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ENDOGENOUS TECHNOLOGY AND THE MEASUREMENT OF PRODUCTIVITY*

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In macroeconomic analysis, the technology of the economy is summarized by a production function. Yet the production function, strictly speaking, is a microeconomic concept. It has a relatively clear meaning when it specifies a well-defined process, such as the production of a crop under well-defined conditions. But there are many crops and environmental conditions. Consequently, we observe many production functions in agriculture. In order to explicate the meaning of the agricultural production function, we must first consider the issue of aggregation, a subject that has been discussed at length in the literature. The problem of aggregation in agriculture differs from the common aggregation problem, however, in that the set of aggregated functions is endogenous to the economic system.

The question raised here is how to represent and measure technology of a sector (or any other level of economic activity) when output is produced by using more than one technique. The chapter is divided into six parts. We begin by presenting the conceptual framework. In the sections that follow, we develop the aggregate production function relevant for empirical analysis; examine the issue of estimation; study the endogeneity of technology; and examine the state variables relevant for empirical analysis. Finally, some implications for future research are identified.

THE CHOICE OF A TECHNIQUE

Each technique can be described by a production function, which is associated with an input requirement set. Technology (T) is defined as the collection of all possible techniques. In symbols,

$$T = \{F_j(x)\} \tag{11-1}$$

*This paper draws on Mundlak (1983).

where $F_j(x)$ is the production function associated with the jth technique. The technology defines an input requirement set obtained by convexification of the input requirement sets of the individual techniques.

These concepts are illustrated in figure 11-1, where the technology consists of two production functions, represented by their unit isoquants. The input requirement set of each technique is bounded from below by its isoquant. The input requirement set associated with T contains all the convex combinations of the individual input requirement set. To obtain it, we note that there exists a cost line with a slope $\bar{\omega}$ that is tangent to both isoquants. Let the inputs be capital (K) and labor (L), then corresponding to $\bar{\omega}$ we have threshold capital-labor ratios $\bar{k}_j = k_j(\bar{\omega})$, $j = 1, 2$ determined by the tangency of the cost line and the two isoquants. Let k be the overall capital-labor ratio. Then for $k \geq \bar{k}_2$ the isoquant associated with T is identical with $Y_2 = 1$. Similarly, for $k \leq \bar{k}_1$, it is identical with $Y_1 = 1$. For $\bar{k}_1 \leq k \leq \bar{k}_2$, it is given by the segment MN along the tangent line.[1]

A technological change is defined within this framework as a change in the technology T. The main objective of empirical analysis is to infer something about the technology from the data. The data can reveal information only about techniques that were actually implemented. For instance, if the two techniques described in figure 11-1 represent two varieties of wheat—Y_1 representing the traditional technique and Y_2 representing the modern technique—it is clear that when the capital-labor ratio in the economy is below the threshold level ($\bar{k}_1$), then only the traditional variety will be employed, even though the modern variety is available. The data in this case do not reveal any information about the modern variety. We thus make a distinction between technology (T) and implemented technology (IT), which consists only of techniques actually implemented.

The choice of technique is made at the firm level. To simplify the analysis, we deal with a single-period optimization and single-output production functions. We distinguish between fixed (b) and variable (v)

[1] The concept of a technique is very general. Techniques can be associated with products. The assumption made at some point in the foregoing analysis that the various techniques produce the same product can cover the multiproduct case by defining the output by its value. Thus, the isoquants of figure 11-1 will represent one dollar's worth of output. Moving from firms to the industry, firms themselves can be represented by techniques. This will require an extension of the optimization framework by including in the constraints a variable specific to the firm and introducing alternative costs for the fixed resources. Then, if the optimization is solved by the market, the exit and entry of firms will be one aspect of the choice of techniques. The consequences of such a choice on the aggregate production function follows the pattern developed above.

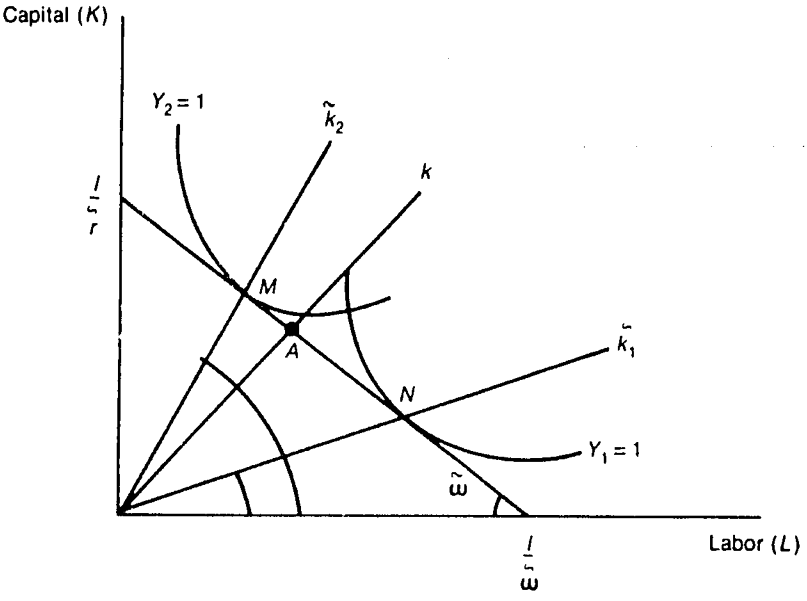

FIGURE 11-1. Choice of technique

inputs and assume for simplicity that the fixed inputs have no alternative cost. The optimization problem can then be described as maximizing

$$L = \sum_j p_j F_j(v_j, b_j) - \sum_j wv_j + \lambda\left(b - \sum_j b_j\right) \tag{11-2}$$

such that $F_j(\cdot) \epsilon T$, where p_j is the price of the product of technique j; w is the vector of factor prices; and b is the constraint on Σb_j.[2] The Kuhn-Tucker necessary conditions for a solution are

$$L_{v_j} = p_j F_{v_j} - w_{\ell} \leq 0 \tag{11-3}$$

$$L_{b_j} = p_j F_{b_j} - \lambda \leq 0 \tag{11-4}$$

$$\sum_j (L_{v_j} v_j + L_{b_j} b_j) = 0 \tag{11-5}$$

$$v_j \geq 0 \qquad b_j \geq 0 \tag{11-6}$$

$$L_\lambda = \Sigma b_j - b \leq 0 \tag{11-7}$$

$$\lambda L_\lambda = 0 \tag{11-8}$$

[2] A similar formulation is used by Glenn Johnson (1972). His formulation also includes salvage values for the constraints. This addition is not essential for the present discussion.

where L_{v_j}, F_{v_j}, L_{b_j}, F_{b_j}, and L_λ are vectors of the first partial derivatives. The solution gives

$$v_j^\star(s), b_j^\star(s), \lambda^\star(s)$$

where s represents the exogenous variables of this problem, to be referred to as the *state variables*

$$s = (b, p, w, T)$$

The solution thus depends on the available technology T, on the constraint b, and on the products and variable input prices. The solution determines both the techniques used and the level of their use, as determined by the optimal allocation of fixed inputs $b_j^\star$ and variable inputs $v_j^\star$.[3] This can be seen by rearranging equations (11-3) through (11-5)

$$0 = \sum_j (p_j F_{v_j} - w_j) v_j + \sum_j (p_j F_{b_j} - \lambda) b_j$$

Due to equation (11-6), when either equation (11-3) or equation (11-4) is negative, then $v_j^\star = 0$ and $b_j^\star = 0$. The implemented technology is the collection of all implemented techniques and it can be described formally by

$$IT(b, p, w, T) = \{F_j(v_j, b_j) | F_j(v_j^\star, b_j^\star) \neq 0, F_j \in T\} \qquad (11\text{-}9)$$

The optimal output of technique j is $y_j^\star = F_j(v_j^\star, b_j^\star)$. The implemented technology, IT, is a subset of T. As such, the envelope of IT is in general not the same as the envelope of T. The difference, of course, is due to the constraints encountered by the firm. Put differently, when the constraints are binding a constrained optimum is inferior to an unconstrained one.

For any set of state variables, equation (11-9) describes a well-behaved technology. Consequently, a profit function can be derived:

$$\pi(s) = \sum_j p_j F_j(v_j^\star(s), b_j^\star(s)) - \Sigma w_j v_j^\star(s)$$

The various theorems dealing with the duality between the profit function and the production function hold true conditional on s. Specifically,

[3] The number of implemented techniques is related to the number of constraints, or the dimensionality of b. This is a familiar property in linear models. However, in this formulation no limit is set on the number of state variables except that it is finite.

$IT(s)$ is dual to $\pi(s)$ and vice versa.[4] Using Hotelling's lemma, it is possible to derive factor demand at the technique level, $v_i^*(s)$, by

$$-\frac{\partial \pi(s)}{\partial w} = v_j^*(s)$$

The aggregate input demands are $v^*(s) = \Sigma v_j^*(s)$ and $b^*(s) = \Sigma b_j^*(s)$. Similarly, the supply of output of technique j is given by

$$y_j^*(s) = \frac{\partial \pi(s)}{\partial p_j}$$

and the aggregate value supply is given by

$$y^*(s) = \sum_j p_j y_j^*(s)$$

AGGREGATION OVER TECHNIQUES

From the foregoing discussion, it is clear that for any given value of the state variables, the techniques to be implemented and the intensity of their implementation—as determined by the endogenous quantities, that is, inputs and outputs, associated with those techniques—are determined simultaneously. The crux of the analysis stems from the fact that at any point more than one technique is used.

The data are generally aggregate in the sense that there is no differentiation of inputs and outputs by techniques. It is therefore important to examine the relationships between aggregate output and aggregate input. To simplify the discussion, it can be assumed that all the techniques produce the same product. Let x represent the vector of inputs, and $x^* = x(s)$ its optimal level. Then total optimal output is given by

$$F(x^*, s) = \sum_j y_j^*(s) \qquad (11\text{-}10)$$

It should be noted that the production function (11-10) is defined conditional on s. Variations in s cause a joint change in x^* as well as in

[4] It is important to note that the exploitation of this property in empirical analysis is restricted by the fact that s varies over the sample. Thus, strictly speaking, each point in the sample comes from a different profit function, which in turn describes a different technology.

$F(x^*, s)$. This is the main difference between the present approach and conventional analysis. In the latter, changes in prices generate a spread of points on a given production function and as such are important for identifying the function. Under our approach, changes in prices generate not only changes in inputs and outputs but a different set of implemented functions as well.

The aggregate production function can then be thought of as an approximation to equation (11-10) in a specific way. For equation (11-10) to be a production function, x^* should be disconnected from s. This can be done by allowing for a discrepancy between observed (x) and optimal (x^*) inputs; we can express the observed output as

$$\Sigma y_j \cong F(x, s) \qquad (11\text{-}11)$$

Strictly speaking, $F(x, s)$ need not be a function, as x can be allocated to the various techniques in an arbitrary way. Only when we have an allocation rule leading to x^* can uniqueness be achieved. However, holding s constant, the implemented technology is determined. Consequently, the difference between x and x^* produces information on that technology. This provides a key to the identification and estimation of the aggregate production function.

Following Fuss, McFadden, and Mundlak (1978), $F(x, s)$ can be approximated, using a weak assumption, by a set of functions:

$$F(x, s) \cong \sum_{i=1}^{m} a_i h_i \cong g(x, s) \qquad (11\text{-}12)$$

where $g(x, s)$ is the approximating function; a_i are parameters; and h_i are known functions. Expanding $F(x, s)$ about x^* and omitting the argument (x^*, s) wherever ambiguity does not result, we set

$a_0 = F(x^*, s), \qquad h_0 = 1;$

$a_1 = \nabla F(x^*, s)$ is the gradient of $F(x^*, s)$;

$h_1 = (x - x^*)$ is the discrepancy between the optimal and actual vector of inputs; and

$2a_2 = \nabla^2 F(x^*, s)$ is the Hessian matrix of F evaluated at x^*.

It then follows that

$$g(x, s) = F(x^*, s) + (x - x^*)'\nabla F(x^*, s) + (x - x^*)'\nabla^2 \frac{F}{2}(x^*, s)(x - x^*) \qquad (11\text{-}13)$$

Rearranging terms,

$$g(x,s) = \Gamma(x^*,s) + x'B(x^*,x,s) \tag{11-14}$$

where

$$\Gamma(x^*,s) = F(x^*,s) - x^{*\prime}\nabla F(x^*,s) + x^{*\prime}\frac{\nabla^2 F(x^*)x^*}{2} \tag{11-15}$$

$$\begin{aligned} B(x^*,x,s) &= \nabla F(x^*,s) - \nabla^2 F(x^*,s)x^* + \frac{\nabla^2 F(x^*s)}{2}x \\ &= \frac{\partial g(x,s)}{\partial x} - \frac{\nabla^2 F(x^*,s)}{2}x \end{aligned} \tag{11-16}$$

If the variables are originally in logs, then equation (11-14) has the form of a Cobb-Douglas function, with one major difference: the coefficients are functions and not constants. This, of course, is the main feature of the present approach. As x^* changes, so do Γ and B. Variations in the state variables affect Γ and B directly as well as through their effect on x^*. In turn variations in x^* affect the input-output combinations. If this model is an accurate description, a constant coefficient production function would fail to explain all sources of variation in productivity. Such variation in productivity would be incorrectly interpreted as random by the researcher who fails to take account of the state variables that determine the implemented technology.

Failure to account for endogenous technology can lead to difficulties in the estimation of production functions. Consider the efficiency frontier approach, which involves the estimation of the production function under the assumption that the function is indeed an envelope.[5] The results derived above show that this objective cannot be achieved. At best, it is possible to estimate the envelope of the implemented technology and not of the technology. But that envelope varies with the state variables, and the question then is, what is the meaning of estimating an envelope ignoring such variations.

Equation (11-14) indicates that the coefficients can vary either with variations in the state variables—as reflected by x^*—or with x. The literature on production functions deals with the latter. For instance, the translog production function (Christensen, Jorgenson, and Lau, 1973) can be derived from equation (11-14) by setting x^* to be identically zero. Thus, although $B(0,x)$ is not a constant, it is invariant to variations in the state variables that affect the implemented technology in that it is implicitly assumed that the observations are generated by a

[5] For discussions of this approach, see for instance the *Journal of Econometrics*, May 1980.

well-defined production function, which is not the case. This may explain the frequent failure of empirical analysis to obtain the concavity consistent with the second-order condition for profit maximization. Such a failure is serious when the first-order conditions are used in the estimation procedure, as is actually the case in such studies. This reflects the fact that the process of formulation and estimation of production functions has not yet reached a satisfactory stage. One direction of research aimed at correcting the situation has been to introduce higher degree polynomials to approximate the production function.[6] It is true that sufficiently high degree polynomials will approximate any function to a desired degree of accuracy. The fact that aggregate technology is a function of the state variables, however, raises questions about the use of higher polynomial functions to represent production technologies. The function that this method intends to estimate does not exist. In principle, there may be as many functions as there are sample points. The key to estimation and interpretation is to take the endogeneity of the technology into account, as is discussed in the next section.

IDENTIFICATION AND ESTIMATION

The key to the estimation of $g(x, s)$ as defined by equation (11-12) is the discrepancy between observed and optimal quantities. Such a discrepancy occurs at two levels. First is the error made by firms in correctly determining $x^*(s)$. Second is the error of specification arising from the fact that the model simplifies reality; the optimal value consistent with the model is not necessarily the same as that viewed by the firm. It should be noted that it is the existence of a discrepancy that is utilized here and as such it is independent of its actual distribution. Thus $x - x^*$ can be white noise and still help in the identification.

Thus, the estimation of $g(x, s)$ requires the estimation of $\Gamma(x^*, s)$ and $B(x^*, x, s)$, which are unknown functions in s, and the unobserved variable x^*. There is no point in trying to determine x^* separately from Γ and B. The procedure is to consider Γ and B as composite functions in s and to expand functions in terms of s. Denoting the vector of state variables by s, we can then write

$$\Gamma(x^*, s) \cong \pi_{00} + s'\pi_{10} + s'\pi_{20}s \qquad (11\text{-}17)$$

$$B(x^*, x, s) \cong \pi_{01} + \pi_{11}\begin{pmatrix} s \\ x \end{pmatrix} + Q(s, , x) \qquad (11\text{-}18)$$

[6] See Galant (1982).

The πs represent coefficients: π_{00} is a scalar; π_{10}, π_{01} are vectors; and π_{20}, π_{11} are matrices whose orders are obvious from the equations. $Q(s,x)$ is a quadratic term, not spelled out as it is likely to be omitted as explained below.

Combining equations (11-17), (11-18), and (11-14) we obtain

$$g(x,s) \cong \pi_{00} + s'\pi_{10} + s'\pi_{20}s + x'\pi_{01} + x'\pi_{s1}s + x'\pi_{x1}x \tag{11-19}$$

where π_{11} is now decomposed in an obvious way to $\pi_{11} = (\pi_{s1}, \pi_{x1})$. $Q(s,x)$ is omitted from equation (11-19), as its multiplication by x' gives third-degree terms that are unlikely to be empirically relevant. Such an omission simplifies the discussion but does not change it in a substantive way.

Even in its present form, equation (11-19) contains potentially too many terms. Its direct estimation is thus likely to yield imprecise results. The number of variables can be reduced by using principal component techniques. This procedure was followed by Mundlak and Hellinghausen (1982) in applying some of these concepts to cross-country analysis of agricultural productivity.

Additional information on the first derivatives can be derived from the factor shares. Let g and x represent logs of output and inputs, respectively, and let θ be the vector of factor shares. Then under equilibrium

$$\frac{\partial g(x,s)}{\partial x} = \theta \tag{11-20}$$

Differentiating equation (11-19) and using equation (11-20), we can write

$$\theta = \pi_{01} + \pi_{s1}x \tag{11-21}$$

Using equation (11-18) without $Q(s,x)$,

$$B = \theta - \pi_{x1}x \tag{11-22}$$

We can then write the production function as

$$y = \Gamma + x'(\theta - \pi_{x1}x) \tag{11-23}$$

The system to be estimated consists of equations (11-23), (11-21), and (11-17). Adding error terms to these equations, the system can be estimated by any system method, such as FIML or one of its approximations.

The dependence of θ on x indicates that the production technology exhibits a varying elasticity of substitution. The variation of θ with s indicates that different techniques may have different factor shares, that is, the techniques may vary in their factor intensity. Empirically, the variations of the state variables may explain to a large degree the variations in factor shares.

Equation (11-21) was obtained subject to the equilibrium condition in equation (11-20). This condition can be modified to allow for distortion in the factor market. This can be done by adding a term $s'\pi_{30}x$ to Γ

$$\Gamma(x^*s) \cong \pi_{00} + s'\pi_{10} + s'\pi_{20}s + s'\pi_{30}x \qquad (11\text{-}24)$$

in which case $\partial g(\ )/\partial x$ will differ from θ by $s'\pi_{30}$. This allows for systematic deviations from equilibrium in the factor market that are related to the state variable. Such a distortion could be made to depend on other variables as well, or even on x itself, following a similar approach. This approach makes it possible to use the information conveyed in the factor shares without imposing the equilibrium conditions. The system to be estimated will now consist of equations (11-24), (11-21), and (11-17).

ENDOGENEITY OF TECHNOLOGY

In what sense is the technology endogenous? The foregoing discussion has shown explicitly that the implemented technology is endogenous in that it depends on the state variables. This is the only aspect of technology that is actually observed. Like any other observed economic variable, it is determined by supply and demand. The supply of new techniques is represented by T. Together, T and the remaining state variables determine the implemented technology. The question is, to what extent is T endogenous? The process of generating new techniques is a subject that has been studied broadly and is not dealt with here in any comprehensive way. One important aspect of it should be brought up explicitly, however, because of its important repercussions for our analysis. The present framework facilitates an insight into Hicks' view of induced innovations being labor saving.

Following Danin and Mundlak (1979), it can be shown that capital accumulation results in the employment of capital-intensive techniques and, conversely, that the introduction of capital-intensive techniques requires capital accumulation. Turning to figure 11-1, even if it is available, technique 2 will not be used as long as $k < \bar{k}_1$. As the capital-labor ratio goes up and passes the threshold level $\bar{k}_1$, technique 2 will be introduced, and its utilization will increase with k. For $k > \bar{k}_2$, only technique 2 will be employed. This analysis can be viewed as dealing with a given industry, say agriculture, in isolation. It assumes that agriculture has two techniques, traditional and modern, and as the capital-labor ratio in agriculture increases, the traditional variety will lose ground to the modern variety. It can be shown that the same result is obtained within an equilibrium analysis for the economy as a whole.[7] The implication is that the introduction of capital-intensive techniques is subject to capital constraints and consequently the rate of adoption of the technique depends on capital accumulation.

New techniques are generated by firms, private or public, that allocate resources to research and development. For a given state of science, a choice can generally be made in determining the research strategy. For the purpose of our discussion, the key variable is the capital intensity of the new techniques. As we have shown, capital accumulation generates demand for capital-intensive techniques. Thus, the producers of techniques should aim at the development of capital-intensive, rather than labor-intensive, techniques. However, overshooting is counterproductive. Because the rate of implementation depends on the rate of capital accumulation, the threshold level of the new techniques should not be too high or the market for such techniques will be limited.

In the absence of a new capital-intensive technique, capital accumulation increases the capital-labor ratios, thus increasing real wages and decreasing the real rental rate on capital. Thus, the owners of capital will be interested in investing their capital in techniques that prevent the rate of return from falling. This generates the demand for the capital-intensive techniques.

For the purpose of simplification, we have dealt with two techniques: traditional and modern. The appearance of additional techniques can be handled in a similar fashion. One particular case—that of neutral technical change (NTC) in the modern technique—is worthy of examination here. As it has been argued that the process of capital accumulation generates a demand for capital-intensive techniques, then—other things being equal—this demand will be realized through the development of the NTC to be implemented on the modern techniques. In a more detailed framework, the cost of producing and changing techniques, as well as the required research time, should be introduced. If the required time is significant, by the time the research is completed the traditional technique may no longer be of any importance. Therefore, effort will be directed at increasing the productivity of the modern techniques. This consideration has a dynamic aspect. With time, the modern techniques

[7] See Danin and Mundlak (1979).

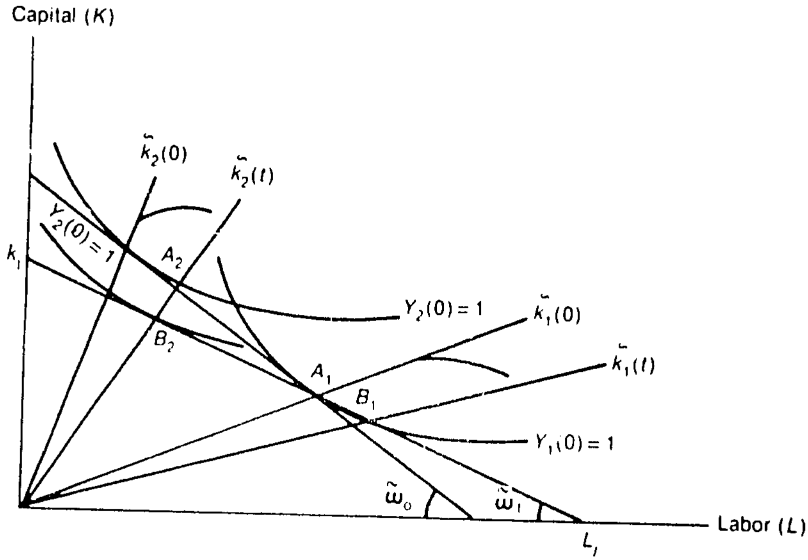

FIGURE 11-2. Neutral technical change and choice of technique

become traditional and, therefore, have already been worked on so that the easy gains may already have been made and additional gains may be subject to increasing cost. Thus, both from the demand side and the supply side, it is likely that the effort of improving an existing technique will be aimed at the modern techniques.

An improvement in the productivity of a technique should increase the degree of its utilization. In part, this can be illustrated graphically in figure 11-2. The initial techniques are represented by $Y_1(0)$ and $Y_2(0)$, with threshold values $\tilde{k}_1$ and $\tilde{k}_2$. Neutral technical change in the modern technique shifts its unit isoquant to $Y_2(t) = 1$. The threshold values decline accordingly to $\tilde{k}_2(t)$ and $\tilde{k}_1(t)$. For any value of k, the relative importance of the traditional variety declines.[8] The net effect of this change is labor saving and thus can be expressed as a decline in the labor share at any level of k. This is believed to be the situation in agriculture where, on a net basis, we observe labor-saving technical change. From this discussion, it emerges that the technology set will be expanding with capital accumulation. To be sure, capital is viewed here in a comprehensive way, in that it includes capital accumulated in research, education, and other forms of human capital. As such, it represents both the supply and the demand of new techniques.

[8] This can be shown analytically, but we omit here the technical details.

It is interesting to compare this approach to the introduction of new techniques with that of Solow's embodied technical change. If the new techniques are embodied in new investment, then the rate of their introduction depends on gross rather than on net investment, as is the case in the present framework. However, the empirical application of this distinction is not immediate. This is discussed in more detail in Mundlak (1984). The foregoing discussion suggests that net investment and depreciation are included in the empirical analysis as state variables with expected positive effects on productivity. This does not tell the whole story, however. A broader framework should also allow for a cost of adjustment that increases with investment. This partial effect of investment on output due to the cost [illegible]djustment is negative. Thus, the expected net effect of investment i[illegible]iguous.

EMPIRICAL IMPLEMENTATION

The primary goal of empirical analysis is the identification of the state variables, which can be classified as those representing technology, constraints, and prices.

The technology variables should represent the movement of the frontier, or what is commonly understood as technical change. Sometimes there are observable indicators of such progress, such as the proportion of the area sown by high-yielding varieties. Such variables themselves are endogenous within the economic system, as discussed below. In general, the set of techniques T is a function of the overall stock of capital in the economy, including the various facets of human capital. The rate of implementation of the new techniques may also be determined by gross investment, although the sign is ambiguous.[9] Per capita GNP can be used as a measure of comprehensive capital (Mundlak and Hellinghausen, 1982). Given that this measure is subject to cyclical fluctuation, its historical peak values are better indicators of T.[10]

The technology constraints are easier to identify. In the cross-country analysis of agricultural productivity, the constraints included the basic resource endowment, such as labor and land, as well as measures of the physical environment. In the study of Argentina's sectoral growth (Cavallo and Mundlak, 1982), the constraints also included the share of agriculture in total credit, as this share reflected a supervised program.

[9] This approach is taken by Coeymans and Mundlak (1983) in the study of sectoral growth in Chile.

[10] See Mundlak (1984).

It is possible to endogenize some of the constraints. Doing so will allow the state variables to be determined by the economy. The state variables will then determine productivity, which affects the state variables. This is basically the approach that has been followed by Cavallo and Mundlak (1982) in the study of sectoral growth in Argentina and by Coeymans and Mundlak (1983) in the study of sectoral growth in Chile.

Prices are generally observable. However, what matters for production decisions are not actual prices but expected prices, which are not observed. Thus, the analysis should be extended to explain expectation formation. When dealing with an industry, prices are likely to be endogenous. Therefore, to obtain a complete model, the production sector should be analyzed together with product demand and factor supply.[11] Thus, when demand is expected to be weak due to cyclical variations, one would expect a lower output. If resources are not adjustable instantaneously, such a downward cycle will cause a decline in measured productivity in conventional studies; in the presented framework, the state variables will explain such deviations from the frontier.

AGENDA FOR FUTURE RESEARCH

This analysis has sought to endogenize productivity and formulate it in a way that has empirical relevance. The previous section reviewed some directions taken in recent research. This research, however, constitutes only a first step. It is, therefore, useful to summarize the main directions that should be followed in future research.

a. Integration of the analysis of product demand and factor supply into the analysis of productivity. As indicated above, this approach integrates cyclical variations in productivity analysis. It also generates the necessary link with which to analyze sectoral growth within the framework of economic growth. If the sector is important, then the study of its factor or product market cannot be isolated. Thus, when agriculture constitutes an important sector of the economy, the off-farm migration of labor or the sectoral allocation of investment is interdependent with developments in the rest of the economy.

b. Integration of technological uncertainty and price uncertainty into the analysis of productivity. The main thrust of our analysis has been on the growth aspects of changes in technology; we have ignored the question of uncertainty associated with the supply and demand of new techniques. Thus, even when a technique is available, its implementa-

[11] See Johnson (1950).

tion is not immediate because of uncertainty considerations (Griliches, 1957). Any empirical analysis should be concerned with this aspect. A related issue is that of the greater variability associated with new techniques relative to existing techniques (Barker, Gabler, and Winkelman, 1981; Hazell, 1984; and Mehra, 1981).

c. Adoption of a multiperiod framework. The investments associated with the generation of new techniques as well as with their implementations should be evaluated within a multiperiod model. The rate of interest will play an important role, suggesting the possibility of extending the analysis by endogenizing the rate of interest.

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