpose of extracting the output response to price. Most of the studies used aggregate time-

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[38] In part, the discussion is based on Mundlak (1996b).

series data, but there were some exceptions (Mundlak, 1964a). On the whole, these studies were formulated within a static framework. As price signals do not come out strong and loud in such studies, salvage is sought in using an appropriate price expectation and in a search for variables other than prices to be included in the equation.

The shift of attention to dynamic considerations gained impetus with the introduction of distributed lags to the supply analysis by Nerlove (1956, 1958). Two basic ideas are behind the formulation: adaptive expectations and partial adjustment. They both have a common idea, a gradual adjustment in response. This is applied to expectation formation whenever a gap exists between the expected and the actual values. Similarly, it is applied to the closure of the gap between the actual output and the long-run desired output. The basic empirical equation that emerges has the form of

$$y_t = bp_t + cy_{t-1} + u_t \tag{24}$$

where b and b/(1-c) are the coefficients of short and long-run supply response respectively. This formulation gave a neat and simple format for supply analysis and was therefore widely adapted. A summary of many studies using this framework is provided by Askari and Cummings (1976).

This efficient form for connecting the price response and the length of run has not provided the necessary insight into the structure of agricultural production, nor of the origin and the nature of its dynamics (Mundlak 1966, 1967). In what follows we concentrate on approaches that attempt to overcome this limitation. As a background, we summarize the main empirical findings of supply analysis reported in the literature:

O.12. The short run supply elasticity, when estimated directly, falls in the range of 0.1-0.3.

O.13. The estimated elasticities decrease with the level of aggregation. Higher values are obtained for the elasticities of individual products than for the aggregate output.

O.14. Indirect estimation of the supply elasticity, obtained through the estimation of factor demand, resulted in larger values than those obtained by direct estimation.

O.15. In the empirical analysis it was observed that adding a lagged output to a supply equation which relates output to price increases the quality of the fit and often eliminates the existing serial correlation. When measures of capital, or of fixed inputs, are added to the equation, the statistical relevance of the lagged dependent variable is reduced or vanishes. A similar result is obtained when a trend variable is added.

O.16. When the sample was divided to subperiods according to the direction of the price changes, it was found that

(a) The supply elasticity was higher for a period of increasing prices.

(b) When capital is included in the supply function, its coefficient was positive for periods of increasing prices and zero for periods of decreasing prices.

(c) When a distributed lag was used, the rate of adjustment was higher for a period of increasing prices.

O.17. The dependence of the value of the supply elasticity on the length of run reflects a constrained optimization. The severity of the constraints vanishes with time. This view leads to a formulation of a well-defined structure.

The work with duality reviewed above supplements the observations O.12 and O.13 and shows in general higher elasticities for factor demand than for the product supply which is the foundation for O.14.

Static analysis

The starting point of the analysis are the behavioral functions in equation (23) above. The strength of the response of output and inputs to changes in prices depends on the relative importance of the restricted inputs. The unrestricted case when all inputs are variables is referred to as the long run and is represented by the following behavioral functions:

$$Y^*(P,W,T),\ V^*(P,W,T),\ K^*(P,W,T). \quad (25)$$

case, the response is given by equations (23), and as such, the empirical analysis of (23) produces a restricted or short-run response. The relationships between the restricted supply and the unrestricted supply is given by the identity

$$Y(P,W,K^*,T) \equiv Y^*(P,W,T). \tag{26}$$

By differentiation,

$$\epsilon^u_{ii} = \epsilon^r_{ii} + \sum_i \beta^*_{ik} \epsilon_{ki} \tag{27}$$

where $\epsilon_{ii} = \partial \ln Y_i / \partial \ln P_i$, ϵ^u_{ii} and ϵ^r_{ii} are the unrestricted (long-run) and restricted (short-run) elasticities, respectively, $\beta^*_{ij} = \partial \ln Y_i / \partial \ln K^*_j$ is the production elasticity of K_j, the jth component of K, in the production of the ith product, and $\epsilon_{ki} = \partial \ln K^*_j / \partial \ln P_i$ is the demand elasticity of K_j with respect to P_i. Thus, the long-run elasticity is the sum of the short-run elasticities and of the indirect price effect which measures the price effect on the investment in the restricted factors. The relationships in (27) are obtained under the identity in (26), and as such they are restricted to the long-run equilibrium. The demand for capital and the incorporation of nonequilibrium values in the analysis are discussed below.

It is obvious that the estimation of equations (27) require an elaborate statistical analysis, and we have already seen that it is difficult to get robust results. There is however a simple way to approximate meaningfully the supply elasticity. As shown in Mundlak (1996b), given the competitive conditions for the unrestricted inputs, the supply elasticity for a price-taker agent is approximately

$$\epsilon = \frac{\Sigma_v S_v}{1 - \Sigma_v S_v} \tag{28}$$

where S_v is the factor share of the vth variable input. The sum is taken over all the unrestricted inputs; it is an estimate of the scale elasticity of the 'short-run' production function, namely, the part of the function that expresses the output as a function of the

unrestricted inputs conditional on the restricted ones. The scale elasticity need not be constant everywhere, as the approximation is defined locally, and as such it depends on the classification of inputs to V and K. What is important for the present discussion is that it can be evaluated in general as the sum of the factor shares of the variable inputs. This framework facilitates the derivation of orders of magnitude of the short-run supply elasticity by using empirical evidence on the elasticities of the agricultural production functions. This can be done at various levels of aggregation. To illustrate, consider the aggregate supply under the simplifying assumption that locally, the factor supply functions facing the industry are perfectly elastic and that there is no redistribution of the restricted factors among the firms in response to price variations in the short run. We assume that land, capital, and often labor are fixed in the short run. These inputs account for approximately 0.8 to 0.9 of total output, implying that the supply elasticity is between 0.11 and 0.25. The lower value is in line with the empirical results as summarized above.

The division between variable and restricted inputs is to some extent arbitrary. Such a dichotomy implies a zero supply elasticity for the restricted inputs and infinite elasticity for the variable inputs. This dichotomy is often assumed in many of the empirical analyses using derivatives of the profit function. It may hold true for the individual firm but not for the industry as a whole. Taking these considerations into account, the analysis is generalized by introducing the factor supply functions. The smaller are the factor supply elasticities, the smaller is the product supply elasticity (Brandow, 1962, and Floyd, 1965). Extended analytic results are given in Mundlak (1996b). For instance, for a production function homogeneous of degree $\mu \leq 1$ in the unrestricted inputs, the supply elasticity is

$$\epsilon = \mu[(1 - \mu) + \Sigma(\alpha_v/s_v)]^{-1} \tag{29}$$

where $s_v \neq 0$ is the supply elasticity of the vth input, and α_v is the factor share in the total cost of the variable inputs. Equation (29) generalizes equation (28) in that when the factor supply functions are perfectly elastic for all factors, that is, $s_v = \infty$, the two equations

become identical. For a linear homogeneous production function, $\mu = 1$, and equation (29) reduces to $\epsilon = (\Sigma \alpha_v/s_v)^{-1}$ which is a finite number. Thus, a constant returns to scale aggregate production function is compatible with a finite supply function because the sector is not a price taker in some inputs.

This expression of the supply elasticity in terms of the factor shares provides the insight for the inverse relationship between the length of run and the size of the supply elasticity. The shorter the run, the more restrictions there are on factor adjustment, and therefore, the smaller is the supply elasticity. Restrictions on the overall factor supply, such as farm land, do not apply to the allocation of the factor to alternative crops. For this reason, the lower is the level of aggregation of the analysis, the larger is the supply elasticity (O.13).

Turning to the relationship between factor demand and the supply elasticities (O.14), we note that the price effect on input demand contains substitution and expansion effects. Of these, only the expansion effect contributes to the supply because the substitution effect of all the inputs cancels out. Technically, this is the meaning of the singularity of the Slutsky, or Hessian, matrix. This explains the findings in Griliches (1959) and subsequent work where the indirect supply elasticity obtained by using the factor demand elasticities gave larger values than those obtained by direct estimation of the supply function; simply, the substitution effect was not eliminated. The same holds for the estimation of the behavioral functions using the duality framework.

Dynamics

The system of equations in (23) and (25) constitutes a recursive structure that determines the time paths of outputs and inputs. The long-run values of K are expressed by (25), whereas the short-run values of V and Y are determined by (23) conditional on K and prices. This analysis is now extended to take account of the fact that K affects output and cost in more than one period.

The firm's problem

It is postulated that the competitive firm chooses inputs that affect the flow of present and future profits with the objective of maximizing its expected present value. We consider here a simple case where a single output, Y, is produced with a durable input, capital, K, and a nondurable, or variable, input, V, that can be hired at the ongoing wage rate, W(t), using a concave and twice differentiable production function, $Y = F(K,V,\tau)$, where τ represents technology. The various variables are functions of time, and the income flow at time t is $R_t = F(K_t, V_t, \tau_t) - c(I_t) - W_tL_t - q_tI_t$. Income and factor prices are measured in units of output, q and W are the real price of the investment good (I) and of the variable input, respectively, and c(I) is the real cost of adjustment (Lucas, 1967; Gould, 1968; Treadway, 1969). The underlying idea behind the adjustment cost is that the marginal cost of investment increases as a function of the investment rate, and hence if the firm acts too fast this cost will be excessively high. The function is convex in I (or in the ratio I/K). Let r be the interest rate, $\beta=(1+r)^{-1}$ is the discount factor; the optimization problem calls for selecting the time path of inputs $\{V_j, K_j\}$ that maximizes the expected value of the firm at the base period, 0,

$$\max_{K_{j+1}, V_j} \{E_0[\sum_{j=0}^{\infty} \beta^j [F_j(K_j, V_j, \tau_j) - W_jL_j - q_jI_j - c(I_j)]\} \quad . \tag{30}$$

subject to $I_j = K_{j+1} - (1 - \delta)K_j$, the initial value K_0, and terminal conditions, where K_j is the capital stock at the beginning of period j, and δ is the depreciation rate.[39]

To obtain the first order conditions we first differentiate (30) with respect to the nondurable inputs, V_j to obtain:

$$E[\frac{\partial F(.)}{\partial V_j} - W_j = 0] \quad . \tag{31}$$

By assumption, the input V_j at any time j has no effect on the revenue in subsequent periods, and therefore its level is determined by equating the expected value of the marginal

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[39] The terminal condition is $\lim_{j\to\infty} E_0\{\beta^j[F_K(j) - c_I(j) - q_j]K_j\} = 0.$

productivity to that of its real price in each period, as shown by equation (31). Consequently, the optimization problem can be solved in steps. First, determine for each period the optimal level V_j as a function of prices and K_j, and substitute the result in the production function to obtain the function, $F(K_j, s_j)$, where $s_j \equiv (\tau_j, W_j, q_j, r, \delta, c)$ is the vector of the state variables. The second stage consists of solving

$$\max_{K_{j+1}} \{E_0 \sum_{j=0}^{\infty} \beta^j [F_j(K_j, s_j) - c(I_j) - W_j L_j - q_j I_j]\} \tag{32}$$

Differentiate (32) with respect to K_{j+1} and rearrange the result to obtain, for the case when an internal solution exists,

$$E_0\{\beta F_K(j+1) - [c_I(j) - hc_I(j+1)] - [q_j - hq_{j+1}]\} = 0 \tag{33}$$

where we use the notation $F(K_j, s_j) \equiv F(j)$ and similarly for other functions, $h \equiv (1-\delta)\beta < 1$, and the subscripts K and I indicate the direction of the partial derivatives of the functions in question. Label the rate of capital appreciation $\hat{q} \equiv \dot{q}/q$ and note that $[q_j - hq_{j+1}]/\beta = q_j[r + \delta - (1-\delta)\hat{q}_j] \equiv \tilde{q}_j$ is the rental cost of capital, or briefly the rental rate, evaluated at time j. It is the product of the initial price of the capital good, q, and the annual "charges" consisting of the discount and depreciation rates, adjusted for the expected capital gain, $E(\hat{q})$. Also, $[c_I(j) - hc_I(j+1)]/\beta = c_I(j)[r + \delta - (1-\delta)\hat{c}_j] \equiv \tilde{c}_I$. This gives the change in the adjustment cost due to a change of the timing of a unit of investment, *on the optimal path*, from one year to the next. We can now rewrite (33).

$$E_0\{F_K(j+1) - [\tilde{c}(j) + \tilde{q}_j]\} = 0. \tag{34}$$

In the absence of adjustment cost, the condition in (34) reduces to the equality of the marginal productivity of capital and the rental rate (Jorgenson, 1967). This condition applies to every point on the optimal path. The addition of the adjustment cost adds to the rental rate, and as such it affects not only the pace of investment but also the optimal level of capital.

The solution can be expressed in terms of the shadow price of capital defined as the present value of the marginal productivity of capital, net of the adjustment cost, in present and future production: $M_t \equiv \sum_{j=0}^{\infty} h^j F_K(t+j)$. The system can be solved to yield

$$E_t \{M_t - (q_t + c_I(t))\} = 0. \tag{35}$$

This condition states that investment is carried out to the point where the shadow price of capital generated by the investment is equal to the cost of investment including the cost of adjustment. The marginal productivity depends on the technology and the inputs at the various points in time, and therefore its evaluation requires an assumption that the investment under consideration is the only investment to be made. If other investments are contemplated, the marginal productivity would have to be evaluated conditional on such investments.

Discussion

The condition in (31) is extremely important for empirical analysis in that it implies that along the optimal path, the use of the inputs which have no effect on the revenue or the cost in subsequent periods is determined by equating the marginal productivities to their real prices in each period. This leads to a recursive system (Mundlak, 1967). First, we determine for each period the optimal levels of the variable inputs as functions of the state variables, including prices and K(t). The solution for K(t) on the optimal time path, is written schematically as

$$K^*[E(q,\hat{q},\delta,r,c,W,P,T)], \tag{36}$$

where we add P, the product price explicitly. All the variables in (36) are functions of time. The introduction of the intertemporal optimization results in replacing (25) with (36), thereby adding state variables as well as uncertainty with respect to the future time path of the exogenous variables. However, the recursive structure remains the same.

The role of prices and technology

The solution is quite sensitive to changes in the state variables. To gain some insight into the meaning of the solution, we use a Cobb-Douglas production function, $Y = AV^aK^b$. The first order condition in (31) provides a solution for V, the nondurable input, V=(a/W)Y. This solution is substituted in the production function to yield, with some simplification,

$$Y = (Aa^a)^{\frac{1}{(1-a)}} W^{-\frac{a}{1-a}} K^{\frac{b}{1-a}} . \qquad (37)$$

The marginal productivity of capital conditional on W is[40]

$$\frac{\partial Y}{\partial K}\Big|_W = \frac{b}{1-a}(Aa^a)^{\frac{1}{1-a}} W^{-\frac{a}{1-a}} K^{\frac{b+a-1}{1-a}} . \qquad (38)$$

This derivative is equated to the rental price of capital to provide a solution for K*, when such a solution exists.

Equation (37) is the short-run supply function conditional on K. Output declines with W, but as W is the ratio of nominal wage to output price, P, output increases with P. To simplify the discussion without a loss in generality, we continue by ignoring the adjustment cost. The condition in equation (34) simplifies to

$$E_0\{F_K(j) - \tilde{q}_j\} = 0. \qquad (39)$$

The long-run values (starred) are obtained by using equations (37) and (39) to yield

$$K^* = (b/\tilde{q})Y^*, \qquad Y^* = (Aa^a b^b)^{\epsilon} W^{-a\epsilon} \tilde{q}^{-b\epsilon}, \quad \epsilon = 1/(1-a-b). \qquad (40)$$

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[40] This derivative is evaluated for V kept at its short-run optimal level, which is different from the derivative conditional on V derived from the production function: $\frac{\partial Y}{\partial K}\Big|_V = b\frac{Y}{K}$.

Prices affect the desired capital directly through the rental rate and indirectly through the effect on the optimal output. It is important to differentiate between the direct and the indirect price effect. A change in the wage rate has only an indirect effect on capital with an elasticity $E_{K/W} = -a\epsilon$. The elasticities of the real rental rate, $E_{K/\tilde{q}}$, are -1, -bϵ, and (a-1)ϵ for the direct, indirect, and total effect respectively. Similarly, the elasticities of capital with respect to a change in the product price are 1, (a+b)ϵ, and ϵ for the direct, indirect, and total effect respectively. Note that the indirect effect (a+b)ϵ is considerably stronger than the direct effect. It is useful to illustrate the order of magnitude of the elasticities in question for arbitrary values of the parameters: a=0.3, b=0.6, and ϵ=10:

variable	Capital Elasticities		
	Direct	Indirect	Total
W	0	-3	-3
$\tilde{q}$	-1	-6	-7
P	1	9	10

To simplify the discussion, we have abstracted from taxes. To add taxes, they have to be inserted in the income expression in (1). Consequently, the prices in the foregoing results have to be adjusted for taxes (Jorgenson, 1963). The empirical evaluation of the effect of taxes is done in two steps: first evaluate the effect of the tax on the time path of the rental rate, and second determine the response of investment to price. It is the latter that is the focus of the empirical analysis.

Neutral technical change is perceived as a change in the multiplicative coefficient (A) of the production function. It affects output and thereby the desired capital level without affecting the capital-output ratio. Following the numerical example above, technical change of one percent causes a 10 percent increase in the desired capital stock. Capital using technical change, captured here as an increase in *b*, generates an increase in capital demand and in the capital-output ratio. The overall effect on output depends on what happens to the degree of the function. When the degree is held constant, an increase in *b* implies a decline of *a*, and therefore, without imposing a more detailed structure, the net effect on output is ambiguous.

Disinvestment

In general, empirical analysis treats positive and negative accumulation symmetrically even though the costs involved are completely different. The cost of acquisition of a new tractor is different from the selling price of a used one. Implications of this additional detail are discussed by Glenn Johnson (1958), Edwards (1959), Johnson and Quance (1972, pp. 185-195), and more recently by Chavas (1994). To place this detail in perspective, we note that on the whole, agricultural investment is positive for most of the time, and therefore the subject of disinvestment is of secondary importance and does not affect our views on the development of agriculture. Its empirical importance is largely limited to the behavioral analysis based on micro data.

There are three important reasons for the difference between the acquisition and the selling price. First, the service life of the new capital good is longer than that of the used one, and therefore it is more valuable. This aspect can be incorporated into the analysis by disaggregating the capital goods by age and vintage and pricing the different goods accordingly. The optimization problem of the price-taker farmer would then include acquisition prices by age and vintage instead of one price. If an old machine is sold, someone is buying it because it meets his needs. This indicates that there is a market for all types of machines which are actually traded. The extension of the analysis to include this heterogeneity should give a different result from that obtained when the farmer is restricted from purchasing the used equipment (who will then buy it?).

Second, part of the gap between the price of new and used equipment can be attributed to marketing charges and asymmetric information. Third, there is the cyclical element. There is a tendency to sell unutilized capacity in bad times when the excess demand for capital goods is declining and with it the price of the used equipment. The price behavior is likely to differ according to the origin of the capital goods. Used machines are supplied by farmers, and for our purpose they should be considered to be capital goods of agricultural origin, the same as cows. Their price is determined endogenously within agriculture and reflects the expected stream of the marginal productivity of capital over its remaining lifetime. To trace the consequences of this extension, it is necessary to work out the market

equilibrium for used equipment. This will result in a market clearing price, and used equipment will be employed according to conditions analogous to equation (35). New machines are of nonagricultural origin, and their supply price reflects the conditions in nonagriculture. Therefore the price may be less sensitive to the cyclical conditions in agriculture as compared to used machines. To sum up, the introduction of a second hand market adds details to the analysis but not a new theory.

The asymmetry between investment and disinvestment is more pronounced in models with internal adjustment costs. Obviously, a demolition of a building or a slaughter of a cow does not stretch out over time. The symmetry assumption simplifies the formulation, but it is unrealistic. Its restrictive nature goes undetected because much of the empirical work is based on aggregate data.

Empirical investment analysis

So much for the theory. The problem is how to implement the results in the empirical analysis. In general, time series of aggregate investment show a positive serial correlation. The determination of the source for this dynamic relation is a key question in investment research. There are two basic approaches. Initially, the dynamics was superimposed on the model, and we therefore refer to it as exogenous dynamics. Alternatively, the dynamics can be developed from the theory, such as in the case of the cost of adjustment, and it is therefore referred to as endogenous dynamics.

Aside from the pattern of the dynamics, the empirical analysis should reveal the response of K^* to changes in its determinants, where K^* is unobserved and therefore is replaced by the actual capital stock, or changes in it. The actual capital stock by itself is not a well-defined variable, but in this discussion we will ignore the issues involved in the construction of the capital stock.

Exogenous dynamics

For a variety of reasons, there is a time difference between the date of a firm's decision on a new investment and its completion. The implication is that a decision taken by the firm in a given year may affect investment in future years, or alternatively, the investment in a given

year reflects past decisions and more so, past signals. Such a time distribution of the response was a major justification for the distributed lags analysis, referred to as the flexible accelerator models, introduced by Chenery (1952) and Koyck (1954). In such models, the actual capital stock differs from the desired stock. Koyck's formulation uses geometric weights to express the current capital stock as a weighted average of past values of desired capital. This process can be presented by an adjustment equation

$$K_t - K_{t-1} = \kappa(K_t^* - K_{t-1}) \tag{41}$$

where κ, $0 \leq \kappa \leq 1$, is the coefficient of adjustment.

The desired capital is unobserved. In the case of a Cobb-Douglas production function, the desired capital stock is proportional to the long-run output, and the latter can replace the first. Introducing this substitution into equation (41) and simplifying, we can write the following investment function, where I_t is the *net* investment in year t,

$$I_t = \kappa\gamma_0 + \kappa\gamma Y_t^* - \kappa K_{t-1} + \text{error} . \tag{42}$$

However, the replacement of K^* by Y^* is of little help because the latter is also unobservable. In practice, actual output is used instead in empirical analysis (Jorgenson, 1963). In so doing, the difference between the short and the long-run supply is overlooked. The elasticities for long-run response express the response with respect to lasting price changes as well as technology. Transitory price changes are likely to affect output according to the short-run supply function, but as such should not affect the capital demand. Consequently, the variable used in the analysis measures with error the relevant variable and thereby introduces a downward bias in the estimation (Mundlak, 1966).[41] The problem can be overcome by aggregating the variables over time and thereby reducing to a large extent the effect of the transitory variations (Mundlak, 1964a, Chapter 6).

The underlying assumption in equation (41) is that the adjustment of the actual stock

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[41] For more detailed discussion of this subject, see Mundlak (1999 forthcoming).

to changes in the desired stock is gradual, but this is not always the case. Often, there are distinct scale economies in the size of the investment, where the unit cost declines with the size of the project, and the optimal size of the investment unit exceeds the demand or requires more resources than are currently available. Consequently, the firm may delay the investment until it is justified to construct a larger project at a lower unit cost (Mundlak, 1964a, Chapter 6). The phenomenon of lumpy investment at intervals longer than a year is inconsistent with the adjustment cost assumption. However, this is not detected in empirical analysis which uses macro data obtained as aggregates over firms and as such conceal it.

Endogenous dynamics

There has been a great deal of empirical work based on the Euler equation on nonagricultural data. The equation involves unobservable variables, and to overcome this limitation, three alternative approaches have been taken; these are reviewed by Chirinko (1993). To illustrate the basic issues at stake, we present an empirical version of equation (33), with the assumption that $c(.) = (c/2)I^2$ so that c(.) does not depend on the capital stock. Let z be the expected gap between the marginal productivity of capital and the rental rate, $z_{t+j} \equiv E_t\{[\beta F_K(t+j+1) - \tilde{q}_{t+j}]\}$. Rearranging, it follows from equation (33) that

$$E_t(I_{t+j}) - hE_t(I_{t+j+1}) = \frac{1}{c} z_{t+j}. \qquad (43)$$

An expected decline in the rental rate or an expected increase in the productivity of capital causes an increase in z, and hence the difference between current investment and expected next year investment increases. This means that at the margin, current investment increases in order to take advantage of the current opportunities.

This equation is used to estimate the parameters of the production function, of the adjustment-cost function, and of *h*. Unlike in the exogenous dynamic models, it is assumed here that the observed capital stock is *always* equal to the optimal one. For the purpose of estimation, F_K is spelled out explicitly in terms of its arguments, and thus the parameters of the production function enter the equation. Similarly, in some applications, the cost of adjustment is formulated so as to depend on some variables, including output. When the marginal

productivity of capital and the adjustment costs are written explicitly in terms of their determinants, the empirical equation contains output and prices.

There are several problems in using this equation for empirical analysis. First, in this formulation the adjustment-cost parameters are, by assumption, the only source for the dynamics. When in reality the time pattern of investment is affected by other causes, their influence will be captured by the cost of adjustment parameters, and the empirical analysis will give a distorted picture of the dynamics. Second, the Euler equation (equation (43)) provides arbitrage conditions between adjacent periods which have to be met on the *optimal path*. When the observations are located off the path, this condition is inconsistent with the data. If the model is stable, deviations from the optimal path generate a correction toward the path. This correction is not described by the model, but it is empirically important and as such affects the estimates. This may be the reason for the fact that empirical estimates obtained from the Euler equations do not produce robust results. Third, the Euler equation is not an efficient way to estimate the parameters of the production function. As argued earlier, it is more efficient to estimate the production function directly. Fourth, recall that $h = (1-\delta)/(1+r)$, so that h is not a stable parameter and should be treated as a variable. When h is treated like a constant, variations in h are captured by the equation error, and as such the error is not independent of the investment term on the right hand side of the equation. This causes a bias in the estimate.

Empirical investment analysis in agriculture

Unlike studies of production or supply functions there are only a few empirical studies of investment in agriculture. Griliches (1960) studied the demand for tractors in the United States in 1921-1957 using a distributed lags framework where the desired stock is determined by the real price of tractors and by the interest rate. The results show the importance of price variables as determinants of investment. As in many empirical applications, the equation contains fewer variables than what is called for by the theory. Presumably, the equation should include all prices and a measure of technology. In general, with a short time series the empirical equation does not sustain all the pertinent variables. One way to deal with this

problem is to replace the prices and other state variables with the rate of return. The higher is the expected rate of return, the higher is the investment demand. The rate of return can be thought of as a proxy for the gap between the expected marginal productivity of capital and the rental rate, labeled as z in equation (43). Mundlak (1964a, Chapter 6) used a panel of farm micro data to study investment in structures using the accelerator formulation and demonstrated the importance of aggregating the data over time in order to eliminate the noise that exists in annual micro data.

The work on agriculture using the cost of adjustment begins with Lopez (1985b) studying the dynamics of the Canadian food processing industry. Vasavada and Chambers (1986) introduced the cost of adjustment in order to incorporate the response of quasi-fixed inputs in productivity analysis of US agriculture. The estimated model, like many of the studies based on duality, does not satisfy the regularity conditions implied by the adjustment cost hypothesis. The adjustment coefficients show a very slow adjustment, ten years to reach the desired capital stock, nine years for labor, and two for land. The model assumes perfectly elastic supply for these factors, hence the adjustment reflects demand only. It is not quite clear why the adjustment of land to changing economic environment should require only two years as compared to the time required for labor and capital. This study was followed up by Luh and Stefanou (1991) who examined the importance of the disequilibrium component in measuring and explaining agricultural productivity growth.

These studies apply firm level theory to aggregate data, a strong assumption when studying the cost of adjustment because the data are also affected by the factor supply. The estimated adjustment rates for capital and labor are similar in the two studies. Yet, there is a difference in the decisions on labor and capital in agriculture. The decision on labor is made largely by rural based households on their employment. As for capital, supply is not perfectly elastic, and agriculture has to compete for capital resources with other industries. It can be concluded that the final outcome of the pace of adjustment is not a reflection of internal firm decisions as much as that of industry supply. This is also consistent with the study by Lee and Chambers (1986) which tests for the credit constraint in US agriculture in 1947-1980. It is concluded that farmers do not face a perfectly elastic supply of funds or credit (p. 865). This

finding is an indication that the assumption of perfectly elastic input supply is questionable. As such, it is also supportive of the discussion on the choice of technique.

Thijssen (1996) studies investment in Dutch dairy farms in a model similar to the endogenous dynamics model discussed above. He finds that the results obtained from the rational expectations version are inconsistent with the theory.

There are many more studies with cost of adjustment in nonagriculture. In summarizing the empirical record in nonagriculture, Chirinko (1993) notes that output performs well in explaining investment and the performance of prices is rather weak. This raises several questions. First, do prices play no role? Second, why is output so important? Third, why do the results lack robustness? Fourth, what is the message?

Price effect -- As illustrated in the foregoing discussion, a change in price has direct and indirect effects on the desired capital stock, and the indirect effect is considerably larger. Thus, part of the effect of output on the desired capital stock is an indirect effect of price.

Output effect -- Changes in output represent not only price effects but also changes in technology. As technology is the engine of growth, it probably plays a key role in explaining actual investment in many cases.

Lack of robustness -- The lack of robustness, we suggest, reflects the fact that the theoretical restrictions refer to the optimal path or steady state but, because of factors not taken into account, may not be a good description of the data. The discrepancy between a model and reality is the rule rather than exception in empirical analysis, but the consequences may be more severe in dynamic models.

The message -- There is a fundamental difference in the role of output in the exogenous and endogenous dynamics models. In the exogenous dynamics case, output is introduced to the model through the explicit expression of the marginal productivity of capital, and as such, the output coefficient is related to the production function. On the other hand, in the endogenous dynamics models it is introduced also, and sometimes solely, through the expression for the adjustment cost. When it is introduced solely through the adjustment cost, it describes a completely different process. It still remains an open question whether or not the empirical results justify linking the effect of output to the adjustment cost.

In conclusion, the endogenous dynamics models have two basic limitations: first, they describe a dynamic process in terms of unobserved variables and thereby lose the main potential of explaining the timing of investment, and second, their only engine for the dynamics is the internal cost of adjustment. There has been no obvious advantage to their performance in empirical analysis nor has there been any insight gained by their empirical application.

The scope for policy evaluation.

In the discussion of duality, the question was raised the as to where do we go from here. At this stage, it is clear that this question should be addressed within the broader framework that has evolved from the foregoing discussion. The core of the production structure, as outlined above, can be summarized by the following functions:

Y(V,K,T)	Production function	(44)
V(P,W,K,T)	Demand for nondurable inputs	(45)
W(V,s(V))	Supply of nondurable inputs	(46)
K*(s(K*))	Capital demand on the optimal path	(47)
K(K*,s(K))	Actual capital	(48)
T(s(T))	Implemented technology	(49)

where s(x) is the vector of the state variables pertinent to the supply or demand of x, as the case may be. Specifically, s(V) are the state variables that affect the supply of the nondurable (variable) inputs, s(K*) affect the capital demand on the optimal path, s(K) are the variables that determine the dynamics of convergence of the capital stock to the optimal path, and s(T) determine the implemented technology. Some of the state variables were discussed explicitly above, others are discussed in the references or are left in an implicit form. In passing we note that the role of these variables in empirical analysis is still to be more fully unveiled in future research. The system should also include land which is not dealt with here explicitly because we have already covered considerable ground without land. Mechanically, we can think of

land as being a component of capital in which case the supply condition of this component should be carefully specified.[42]

To obtain the dynamics of the supply, substitute the functions (45)-(49) in the production function to obtain

$$Y[P, W, s(V), s(K^*), s(K), s(T)]. \tag{50}$$

Obviously, a function of the form Y(P,W) can not capture all the complexities of equation (50). The function Y(P,W) serves as an approximation whose quality depends on the importance of the missing state variables which in turn depend on the data base. More generally, this is the problem of estimates based on duality. When dealing with micro data with constant technology, the only relevant issue that will differentiate between the two is the handling of capital. On the other hand, when dealing with aggregate time-series data, all the state variables may have an important impact.

Can such systems be evaluated empirically? The answer is positive as has been demonstrated by Cavallo and Mundlak (1982) and Mundlak, Cavallo, and Domenech (1989) for Argentina, Coeymans and Mundlak (1993) for Chile, and at a lower level of aggregation, by McGuirk and Mundlak (1991) for the Punjab agriculture under the green revolution. These studies show clearly that agriculture responds to prices following endogenous dynamics, of a different form from those discussed above, and that it takes time for the response to reach its full course.

Studying the production structure in all its complexities, is both research intensive and promising. What is the alternative? I will leave it for the reader to formulate his or her own answer. However, in thinking of an answer, we have to keep in mind that more than 70 years have passed since the work of Douglas. During this period, considerable work and ingenuity have been directed to improve the specification and the estimation method but as we have indicated, there is no simple robust way to describe reality. In part, the reality has many faces and in part the researchers have many faces. Like in Rashamon, we vary in our reports of the

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[42] For a discussion of land, see Mundlak (1997).

same phenomenon.

With this background, we can now address the cardinal question of what effect policy can have on production. Traditionally, the evaluation of policy is limited to the examination of resource allocation. The present framework introduces an additional dimension, the determination of the implemented technology. The dependence of the implemented technology on the environment is the key factor to the understanding of why less developed countries lag persistently beyond the performance of the developed countries. The economic environment is affected by policies, sector specific as well as sector neutral. The response to changes in the economic environment is not immediate, and it is therefore important to spell out the role of the dynamics of response through resource allocation and the choice of the implemented technology. This is what the above structure does.

Table 1: Empirical Production Functions with Estimated Elasticities for Specific Countries						
Country/Study	**Period**	**Sample**	**Labor**	**Land**	**All**	**Comments**
U.S.--Iowa (Tintner & Brownlee, 1944)	1939	468 farms	24	34	0.99	
U.S.--Iowa (Heady, 1944)	1939	micro	03	23	0.85	
U.S. (Hildebrand, 1960)	1950-1952					
Southeastern Kansas		107 farms[ab]	38	49	1.23	
West-Central Kansas		144 farms[ab]	32	43	0.88	
U.S. (Griliches, 1963a)	1949	68 regions	52	17	1.35	Regression includes education.
U.S. (Griliches, 1964)	1949, 1954, 1959	39 states[a]	51	15	1.28	Regression includes education.
India--eastern Upper Pradesh (Hopper, 1965)	1954	43 farms	01-02[c]	24-35[c]	0.81-0.95[c]	Dependent variable is expected output. Inputs were standardized.
U.S. (Kislev, 1966)	1949 1959	68 regions 3000 counties	47 40	28 17	1.26 1.05	Regressions include regional dummies.
India--South (Chennareddy, 1967)	1957-1958	104 farms	26	42	1.03	
Greece (Yotopoulos, 1967a)	1964	430 farms	44	09	0.88	Regression uses capital flow with rate of discount of 15%.
Israel (Mundlak, 1961)	1954-1958	66 family farms	12	0	0.80	Regression with time and farm dummies

Israel (Sadan, 1968)	1936-1960	33 kibbutzim[a]	31	04	1.06	
India (Sahota, 1968)	1954-1957	100[ab]	23	48[d]	1.00[d]	Dependent variable is output per acre. Regression includes fertilizer and irrigation.
U.S. (Headley, 1968)	1963	States	15	18	1.14	Regression includes machinery and other as separate inputs.
U.S. (Tweeten & Quance, 1969)	1921-1941, 1948-1966	aggregate U.S.	25	28	1.02	
Mexico--Bajio Valley (Ulveling & Fletcher, 1970)	1963	100 farms	21	47	1.07	Includes indices of production technique to allow for variable production elasticities.
Colombia (Colyer & Jimenez, 1971)	1968	27 farms 25 farms	05[e] 46[e]	78 42	1.07[f] 1.42[f]	Participants in credit program. Nonparticipants.
India (Herdt, 1971)	1960-1961 1964-1965	16 states	23 40	36 31	1.02 1.17	
Malaya (Huang, 1971) Kelantan Selangor Province Wellsley	1965-1968	 84 farms 76 farms 62 farms	 56 16 34	 33 83 56	 1.08 1.08 1.05	
India (Lau & Yotopoulos, 1972)	1955-1962		77 54	37 57	1.08 1.00	Estimated directly. Derived indirectly from profit function assuming CRS.

Taiwan (Yotopoulos, Lau, & Lin, 1976)	1967-1968	cross section[g]	26 44	06 41	0.94 1.00	Estimated directly. Derived indirectly from profit function assuming CRS.
Taiwan (Shih, Hushak, & Rask, 1977)	1964-1970	53 farms[a]	12	32	0.82	
Taiwan (Wu, 1977)	1964-1966	310 farms[ab]	18	31	0.87	Regression for crop production.
Thailand (Mittelhammer, Young, Tasanasanta, & Donnelly, 1980)	1950-1976	aggregate	59 58 48	34 35 34	1.09 1.09 1.03	Mixed estimation. With exact linear restrictions. Principal components regression.
U.S. (Kislev & Peterson, 1991)	1978 1982 1987	48 states	27 27 22	10 11 13	1.30 1.29 1.29	
China (Fan, 1991)	1965-1985	29 regions[a]	43[h]	26[h]	1.13[h]	Regression includes dummy variable for time trend.

[a] Data pooled for time period.
[b] The sample size reported is the total number or observations.
[c] Range of results for four crops: barley, wheat, gram, and pea.
[d] Constant returns to scale is assumed. The coefficient on land is derived as a residual from the rest of the coefficients.
[e] Only hired labor is included in the labor variable.
[f] Sum of coefficients includes coefficient on credit.
[g] Averages of 400 farms grouped according to five sizes and eight regions (n=40/year).
[h] Range of coefficients: Labor 27-44, Land 24-38, Sum 1.03-1.16.

Table 2: Production Functions with Estimated Elasticities - Cross Country						
Study	**Period**	**Sample**	**Labor**	**Lan d**	**All**	**Comments**
Bhattacharjee (1955)	1948-1950	22 countries	30	36	1.00	
Hayami (1969)	1960	38 countries	45[a]	20[a]	1.00[a]	Elasticities used for productivity measures.
Hayami & Ruttan (1970)	1955, 1960, 1965	38 countries	40[b]	10[b]	1.00[b]	Elasticities used for productivity measures.
Nguyen (1979)	1970 1975	40 countries 35 countries	38 37	02 -03	0.99 0.92	Regression includes education.
Mundlak & Hellinghausen (1982)	1960-1980	58 countries[c]	46	16	1.00	Uses principal components method.
Antle (1983)	1965	66 countries	33	17	0.92	Includes infrastructre and education.
Kawagoe, Hayami, & Ruttan (1985)	1960, 1970, 1980	43 countries	45[d]	10[d]	1.00[d]	Elasticities used for productivity measures.

[a] Range of coefficients: Labor 43-53, Land 18-25, Sum 0.96-0.97.
[b] Range of coefficients: Labor 34-49, Land 06-12, Sum 0.94-0.98.
[c] Data is pooled for time period.
[d] Range of coefficients: Labor 41-55, Land 01-10, Sum 1.01-1.10.

TABLE 3 – CROSS-COUNTRY PANEL

Variable	Within time and country		Between time		Between country	
	Estimate	t-score	Estimate	t-score	Estimate	t-score
Inputs:						
Capital	0.37	6.90	1.03	6.01	0.34	13.13
Land	0.47	3.78			-0.03	-2.82
Labor	0.08		-0.16	-0.16	0.26	13.67
Fertilizer	0.08	1.53	0.14	0.33	0.43	21.91
Technology:						
Schooling	0.09	0.55	-0.28	-0.06	0.02	0.52
Peak yield	0.83	3.80	-0.32	-0.07	0.06	4.19
Development	0.52	3.36	-0.21	-0.33	0.31	2.97
Prices:						
Relative prices	0.04	1.78	0.02	0.09	0.01	1.95
Price variability	-0.03	-0.97	-0.07	-0.26	-0.08	-2.82
Inflation	-0.00	-0.75	0.04	0.71	0.07	4.25
Environmental:						
Potential dry matter					0.16	2.68
Water availability					0.44	7.96

Note: R-square for 777 obs. = .9696,
1970-1990, 37 Countries.

Source: Mundlak, Larson, and Butzer (1997).

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