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Plowing Through the Data

by

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PLOWING THROUGH THE DATA

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Abstract

In this paper we report on work that has aimed at measuring and understanding the sources of productivity differences among firms and their changes over time. These issues have been investigated at the micro level, which is the decision-making level. The relationship between inputs and the economic environment is informed by an underlying economic model. The issues involved in the specification and estimation of production functions are related to the role played by errors in the production and optimization decisions. Under this general umbrella, the paper traces my interaction with the literature on some key subjects in production and supply.

Turning to the macro level, we review subjects related to the analysis of agriculture as a sector of the economy and the determinants of agricultural growth. The incentives and constraints are affected by sector-specific and sector-neutral policies, by world prices, and by the implementation of new technology. The paper concludes with a review of empirical work on these subjects.

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How does one reflect on the outcome of a random walk? This in essence, is what I am setting out to do, and the easy way to do it would be to do what some of us do best, namely, talk about the past. It would have been more impressive if I could pretend to have followed my trajectory with the clarity of a crystal ball. A natural starting point in my case is high-school, where I took a turn in the direction of agriculture, revealing my convictions at the time. Eventually, as outlined below, I invested much of my research efforts in two main fields, production and agricultural growth, and they will be the main subject of this review. The two are not independent, and in both cases I have tried to understand what the data tell us. Situating my work in the rich literature was largely accomplished in Mundlak, (2000; 2001a), which allows me here to walk through my efforts without elaborating on all the pertinent work

Background

I came to economics from agriculture, having spent the last two years of high school at an agricultural school (Kadorie). Two years later I found myself serving as a farm manager in a new kibbutz in Israel, and soon realized that I could benefit from a university education. The natural place to pursue that was the Faculty of Agriculture of The Hebrew University, but admission to The Hebrew University required state matriculation, for which graduation from the Kadorie School did not qualify. Fortunately, however, it was sufficient for admission to U.C. Berkeley, and that is how I arrived in California in the fall of 1950. Most of the U.C. agricultural program was offered at the Davis campus, where I received my first degree. With an eye on returning to the farm, I was mainly interested in the agricultural production courses, less so in the underlying physical sciences. There were two major tracks, agricultural education and agricultural economics, that allowed a choice of a mixed portfolio of production courses: I chose economics. As a matter of choice, I was exposed to the courses in economics only in the latter stages of the program, but that was enough to convince me to move on to Berkeley for graduate work.

The course work at Berkeley included economic theory work at the Department of Economics. I also took a Master program in statistics. My PhD thesis dealt with the construction of objective production forecasts formulated within a decision theory framework (Mundlak 1956). It was supervised by George Kuznets and David Blackwell, and influenced by Blackwell & Girshick (1954). I constructed loss functions for some specific marketing and policy actions in agriculture and developed the minimum risk forecasts. The message that I have carried forward from that work is that with the same information set the choice of forecast is not unique and is influenced by the loss function.

First Steps

Shortly after my return to Israel, I embarked on two empirical studies that influenced my future work. The first was an analysis of the economic performance of family farms in cooperative villages (Mundlak 1964a). The second, more macro in nature, called for forecasts of short- and long-term supply and demand of Israeli agriculture (Mundlak 1964b). I begin with a review of the first study and the subsequent evolution of my interest in production analysis.

<u>Moshavim</u>

I was offered an opportunity to analyze the performance of a panel of moshav farms assembled for the Falk Institute for Economic Research in Israel, headed by Don Patinkin. A moshav is a village whose members cooperate in marketing, purchases, credit, and public projects such as water supply. The individual farms were originally endowed with a bundle of resources adequate for earning an income, when working fulltime on the farm, equal to that of urban wage earners. Trading in land, water rights, and production quotas was forbidden. In order to achieve income equality within the moshav, each farm was endowed with the same bundle of resources. Thus, the study of the developments over time in a given moshav can be viewed as a controlled experiment conducted under equal initial conditions.

The ideology of equality was also applied to the population of all moshavim. Inter-village differences in the physical environment, such as climate, soil type, water availability, proximity to markets and so on, called for differences in the level and composition of the resource endowment across moshavim so as to create equal opportunities.

Yet, in spite of the equality in the initial conditions, inter-farm differences were developing over time. There were differences in product composition, in the intensity of land cultivation, in land rental, in the use of hired labor or working away from the farm, and, most importantly, in income. These differences point to a dissonance between reality and the original ideas of equality. The heterogeneity in development is attributed to idiosyncratic differences in effort, in production efficiency, and in response to opportunities. The differences in resource use and accumulation are attributed to response to incentives, and the difference in output is attributed to differences in inputs and the idiosyncratic effects. The analysis of this process involved the analysis of productivity and of product and input response to prices. The review begins with the empirical analysis of the production function. The discussion of agriculture as a sector will follow in the latter part of the review.

Issues in the specification and estimation of production functions

The starting point was the attempt to estimate a production function from a panel of moshav farms, and that introduced me to the literature of the time. The Cobb-Douglas function offers a simple framework for discussing fundamental issues in the estimation of production functions. The idiosyncratic variable, referred to as the effect, is recognized explicitly in the equation as a variable even though it is unobserved. The treatment of the effect depends on the role it plays in the firm's decision. When it has no direct impact on the firm's decision, the variable becomes a component of the unobserved equation error, and as such it is innocuous. When the firm is aware of the effect, however, to the extent that it guides its optimization decision, the effect constitutes a transmitted error. If it is ignored the OLS estimator of the production elasticities is biased (Marschak & Andrews, 1944).[1] The general case is where the equation error consists of transmitted and non-transmitted components. Since the non-transmitted component is innocuous, the problem is to overcome the impact of the transmitted error (Mundlak & Hoch, 1965).

The data used in the analysis are time-series, or cross-section, or both. When the effect is observed, it becomes part of the regressors and the OLS estimates of the elasticities will be unbiased. In reality, the effect is not observed, but, with panel data, it can be estimated (Mundlak 1961a; 1963a). The outcome of the regression analysis of panel data depends on the way the data are pooled. With panel data, there are three orthogonal canonical regressions: between-firms, based on firm averages; between-time, based on time averages; and within, based on deviations from firm and time averages.[2] The coefficients of the between regressions are biased because of the transmitted error, whereas those of the within regression are unbiased. Any estimator of the production elasticities linear in the observations is a linear combination of

[1] In the discussion I will not make an explicit distinction between bias, large sample bias, and consistency.
[2] If time effects are not included, the within estimator is based on deviations from firm averages.

the three canonical regressions and as such it is biased, except for the extreme case of the within estimator.[3]

There are two inherent limitations to the within estimator. First, while the number of observations in the sample is fixed, the number of estimated parameters increases considerably by estimating the effects, and the degrees of freedom decrease accordingly. Second, by ignoring the between-firm and between-time variations, the estimator uses only part of the sample information. The random effect model was introduced with the intention of overcoming these limitations (Balestra & Nerlove; 1966, Wallace &Hussain, 1969). In that model the effects are treated as random rather than fixed, and thereby the number of estimated parameters is reduced and the statistical precision of the estimates increases. The modification changes the variance of the equation error, and that has led to a GLS estimator.

This approach falls short of its intentions (Mundlak 1978a). First, the distinction between random and fixed effects is a matter of what the model is conditioned on and is independent of which estimator is used. Second, the GLS estimator in the random error model is linear in the observations and as such it is a linear combination of the canonical regressions and thus inconsistent. The problem of inconsistency can be solved by allowing explicitly for the transmitted error, in which case the GLS estimator becomes identical to the within estimator.

The next substantive turning point in the literature came with the appearance of the dual approach, which utilizes the duality between the production function, on one hand, and cost, revenue and profit functions, referred to as the objective functions, on the other hand (Cf. McFadden 1978). The behavioral functions, namely factor demand or product supply, are derived from the first partial derivatives of the objective functions. The framework is very

[3] The ideas discussed here and in the literature about panel data are not restricted to production functions, but we will stay with the production function case.

useful analytically, and it also solves the problem of inconsistency involved in the direct estimation of the production function. It does not, however, use all the available information. One way to describe the empirical application of this approach is to view the pertinent prices as instrumental variables in estimating the production function. The prices are presumably correlated with the quantities, and are uncorrelated with the production function error, including the transmitted error. Thus the estimator is consistent, and its efficiency increases with the spread in the prices and decreases with the degree to which the first order conditions are actually met. But because the spread in prices among firms in a competitive economy is likely to be small, the estimator is likely to be subject to high variance.

In comparing the performance of the dual and the primal estimators, it helps to recall how the data trace the production function. In the absence of the transmitted error, the variability in inputs traces the function. The variability in inputs, in turn, is attributed to variability in prices and also to deviations from the first-order conditions, referred to as allocation error.[4] The larger the variability of these two components, the more precise the estimated coefficients are. All this information is utilized by the primal estimator. The dual estimator on the other hand uses only the price variability and ignores the allocation error and is therefore, from the point of view of statistical efficiency, inferior to the primal estimator.

The existence of transmitted error complicates the comparison of the primal and the dual estimators. In this case, to achieve consistency of the primal estimator it is necessary to eliminate the transmitted error component by using the within transformation. This reduces the inter-firm price variability and thereby reduces the efficiency of the primal estimator. It is argued that the allocation error is likely to dominate the loss in the price variability, so that the

[4] The term allocation error refers to the view of the econometrician. It is not necessarily an error on the part of the firms, as explained in what follows.

within primal estimator is likely to be more efficient than the dual estimator (Mundlak, 1996). In the next section I extend the analysis to deal with heterogeneous technology. In that framework the prices are related to the production function error and thus do not qualify to serve ast as instrumental variables.

The discussion assigns a key role to the allocation error, which may arise due to a difference between the prices perceived by the firm and those observed by the econometrician. Some of the prices are related to present transactions, whereas others are related to future transactions. Uncertainty prevails with respect to future prices and the firms construct their own forecasts. As discussed earlier, more than one forecast can be constructed on the basis of given information set and the choice depends on the risk and the attitude toward risk. When the utility function of the firm consists of expected profit and its variance, the allocation error is subject to the firm effect (Mundlak 2000 344-346). A more general approach is to express the utility function of the firm in terms of profits and additional arguments, in which case the price is not the only determinant of the inputs (Mundlak & Volcani, 1973). An illustration of the importance of this generalization appears in Mundlak (1971). Aside from that, there may be an error in the optimization. So far we have been dealing with micro data. At the market level, there is a difference between published market prices that represent some kind of an average and the prices observed by the firms, which reflect the positioning of the farms from the center.

The simplicity of the Cobb-Douglas function is costly in that it is too restricted. A natural generalization was to eliminate the restriction of unity elasticity of substitution, while still keeping it constant. This resulted in the constant elasticity of substitution (CES) function in the two inputs case (Arrow et al. 1961). With more than two inputs, there are several definitions of the elasticity of substitution, *all* of which converge to the two inputs case. This convergence is due to the singularity of the Hessian matrix and cannot serve as a proof of the quality of a particular definition. The correct lens through which to evaluate the elasticities of substitution in the theory of derived demand is discussed in Mundlak (1968).

The next stage was to generalize the specification to allow variable elasticity of substitution. Flexible functional forms were developed such as the generalized Leontief systems (Diewert 1971) and the translog function (Christensen et al. 1973). At that point the literature was expanding to cover other forms as well. The survey by Fuss et al. (1978) placed the discussion within a uniform framework of linear parameter functions and examined their structural properties.

The empirical literature deals mostly with a single aggregate output, even though output consists of more than one product. In principle, multiproduct function should be the first choice, but it turns out to be more complex to deal with empirically. There is the question of choosing an algebraic specification that will be parsimonious in the number of variables. Mundlak (1964c) discusses the imposition of the condition of rational decisions on the function, a subject that had been overlooked in earlier studies. An empirical application using separability to reduce the problem of colinearity through the use of the multistage CES function appears in Mundlak & Razin (1971).

The common practice is to express aggregate output as a function of aggregate inputs. There is a question related to the meaning of the aggregate product (Mundlak 1963b). The root of the problem is that the aggregate value output is not a single-valued function and its parameters depend on the output composition along the expansion path in the product space. This is a conceptual problem, which has not been dealt with empirically. To overcome this problem, we adopt the heterogeneous technology framework discussed below and consider the production functions of the individual products as techniques. In the absence of knowledge on the allocation of the aggregate inputs to the various products, it is assumed that this allocation represents a rational choice. Thus, with the appropriate assumptions about the technology and firms' behavior, there exists an optimal solution for the aggregate output conditional on the state variables. The latter include all the pertinent prices, fixed resources, the available technology and other variables describing the economic environment (Mundlak 2001a; Mundlak et al. 2010). The second-order approximation to the underlying efficiency frontier has a quadratic form in those variables.

Heterogenous tehnology

To pursue the subject of identification, we depart from the chronological order of the review and turn to heterogeneous technology (Mundlak 1988).[5] A common assumption in the empirical work has been that the observations in a sample are generated by the same production function (homogenous technology). In reality, firms choose which technology to employ jointly with their decision on the level of inputs. This is a fundamental property that cannot be ignored, yet is avoided in much of the literature. Because the circumstances within which firms operate differ, firms make different choices, so that the implemented technology is heterogeneous in that there may be more than one function associated with the generated data. Consequently, the observations in the sample represent moves between functions as well as movements along a given function; these movements are not independent. The empirical formulation, therefore, should allow for the dependence of parameters of the function and of the inputs on the state

[5] As a matter of terminology, a technique represents the most elementary process of production and is denoted by a production function. Technology is a collection of techniques.

variables. In that sense, the implemented technology is endogenous. A second-degree approximation leads to a quadratic function in the inputs and the state variables.

The economic environment is described by state variables consisting of the available technology, prices, constraints, and the like.[6] The available technology is thought to be the collection of all the available techniques, and as such it represents the state of knowledge. The determinants of the derived inputs and of the optimal output include the state variables and therefore in the present framework they cannot be used as instrumental variables. For instance, prices are associated with the choice of inputs, but also affect the choice of the function itself, and thus the instrumental variables fall into the category of state variables. The same argument also applies to the GMM estimator.

The foregoing discussion has dealt with the optimizing firm and is therefore micro in nature. The empirical application requires an explicit definition of the technology as observed by the firm and knowledge of the input allocation by the techniques. That information is generally unavailable, and what is available are observations of total output and input at the firm level, which are aggregates over techniques. The question is what meaning can be attributed to the aggregate function. The discussion hinges on the fact that the aggregate of the optimal values is well defined conditional on the state variables, but it is unobserved because the optimal values are not observed. The difference between the aggregate of the optimal values and the observed values constitutes an allocation error from the vantage of the econometrician. It is this allocation error which serves as an identifying variable in the estimation. The same idea applies to aggregates of micro-variables over firms.

[6] The term state variable has a different meaning in dynamic models, but it is the best one I can think of at this time.

The quadratic function in question is linear in logarithms, and the intercept and the slope are functions of the state variables. This way the function allows for structural changes and is related to the literature on variable coefficients.[7] The specific attribute of this formulation is that it relates the structural change to variables relevant to the economic performance and does not impose a single force of change. State variables, such as the available technology, represent evolution, whereas others, such as prices or policies, may cause cyclical or abrupt changes. It is part of the research to identify the pertinent state variables and to estimate the coefficients rather than enforce a single pattern.

The state variables and the effects play a similar role in that both generate a correlation between the inputs and the function error (jointness property). The question is whether we can account for the unobserved effects in terms of the observed state variables. To answer this, we extend the auxiliary equation in Mundlak (1961a) and regress the estimated fixed effects on the state variables and the inputs. This exercise can help to identify variables that "explain", and might replace, the effects in the equation. To achieve a good fit of this equation, the state variables should be subject to time and country effects and to a relatively small share of the residual in the total sum of squares. In the estimation of the production function for agriculture from a panel of countries discussed below (Mundlak et al. 2010), the state variables accounted for most of the time effect, but less so for the country effect. It remains for further research to try out another set of state variables that account for more of the country effect.

The information derived from the auxiliary equation may be insightful, but it does not affect the way the model is estimated. Suppose we find a set of variables that fully account for the effects and these are introduced into the regression, the OLS estimator of the pooled data

[7] A review of the subject appears in Mundlak (1978); Rausser et al.. (1982)

will be identical to the within estimator. This is pertinent in reading the more recent literature which has emerged out of a pronounced dissatisfaction with the within estimator because it has not been successful in solving the endogeneity problems. This criticism is actually about the results and their precision and not about the failure to solve the endogeneity problem. The claim is that too often the elasticity of capital is unrealistically low (Ackerberg et al. 2005; 2007). This is more of a phenomenon with micro-data rather than with aggregate data. In trying to reconcile this difference, we note that the firm's *present* level of capital is determined by expected *future* output, past decisions, and costs of adjustment in the capital stock. Consequently, there is an error of synchronization in that the within-firm annual variations in capital do not match the corresponding variations in current output. This problem does not exist in a panel of countries where aggregation washes out the synchronization error at the firm level. It is also muted in a between-firm regression because the between-firm variation in capital stock dominates the lack of synchronization between output and capital stock.

The innovation in the recent literature is the use of information on the evolution of the firm effect over time due to the dynamic decisions of the firm. An interaction term is added to represent the evolution. Because the interaction term is unobserved and not directly measured, the central idea here is to find a scalar variable that is a monotone function of the interaction. The function is inverted to extract the effect and replace it in the production function. This formulation, incidentally, does not contain a time fixed effect, which represents innovations common to all firms, such as the green revolution in agriculture or the appearance of information technology in all sectors. This omission is likely to affect the analysis when the two main effects dominate the variability of the interaction term.

Where does this approach take us? If the main effects are known and introduced as variables in the production function, the pooled data OLS estimate of the production function coefficients will be the within estimate. Thus, replacing the effects by their estimates introduces a measurement error. This cannot generate improvements over the within estimator.

Concern has been expressed that there is a great deal of diversity in the estimates from panel data depending on how the data are pooled (Griliches & Mairesse 1998; Mairesse, 1990). There are several reasons for this diversity. First, the jointness property causes inconsistency of the canonical between-regressions. Different pooling means different weights for the between regressions, and their bias changes accordingly, and so do the estimates. Second, the diversity is a problem when the working hypothesis is that the technology is homogeneous and all the observations are generated by the same production function. That is not the case when the technology is heterogeneous, so that different pooling of the data results in diversity of the implemented technology and thus in the estimated coefficients. The general model presented here indicates that one should expect diversity, and that, in fact, it serves as a starting point for the construction of more meaningful models. Third, there is a sampling error which reduces the precision of the estimates. This is particularly important for estimates based on the within transformation. Fourth, this is related to the functional form, discussed above.

Supply

For a long time it was the belief in academic circles influencing development policies that farmers do not respond to prices. On the basis of that belief, coupled with the assumption that domestic markets are isolated from world prices, it was thought possible to carry out polices that lead to deviations from world prices without affecting agricultural production. These premises provided the intellectual support for what is known as the bias against agriculture in developing countries. These premises are wrong. In this section I will deal with supply response, and with agricultural prices in the following section.

Supply analysis is related to that of production, but there is a difference in the questions that are asked. In the case of supply the questions are: do farmers meet the requirements of rational choice, what are their criteria for such a choice, and how long does it take them to respond to a change in the prices or other elements of the economic environment? The traditional supply analysis relates the outputs to prices. My first work in graduate school dealt with this subject, demonstrating the existence of price response (McCorkle & Mundlak 1956). The important issue of the timing of the response was introduced effectively to the literature by Nerlove (1956; 1958) through the distributed lags model, which assumed a uniform delayed response to price changes. That diverted interest to the pattern of time response of output to price changes. The simplicity of the model resulted in wide application. That simplicity, however, is achieved by imposing restrictions on the pattern of behavior which do not differentiate between the response in the short and in the long run, and by ignoring the dependence of the response of output to that of the inputs (Mundlak, 1966; 1967). In addition, the empirical results are sensitive to the time unit of the observations, and consequently the underlying dynamics does not differentiate between, say, weekly and annual observations (Mundlak 1961b). The flexibility of adjusting the inputs to price changes is discussed in the section on growth below.

How important are the constraints that generate the difference between short- and long-term elasticities? To answer this question, we can use the duality property by going from production function to supply. A simple exercise shows that the difference can be substantial, from which we learn that the dynamics of supply is related to the dynamics of the constraints removal (Mundlak 2000, pp. 209-10). This is particularly important for the capital constraints to which we return below.

One of the most challenging subjects in supply response is the explanation of the beef cycles, which last for about 8-10 years. This subject has broad implications for business cycles at large. The beef cycles are supposed to be easier to explain because the underlying technology is much simpler than that of the entire economy. The literature on beef cycles has dealt with explanations of past cycles, but has fallen short of a model that can accurately predict future cycles. To get an insight into the nature of the cycles, Mundlak & Huang (1996) compare the beef cycles in three countries, analyzing four series for each country – slaughter, price, stock of cows, and total herd. The paper shows the existence of cycles that feature a surprising regularity for all four time-series, thereby improving on the results and interpretation reported in the literature (Cf. Rosen et al. 1994). The significance of this finding relates to the way the dynamic decisions are made. The three countries exhibit very similar cyclicity in spite of their different technologies and economic environments, and this is a step forward in the search for an adequate model, because it directs the research towards the common element – breeding and slaughter practices. I have conjectured that the failure to replicate the cycles by simulation is related to the decision on the age of the slaughtered cows. The custom modeling assumes that the reduction of the size of the herd is achieved through the sale of the older cows because the number of their future offspring is smaller than for younger cows. Empirically, however, heifers are also sold, suggesting that there is also another mechanism for adjusting the herd size. With this extension the model should allow for two exit points.

Agricultural prices

The belief in the isolation of domestic agricultural prices from world prices was based on extreme differences in price *levels* across countries. Such differences can be attributed to several factors related, among other things, to trade policies, taxation and the value of the domestic currency. There is, however, a common trend of decline in world prices. The question of interest is whether domestic *relative* agricultural price changes are correlated to such changes in world prices. Empirical analysis shows that changes in world prices are transmitted to domestic prices and, furthermore, a large proportion of the variability in domestic prices can be attributed to the variability in world prices (Mundlak & Larson 1992). This implies that governments are limited in their efforts to isolate domestic markets because it is too costly in terms of domestic resources. The transmission of world prices is an indication of the existence of globalization forces in world agriculture. Interestingly, and not unrelatedly, there is also an association with the long-term swings in a country's agricultural land prices (Mundlak et al. 1998).

The strength of the contribution of world prices relative to that of the domestic component depends on the real exchange rate, and therefore depends strongly on macro-policies. On the face of it, macro-policies are geared to affect the economy as a whole and, as such, seem to be sector-neutral. That, however, is not the case, and, in fact, in real terms agriculture is more sensitive to macro-policies than nonagriculture. This is due to the fact that the tradable component in agriculture is more important than in nonagriculture, and consequently the world price component in agriculture is more important than in nonagriculture. The effect of macro economic policies on sectoral prices is demonstrated for the case of Argentina in Mundlak et al. (1990).

Agricultural productivity

Changes in output are decomposed to those caused by changes in inputs (TF) and in total factor productivity (TFP). Changes in TFP are viewed as a measure of technological change. It is noted that TFP measures the productivity change demonstrated by the implemented, and not by the available, technology. The two components are functions of the state variables, and thus a change in the state variables triggers a change in the two components. The degree of the change depends on the severity of the constraints on expansion, and therefore the relative importance of TFP and TF is determined accordingly.

There are numerous empirical estimates of the relative importance of TFP in agricultural growth, and results vary widely not only between countries, but also for a given country over time. Taking a long-term perspective, TFP in the US accounted for roughly 10 percent of agricultural output growth in the period 1800-1850, but gradually grew to practically 100 percent of output growth in the period 1950-2000 (Mundlak 2005).

Some view the TFP as the driving force of growth (Prescott 1998; Easterly &Levine 2000). This view is not supported by the experience of U.S. agriculture, which shows that in periods of strong agricultural growth the TFP constituted only a fraction of the total growth, whereas in periods of poor agricultural performance it was considerably higher than the output growth (Mundlak, 2005). This variability is consistent with the view that productivity changes are an economic phenomenon of which the available technology constitutes only one component.

The distinction between productivity changes and a change in the available technology helps us to reflect on one of the more popular propositions in agricultural development, namely the induced innovation. The proposition states that the resource endowment of a country dictates the innovation path of its agricultural technology. The claim is that in the land-abundant United States innovations were oriented toward labor-saving, whereas in Japan, where land was relatively scarce, innovations were oriented toward land-saving (Hayami & Ruttan, 1985). It is noted that the empirical support is based on actual inputs and output data, and as such it is related to the implemented technology rather than to innovations. A careful analysis shows that the changes in the implemented technology in both countries were labor-saving, and this is inconsistent with the proposition (Mundlak 2005). This is not to say that the idea is wrong; it is simply not substantiated by the data, however, and therefore a different approach is called for to identify what induces research and development.

Production function is a micro-concept connected with the decision-making unit. In a world of heterogeneous technology, firms choose the techniques and the inputs jointly, depending on the state variables. These are optimal values, and they are uniquely defined at the firm level conditional on the state variables. The aggregation over techniques and over firms yields the aggregate country optimal values. These optimal values are well defined, but not observed. The empirical macro production function is obtained from observed rather than optimal values. The differences between the observed and optimal values constitute the allocation error, which, as discussed above, serves as a source of identification. The technology set consisting of the optimal values defines the implemented technology. Since it is determined by the state variables, it is endogenous. The aggregate production function presumably imitates the micro function, but the two do not necessarily share the same properties. For instance, the aggregate function is not necessarily concave even when the functions associated with the individual techniques are concave, the reason being that the observations are generated by movements between functions and not only along a given function.

Cross-country variability in productivity largely reflects variability in the implemented technology even when the available technology is constant, whereas changes over time reflect changes in the available technology and its implementation. I now turn to review the empirical analysis of a panel data of countries, and also of time-series data for three countries. The empirical results demonstrate some of the ideas discussed above, and also provide evidence related to agricultural, and overall, development.

The natural inputs in the agricultural production function are land, capital, labor and fertilizers. Although measures of agricultural capital stocks are fundamental to such an analysis, such data have not been readily available for countries outside of the OECD. To overcome this deficiency, a panel data set on the capital stock for agriculture was constructed (Larson et al., 2000) and revised and extended for a recent study, using a sample of 30 countries for the period 1972-2000 (Mundlak et al. 2010).[8] The decomposition of the total sum of squares of the variables in the sample highlights the dominance of the between-country variations. In the case of output, they amount to 89.5 percent of the total, whereas variations over time amount to 9 percent, and the residual amounts to only 1.5 percent. A similar picture is obtained for all the inputs.

The estimated equation has the Cobb-Douglas form where the intercept and the slope are functions of the state variables. The results to be discussed here ignore the dependence of the slope on the state variables. In this case the state variables influence the estimation through the influence on the intercept.[9] Using the panel structure of the data, the three canonical regressions were estimated and turn out to be substantially different. This confirms the basic initial hypothesis that the regressions summarize the combined effect of changes in inputs and

[8] This modifies and extends Mundlak et al.(1999)
[9] For a discussion of the estimation of the full quadratic equation, see Mundlaket al. (1989).

technology. The dependent variable is the log of value added.[10] The within regression is considered to be consistent and serves as a basis for the discussion.

The estimates, conditional on the state variables in the sample, show high elasticities for capital (0.37), land (0.45), and fertilizer (0.10), and relatively low elasticity for labor (.09). These results are strikingly different from those reported in the literature related to the analysis of cross-country data, where the results are not obtained from within regressions, and are therefore inconsistent.[11] The high capital elasticity means that agriculture is capital cost-intensive. That is, in an environment of free flow of resources, agriculture is more sensitive than nonagriculture to the variability in the cost of capital, and less so to the wage rates. The elasticity of fertilizer is considerably lower than that obtained in the between-country regressions, but it is still too high according to economic considerations. Since the dependent variable is value added, the elasticity should be closer to zero (envelope theorem). A deviation from zero is inferred to signal a constraint on the supply of fertilizer, causing the shadow price to exceed the official price implicit in the calculation of value added.

To summarize the results of the between regressions, the capital elasticity is 0.83 in the between-time regression and 0.27 in the between-country regression. The high value of the between-time elasticity suggests that the pace of the implementation of changes in the available technology was strongly constrained by the level of the capital stock in agriculture. Similarly, the land coefficient in the between-time regression is high. The land elasticity in the between-time regression is 0.34, indicating an increase in the shadow price of land associated with the increase in productivity, while at the same time there was only a slight increase in the agricultural area. What is striking in the between-country regression is the low elasticity of land,

[10] On the relationship between value added and production functions, see Bruno (1978), and Mundlak et al. (2004).
[11] The early literature is reviewed in Mundlak et al. (1999)

0.02, and the high elasticity of fertilizer, 0.41. This suggests that the techniques used by the more productive countries were land-saving and fertilizer-intensive.

The contribution of the state variables shows that agricultural productivity was positively related to agricultural real prices and negatively related to their variability. This contribution of the incentives is over and above their contribution to the use of inputs. Also, agricultural productivity was positively related to countries' level of development, indicating that the infrastructure, physical and human, is conducive to agricultural productivity. Finally, institutional variables had no substantive effect on productivity.

The role of resource constraint in the implementation of new productive techniques is discussed in Danin & Mundlak (1979). The case in point is the green revolution, which has taken a long time to be implemented, despite its introduction of superior varieties of cereals. This raises the question: if it is so good, why not apply it without delay? The answer lies in the scarcity of resources needed to develop the irrigation systems and acquire the fertilizer supply for the growth of the superior varieties. This is demonstrated for the Indian Punjab, the flagship of the green revolution, in McGuirk & Mundlak (1992).

To place the results in perspective, we turn to a study of agriculture in three Asian countries, Thailand (1971-95), Indonesia (1961-98), and the Philippines (1971-98), based on time-series data for each country (Mundlak et al. 2004). As in the country panel discussed above, the dependent variable is the log of value added. The regression contains state variables measuring human capital, public investment and prices. The data are subject to multicolinearity and a principal components technique was used in the estimation.[12]

[12] Following Mundlak (1981), the largest number of principal components was eliminated so as to obtain the tightest confidence region for a given level of confidence.

On the whole, the results convey a similar message to that of the country panel. The sum of the input elasticities varied from 0.91 to 1. The fertilizer elasticity varied among the countries in the range of 0.061 - 0.084. The labor elasticity varied in the range of 0.144 - 0.199. Land was differentiated into irrigated and rain-fed land, and the elasticity of both kinds fluctuated around 0.5. The only substantive difference was in the capital elasticity, which varied from 0.031 for Indonesia to 0.415 for Thailand. The price elasticity of productivity varied between 0.034 and 0.320.

The empirical results demonstrate the use of the methodology; the question is what insight we gain into the economies in question. To answer that, we report the marginal value productivity (shadow price) of the major inputs reported in 1993 U.S. dollars and compared with those obtained from the panel of countries in 1990 U.S. dollars. The marginal value productivity, at the mean values, for fertilizers is 538 for Thailand, 842 for the Philippines, and 1493 for Indonesia. As indicated earlier, under the free flow of resources in a competitive economy the marginal value productivity should be zero. The computed values, therefore, indicate the magnitude of the distortion. Dividing the distortion by the market prices yields the distortion rate, amounting to 0.62, 0.92 and 2.01 for the three countries, respectively. For the panel, by comparison, the distortion at the median of all the sample points is 1097.

The shadow price of capital was 9 percent for Indonesia, 15 percent for the Philippines, and 20 percent for Thailand. The median value for the panel is 16 percent for fixed capital and 4 percent for capital of agricultural origin.

The situation for labor is more complex because of data problems. The marginal value productivity of labor and the wage rates in parentheses are 79 (311), 160 (349), and 108 (493) for Thailand, the Philippines and Indonesia, respectively. For the panel, the median marginal value is 307, and there are no data on wage rates. The story here is not the cross-country differences, but mainly the gap between the shadow wage and the reference wage.[13]

The gap between the shadow and actual prices triggers changes in inputs, and thereby in shadow prices, over time. When the production function is held constant, it is expected that the changes in inputs will lead to a closure of the gap. When the function is allowed to change, the direction of the inputs change is ambiguous. In the present case, the shadow prices decline for fertilizers but increase for labor in all three countries, thus representing the dominance of movements resembling those along a given function. As for capital, the shadow prices decline sharply for Indonesia, mildly for the Philippines, and rise for Thailand. The Thai case is consistent with capital-intensive technological change.

Finally, despite the fact that the green revolution was the major event affecting the three countries, the relative importance of the TFP in the growth of agriculture was far from equal: 10 percent in the Philippines (1961-1998), 32 percent in Thailand (1971-1995), and 44 percent in Indonesia (1971-1995). On the other hand, the new technology attracted capital and fertilizers and also augmented their elasticities, and this is reflected in the relatively high share of TF in the total growth.

Agricultural growth

The work on long-term forecasts for Israeli agriculture aroused my interest in developing an analytic framework for the evaluation of agricultural growth in relation to overall growth. The

[13] For Thailand and the Philippines, the data report daily wages, while labor is annual. To obtain annual wages it is necessary to assume the actual employment in agriculture. Labor is defined as the economically active population in agriculture. Because of the seasonality of agricultural production, not all of the labor is fully engaged in production all year around. The annual shadow wages are obtained under the assumption of 150 days per year of active employment in agriculture. The problem does not exist for Indonesia where the reported wages are on an annual basis

framework consists of two major components: first, viewing agriculture as a sector in the economy and, second, identifying and quantifying the dynamic forces that determine the pace and direction of agricultural growth. I first presented an early formulation of agriculture as a sector in the framework of a two-sector economy in Mundlak (1969). The supply side of the model is common to models used in trade theory, where the demand is dictated by world prices and independent of domestic decisions. The contribution lies in adapting the model to agriculture through the introduction of demand functions, which is essential to the understanding of agricultural growth. The comparative static framework is sufficient to identify major forces that affect the trajectory of agriculture, such as the importance of low income and the price elasticity of demand, and the impact of technological change in agriculture, and in nonagriculture. These forces are responsible for the global phenomenon of the declining relative position of agriculture in the economy. The dynamic aspect deals with the pace of technological change and of resource allocation in a non-equilibrium position (Mundlak 1970; Mundlak & Trop 1980). The incorporation of heterogeneous technology in growth analysis is discussed in my Waugh Lecture at the American Agricultural Economics Association (Mundlak 2001b).

The dynamic forces have generated an excess supply of labor in agriculture and that leads to labor migration from agriculture to the rest of the economy. The pace of this migration is not sufficient to equate the wage rates across sectors for any long period of time. This wage gap has been viewed by agricultural economists as an indication of a chronic disequilibrium in agriculture, (Schultz, 1947; Griliches 1963; Gardner 2002). The view is based on static considerations, and it is inconsistent with the assumption that farmers are rational and efficient. The problem is resolved when the behavior over time is viewed as a dynamic process in which potential migrants evaluate their lifetime opportunities. This leads to the empirical migration equation, which relates the rate of labor migration to nonagriculture as a function of the income differential between the two sectors (Mundlak 1978b; 1979; Larson & Mundlak 1997). Similar considerations apply to the flow of capital to agriculture.

The various subjects discussed above were all pulled together to construct a dynamic growth model describing the evolution of Argentinean agriculture during 1940-1972 (Cavallo & Mundlak 1982), later extended to cover the period 1913-1984 (Mundlak et al. 1989). The model incorporates a price block that traces the evolution of agricultural prices, taking into account the impact of the macro and trade policies on the relative agricultural prices, an input block, which contains the intersectoral resource flow, and a production block. All the blocks are affected by the state variables that influence the implemented technology. The model has been used to simulate the growth of Argentinean agriculture. Sensitivity analysis was conducted to detect the impact of possible changes in past policies on the evolution of agriculture and the economy at large. The exercise shows that the policies matter substantively, and that it is possible to generate a considerable amount of growth by maintaining an economic environment that facilitates the full expression of the potential embedded in society. For instance, to be concrete, the conclusions apply to crop yields. Yields of the 20 most important crops in Argentina were above those in the U.S. until about 1920, at which point they started to lag behind. The gap then grew for a long time, but started to narrow in response to the economic reforms of the 1990s. I had another opportunity to review the model when asked to write a chapter on agriculture for *Essays in the New Economic History of Argentina*, 2003. In that chapter, coauthored with M. Regδnaga (Mundlak & Regδnaga 2003), the time coverage was extended at both ends, backward to 1880 and forward to 1998. The conclusion was that, without the necessary economic environment, the economy fails to utilize its potential. The fact that a country is blessed with natural resources increases the potential, but doesn't make the challenge of utilizing it any easier. The conclusion is reinforced by a straightforward comparison of events in the difficult period of the 1980s with the post-reform period in the 1990s. The analysis is also consistent with the developments of the first 40 years following the consolidation of the federal government in 1880.

Together with J. E. Coeymans, I studied the role of the economic environment on sectoral growth in Chile in 1962-1982, a period of major political and economic changes. The study differs from the Argentinean studies in some structural details, but reaches a similar conclusion – it was only when a stable macro environment was achieved that agriculture, and the economy at large, started to grow (Coyemans & Mundlak 1993).

To place the view on economic development in perspective, I examined the development of U.S. agriculture over a very long time span, from 1800 to the end of the 1990s. The study is based on the literature, in large part by economic historians. Again, the paper highlights the importance of the economic environment to the development of American agriculture. Specifically, it appears that the two important revolutions in U.S. agriculture – the change from human power to draft power and, later, the change to tractor-driven cultivation – took place only when the incentives were there, even though the technology had been known for some time. The first revolution occurred around the Civil War, the second in connection to World War I. The paper uses the analytic framework to review the developments in agricultural technology, productivity, prices and resource allocation along the lines discussed above.

Finally, my 1997 Elmhirst Lecture at the International Conference of Agricultural Economists summarizes the global picture and its policy implications, and highlights some important welfare implications of agricultural development (Mundlak 1999). I argue that improved technology caused supply to grow faster than demand, resulting in a continuous decline of real agricultural prices. This in turn fostered the labor migration out of agriculture and thereby mitigated rural poverty. The long-term swing of land prices, measured in terms of the consumption good, barely changed, meaning that the benefits of agricultural growth were enjoyed mainly by consumers and by the economy at large, due to the labor supply flowing out of agriculture and thus facilitating the development of nonagriculture. I argue that the benefits to society at large justify the public investment in agricultural research. This conclusion is consistent with private spending on such research, which naturally is forthcoming only after the evaluation of the expected profits.

Much of this work, including the methodological contributions, constitutes the core of Mundlak (2000).

Final word

I was asked to conclude with a message about future work. I would suggest adhering to the following sage advice from Herman Melville ("Hawthorne and His Mosses," from *The Literary World* (1850)): *It is better to fail in originality than to succeed in imitation.*

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