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THE DYNAMICS OF SUPPLY: RETROSPECT AND PROSPECT *

by

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"...Per altra via, per altri porti
verrai a piaggia, non qui per
passare..."
Dante Alighieri, <u>Inferno</u>. Canto III vv. 91-92

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1. Introduction

It is, I think, safe to say that there are few topics of greater current interest than the agricultural production and food supply problems in low-income and developing economies. In the preface to the proceedings of a recent conference on "Distortions of Agricultural Incentives," T. W. Schultz (1978, p. vii) wrote:

> "The biological constraints on potential food production have been substantially reduced by advances in agricultural research and by the availability of additional capital. But it has become increasingly evident that the adoption of the research contributions and efficient allocation of the additional capital are being seriously thwarted by the distortion of agricultural incentives."

I also concur in Schultz's belief that (1978, p. 4):

> "Farmers the world over, in dealing with costs, returns, and risks, are calculating economic agents. Within their small individual, allocative domain they are fine-tuning entrepreneurs, tuning so subtly that many experts fail to see how efficient they are. . ."

Often costs and returns which individual farmers confront are expressible in terms of market prices, although the risks they face are usually not so easily quantifiable. Whether or not, however, such market forces impinge directly and visibly on individual farm entrepreneurs, it will nonetheless be true, if we accept the presupposition of optimizing behavior, that shadow prices and opportunity costs are crucial determinants of agricultural supply. It follows that responses to changing "prices" for outputs and inputs, whether made visible by markets or not, must be a key element in our attempt to understand the agricultural production and food supply problems in low-income and developing economies, as well as in the highly efficient and productive agricultural sectors of the developed and high-income countries of the world.

In what follows I examine what has been done on the problem of measuring agricultural supply response since the publication of my own work on the subject more than two decades ago (1956, 1958). Much of this work, that available in English and done up to about 1976, has been exhaustively summarized by Askari and Cummings (1976, 1977), on whom I principally rely. Although many useful and interesting modifications have been made, particularly in applications to dynamically complex production processes, such as those for perennial crops and livestock, and to the study of agricultural supply response in developing economies, the adjustment and expectational models which were used in my own work remain basic in most of what has subsequently been done. In a lecture delivered in 1970 to the World Congress of the Econometric Society and later published (1972), I pointed out the *ad hoc* nature of most distributed lag formulations used in empirical econometrics, including those resulting from the models used in my work on supply, and entered a plea for the development and implementation of "econometrically relevant" dynamic models of optimizing behavior.

It is easiest to see the need for such dynamic models in the case of production processes which are *biologically* of relatively long duration, such as those for perennials and livestock; moreover, the biological structure can be used, in the first instance disregarding other durable inputs, to determine the dynamic structure (Carvalho, 1972; Nerlove, Grether, Carvalho, 1979, pp. 327-353). It should be emphasized, however, that the same arguments apply to any processes involving durable inputs, including structures, implements, and improvements to land, and it is less easy to develop appropriate models which capture essential dynamic features in these cases. Following a brief review of what has been done on the problem of measuring agricultural supply response, I turn to the question of how to make distributed lag formulations less ad hoc, in the sense of being based on dynamic optimizing behavior, specifically within the context of livestock and perennials.

This discussion does not fully resolve the dynamic problems involved in studying agricultural supply response in the context of a developed economy; moreover it does not touch at all on the essential dynamics of supply response in developing economies. Below, I suggest that to understand these dynamics it is essential to consider the causes of changes in the agricultural sector, the complex of forces set in motion by technological improvement, public investment in infrastructure and the development of markets, and the differential abilities of economic agents to deal with the resulting disequilibria. In most developing economies the agricultural sector is so large and so central to the whole process of economic growth and demographic change, that supply response cannot be treated as an isolated phenomenon. Moreover, in these economies, markets, at least as we know them in developed economies, may be poorly organized or may not exist at all; it follows that the relevant "prices" motivating producer behavior may be difficult or impossible to observe directly. Many of the trade-offs in the allocation of resources may take place within individual farm households or between these households and relatively isolated labor or product markets. Traditional methods of aggregative time-series analysis of supply cannot even begin to capture these kinds of responses.

Finally, I attempt to draw some general conclusions about the data and analytical methods needed to push forward further the frontiers of our knowledge of the dynamics of supply in a complex and developing world.

2. Retrospect

In their exhaustive survey of the English language literature on agricultural supply analysis, Askari and Cummings (1976), take note of more than 600 estimates of supply response to price. The studies surveyed deal, for the most part, with annual food crops in developed countries or in areas for which reasonably good price data exist, e.g., South and East Asia. A number of studies surveyed cover non-food annual crops such as fibres and tobacco, semi-perennials such as sugar, perennials such as cocoa, coffee, tea and rubber, and livestock and livestock products. The last group are all for developed countries for which livestock data are relatively complete. Although many of the studies, particularly those dealing with perennials, introduce important modifications and extensions, the basic model employed in most is the formulation I advanced some years ago (1956, 1958). Stripped to its essentials, this model for an annual crop consists of three equations:

(1) $$A_t - A_{t-1} = \gamma\,(A_t^* - A_{t-1})$$

(2) $$P_t^* - P_{t-1}^* = \beta(P_{t-1} - P_{t-1}^*)$$

(3) $$A_t^* = a_0 + a_1 P_t^* + a_2 Z_t + u_t$$

where

A_t = actual area under cultivation in t,

P_t = actual price of the crop per unit in t,

A_t^* = "desired" or equilibrium area to be under cultivation in t,

P_t^* = "expected normal" price in t. for subsequent future periods,

Z_t = other observed, presumably exogenous, factors

u_t = unobserved, "latent," factors affecting area under cultivation in t, and β and γ are "coefficients of expectation and adjustment" reflecting the responses of expectations to observed prices and observed areas under cultivation to changes in equilibrium areas.

The statistical problems of estimating a model such as (1)-(3), particularly of identifying relevant observed exogenous variables, not subject to expectational lags, and problems due to serially-correlated disturbances are well-known. In addition, the use of area cultivated, one input in the production process to represent planned output, the problem of choosing the relevant price or prices, and other issues of specification, such as the inclusion of expected yields, weather conditions, and price and yield variances to take account of elements of risk, have been widely discussed in the literature.

Important modifications of the basic model have been made in connection with its application to cereals and basic food crops in developing countries. These commodities are at least partly consumed on the farms on which they are grown so that a key question becomes the response of marketed surplus to price. Among the studies of particular interest are those of Raj Krishna (1963, 1965) for rice and wheat in the Punjab, of Behrman (1966, 1968) for rice and other food crops in Thailand, and of Nowshirvani (1968) for a number of food grains in various regions of India. An important point made in these studies is the need to take into account the income elasticity of consumption within the farm household. Nowshirvani (1968, 1971) shows also, in a model involving both food grains and strictly cash crops and a farm-household utility function expressing risk aversion, that stabilization of food prices may sometimes lead to a reduction in supply. Askari and Cummings (1976, pp. 52-162) discuss a very large number of such studies, including some for food grains in developed economies. Some of the investigations also introduced prices of other factors, size of farm, and variables related to irrigation, tenancy status, health, and so forth.

Using their collection of elasticities, Askari and Cummings (1976, pp. 342-382) attempt to get at some of the factors which might explain variations in supply response to price across regions and commodities, finding that higher income levels and larger farm sizes, availability of irrigation and reduced yield variability, greater literacy levels, and ownership as opposed to tenant-status, all increase responsiveness to variation in output prices.

I return below to some of the problems I see in these applications of the basic supply response model on a crop-by-crop basis in developing economies in which substantial changes are occurring in the availability of new varieties and of inputs other than land and labor, and in which major improvements in infrastructure are taking place.

Applications of the basic model have also been made to various non-food annual crops such as cotton, jute and tobacco. (See Askari and Cummings, 1976, pp. 163-218). Perhaps the most interesting applications and modifications of the basic model, however, are in connection with perennial crops. Such crops, once planted, yield a flow of output, continuously or discretely, over a period of years. Many are tree crops, which must mature several years after planting before any output is forthcoming, and for which thereafter yields are dependent upon the age of the tree and may also depend upon other inputs. In the earliest studies of perennials, the vintage or effect of the age distribution of the stock has been noted, and the decisions to plant new stock or cull older trees have been viewed as investment decisions under uncertainty, at least with respect to product prices, if not also input prices or prices of crops which might compete for land or labor. Moreover, the decision to harvest from a given stock at any particular time may also reflect opportunity costs or labor costs during and immediately surrounding the harvest period.

A number of difficulties arise in connection with the study of many perennial crops in developing countries. First, except in rare instances, continuous information over time is lacking on new plantings and current age structure, although such information may be available irregularly. This means that a key variable in the analysis, namely the age distribution of the stock, may have to be determined within the supply model itself, i.e., inferred from a time series of actual output (Hartley, 1979). Second, government intervention in the marketing of perennial crops is wide-spread. One effect, for example, in the case of Ghanaian cocoa, is to lead to smuggling of significant amounts of output. The existence of marketing boards which create substantial spreads between prices paid to producers and the prices at which the crop is sold and which hold large stocks of the commodity in question may also lead to significant problems in formulating appropriate models of expectation formation (Bacha, 1972). Third, as indicated above, there is frequently an imperfect relation between output and the stock of the perennial, since the existence of alternative uses of other inputs and variable prices and yields makes the decision not to harvest, or to harvest only partially a viable option. Depletion of the stock may vary not only because of culling but because of the differential effects of weather and disease. Finally, technical change in the form of improved varieites introduces a new element of uncertainty especially in view of the long time horizon.

Notable among the studies of perennials are those of: Bateman (1965,1968), Behrman (1968) and Stern (1965) on Ghanaian cocoa; Behrman (1969), Stern (1965) and Chan (1967) on Malaysian rubber; and by Arak (1967, 1968, 1969) and Bacha (1968) on coffee. Most of thest studies utilize stock adjustment models and price expectation formation models similar to (1) and (2) above but adapted to the long lags involved between planting and the emergence of output. Stocks are inferred from a sequence of outputs so that the models quickly become rather complicated, especially when a competitive relation between several perennial crops is considred. Wickens and Greenfield (1973) have been critical of previous investigations for neglecting the important distinction between investment and harvesting decisions and have attempted to estimate a more complex model for Brazilian coffee. The most elegant work to date on perennials is that of French and Matthews (1971) on U. S. asparagus (a perennial crop with a bearing life of 10-15 years). Their model distinguishes between the quantity of produce and bearing acreage, new plant and removals of old plants. It must be recognized, however, that the data available are greatly superior for this crop than for most perennials important in developing countries.

Livestock and livestock products have been studied mainly for developed economies. The most common approach has been to employ some variant of the adjustment model (1) applied to a measure of "capital stock." In the case of milk, for example, in which production is continuous, seasonal factors have been introduced. Various combinations of current and lagged prices are used but rarely has much specific attention been devoted to the problem of expectations formation. A large number of studies is summarized by Askari and Cummings (1976, pp. 299-341) notable among which are Halvorson (1958) and Gardner (1962,1972) on milk, Dean and Heady (1958) on hogs, and Jones (1965) and Jarvis (1969, 1974) on beef. My own work with Carvalho and Grether (1979) and Carvalho (1972) is discussed below since it is of a rather different character than the aforementioned studies.

While Jarvis (1969, 1974) did attempt to estimate a specifically capital-theoretic model, he was handicapped by lack of data on births and had to reconstruct them from herd size, slaughter and deaths. Mascolo (1979) had similar problems in his study of the Brazilian cattle industry in which, however, he attempts to follow the lines of Nerlove, Grether, and Carvalho (1979) and Carvalho (1972).

Despite the greater complexity of perennials and livestock in a dynamic sense, there does not appear to have been an attempt to go beyond an essentially static formulation of the demand for the stock from which output is produced. Dynamic considerations are introduced through fixed, biologically determined lags together with *ad hoc* stock adjustment and/or price expectation formation models, such as (1) and (2), originally used in the study of annual crops. In the next section, I address myself to this issue and show how more econometrically relevant dynamic models can be constructed for livestock and perennials under certain simplifying assumptions. Many of the same arguments can be made with respect to annual crops if long-lived capital equipment, structures, or land improvements are significantly involved in production. In the section following the next, I take up the far more serious difficulties encountered in the study of agricultural supply response within the kind of dynamic setting encountered in a developing economy in which the agricultural sector is concurrently being transformed from traditional to modern.

3. Distributed Lag Models of Supply Response Based on Dynamic Optimization Behavior

The basic supply response model discussed in the preceding section incorporates dynamic elements in two different ways: First, a distinction is made between a long-run equilibrium position toward which producers are assumed to be moving and their current position. The former is determined on the basis of a *static* theory of optimization, in this case the standard micro-economic theory of the firm and the assumption that the exogenous variables of the problem, in this case mainly prices, are given once and for all. Elsewhere (1972, p. 225), I have called this the assumption of static, or stationary, expectations. The important point is that whatever these expectations are and however they are formed, the concept of a long-run equilibrium solution to the optimization problem is well-defined only if it can be assumed that the values of the exogenous variables expected in the future are unchanging; it does not matter if the constant future value of each variable differs from its current value, as indeed it plausibly will. Having a well-defined notion of a long-run equilibrium position then permits us to examine the question of why producers are currently at a position different from that equilibrium. At this point the discussion usually becomes vague; one can argue in various ways (Nerlove, 1972, pp. 228-231), but perhaps the most common approach is through the introduction of adjustment costs. Rarely, however, are models explicitly introducing these costs formulated on the rationale for such costs carefully examined. (The literature up to about 1970 is surveyed and two models of investment behavior incorporating both separable and nonseparable adjustment costs are discussed in Nerlove,1972, pp. 231-241; see also Nerlove, Grether, Carvalho, 1979, pp. 317-320.) The dynamic element in the basic supply response models is introduced at this point without a formal theory by the simple ad hoc assumption that each period, if we are dealing with discrete time, a fraction of the difference between the current position and the long-run equilibrium is eliminated,i.e., equation (1) above.

In the next section, I argue that the matter of adjustment to equilibrium, if indeed equilibrium is an appropriate concept, in the agricultural sector of a developing economy in the process of transformation is far too important to be treated in such an *ad hoc* manner. The simple adjustment process assumed in the basic supply response model is undoubtedly also inadequate to describe the dynamics of supply in a developed economy in which technical change is occurring at a rapid, if uneven, rate, and in which the demands for agricultural outputs and the supplies of inputs are subject to substantial shifts. In the case of perennials and livestock, however, there is no need to introduce an *ad hoc* adjustment model since the intrinsic biology of the production process already provides most of the essential dynamic structure.

The second way in which dynamic elements are incorporated in the basic supply response model is through a description of expectation formation, e.g., the adaptive expectations generated by equation (2), in which expected "normal" prices are revised each period in proportion to the difference between last period's observed price and the previous expectation. Above, I argued that static, or stationary, expectations are necessary to make the concept of a long-run equilibrium meaningful; the adaptive expectations model does not violate this principle, since it is not solely next period's price to which P_t^* refers but "normal" price, i.e., an average price expected to prevail in all future periods. The argument that farmers rationally should respond, not to the best forecast they can make of next period's price, but rather to some average or "normal" level, rests intuitively on the idea that there are costs of adjustment. However, virtually any plausible model one can construct, with costs of rapid adjustment of, say, a durable factor of production, will generally involve response to prices in many future periods although the weights which attach to the more distant future will usually be be less than to the near future. Moreover, unless the optimization problem has a specific form, it will generally be nonoptimal to behave as if one were responding to a point estimate of each future value. (Theil, 1957; see also the discussion in Nerlove, Grether, Carvalho, 1979, pp.334-33 When the optimization problem is of this specific form, however, we say that there exist certainty equivalents to the uncertain future values of the variables to which response is occurring. Such certainty equivalents are the conditional expectations of the variables to which they refer; they are minimum-mean-square-error forecasts based on the information available up to the time the forecast is made and taking into account the structure of the system generating the data. Muth (1961) has termed such forecasts "rational expectations."

Apart from whether they are certainty equivalents, when are adaptive expectations rational in the sense of being conditional expectations? Muth (1960) provided an early answer to this question which I later generalized (1967). For a simple unobserved-components model of the time series of, say, prices, it can be shown that the minimum-mean-square-error forecast for next period and for every future period is the same exponentially weighted moving average of past values (Nerlove, Grether, Carvalho, 1979, pp. 320-303). In general, several endogenous variables, such as prices and quantities, will be determined by a series of structural relationships, such as supply and demand functions, reflecting the behavior and expectations of different groups of economic agents, such as farmers and consumers. In this case, the behavior of farmers who respond to to conditional expectations of an endogenous variables, such as price which is determined in the market by the equilibrium of supply and demand, cannot be characterized so simply: generally the distributed lag relationships will contain parameters of the structural system, as well as parameters reflecting the serial properties of the structural disturbances. These relationships among the structural parameters and the characterizations of the conditional expectations of endogenous variables imply certain restrictions on the form of the minimum-mean-square-error forecasts of future variables.

Time-series modelling and forecasting is a complex subject of considerable current interest. Much of the recent literature leads away from the structural equation approach of traditional econometrics. Single and multiple time-series models are formulated in terms of fairly simple moving-average autoregressive processes (ARMA processes) involving relatively few parameters (Nerlove, Grether, Carvalho, 1979, pp. 103-146). If the exogenous variables of a structural system are expressible in terms of ARMA processes, or if their effects can be removed prior to analysis, then under certain conditions, the final form of a structural equation system can be reduced to one in which each endogenous variable is expressible in terms of an ARMA process, which, however, may be relatively complex and involve restrictions across the various representations (Zellner and Palm, 1974; Wallis, 1977) . A simple supply and demand example is contained in my recent book with Grether and Carvalho (1979, pp. 302-308). There, we call conditional expectations, or minimum-mean-suqare-error forecasts, based on univariate or multivariate time-series analysis neglecting such restrictions as may arise from the simultaneous determination of several endogenous variables with a structural system, quasi-rational expectations. Such forecasts are easy to obtain by formulating and estimating relatively simple univariate or multivariate time-series models (a univariate model being one in which only information on the past of the series itself is used, whereas a multivariate model allows the information contained in the past values of related series to be used in estimation and foreeasting). If we assume the economic agents, whose behavior we are attempting to describe, are aware of the underlying structure, quasi-rational expectations offer an approximation to fully rational expectations and a far less arbitrary, less *ad hoc*, approach to expectation formation than the adaptive expectations used in the basic supply response model. In general, however, such forecasts will not be the same for different future periods, i.e., they will not represent static or stationary expectations in the sense defined above.

If, then, we reject the adaptive expectations model, and, with it, the proposition that farmers respond to the expectation of some average of prices in all future periods, we must also dispense with the notion that farmers are adjusting toward a well-defined long-run equilibrium in each period, because this equilibrium is well-defined only for stationary expectations. I hasten to add that this does not mean stationary equilibria are totally irrelevant in the analysis of agricultural supply response; indeed, a long-run equilibrium with stationary expectations may characterize traditional agriculture in countries prior to development and may approximate the final position of farmers after response to a one-time major shock. This, however, is not dynamics but comparative statics. As I have argued elsewhere (1972), an econometrically relevant dynamic theory would characterize response paths of economic agents who are optimizing their behavior under dynamic conditions and forming expectations of the future on the basis of all information available to them. Such a theory would not, in general, involve the notion of a long-run equilibrium toward which adjustment is being made nor simple forms of stationary expectations. Formulation of models based on this principle is not an easy task, nor may you think it worth the effort when you have seen the example of a recent attempt to model the U. S. cattle industry, to a brief sketch of which I now turn.

A simplified model of the U. S. cattle industry was developed and estimated by Carvalho (1972); a modified version of this model is presented and reestimated in the final chapter of Nerlove, Grether, Carvalho (1979, pp. 327-353). Neither the market for feed nor the milk sector are considered explicitly, although these markets impinge on the cattle market through the costs of inputs and the prices of beef, especially utility beef and veal,which come in large part from the dairy sector. The reproductive herd consists of cows, heifers older than 18 months, and bulls. The latter are neglected. We assume the production of young animals to be proportional to the size of the reproductive herd and that one-half ot these are males which are castrated to become steers. The optimal decision concerning heifers is whether:(1) to slaughter, (2) to place on feed, (3) to add to the reproductive herd, or (4) to breed, in which case the heifer becomes a cow by definition. In the case of a steer, however, there are only two choices: (1) to slaughter now, or (2) to keep on feed. Cows may be: (1) kept in the reproductive herd, (2) placed on feed, or (3) sold for slaughter. Additions to the stock of cows occur through the addition of newly-bred heifers; subtractions occur through the sale of cows for slaughter or natural mortality. (The latter is small and we neglect it.) Because there are biologically determined lags between the time a cow can be bred and the time her offspring can be slaughtered, added to the reproductive herd, or placed on feed, and because there are intrinsic costs of aging which make it unprofitable to hold an animal forever, there is a natural dynamic structure in this problem: What the producer does now will affect the constraints under which he operates for some time into the future,but not forever; therefore his current decisions must reflect what he now expects conditions will be in relevant future periods; but, because the lags involved are finite and animals cannot be held forever, the <u>indefinite future</u> does not matter. The same dynamic characteristics also apply in the case of perennial crops. When very long-lived capital is involved in a production process, then, in principle, the very distant future is involved in current decision making, but, if the future is discounted and if capital depreciates, in practice only the near future will mater.

In the empirical example reported in Nerlove, Grether, Carvalho (1979, pp. 338-353), we choose calendar quarters as our observational unit. Specifically: The gestation period is 9 months or 3 quarters; we assume births are proportional to the stock of cows in the reproductive herd and that one-half of all births are male; bulls are neglected and we assume that an animal is not considered added to the stock of heifers or steers on feed nor to the reproductive herd until nine more months have passed. The decision variables each period are numbers of: (1) Steers to be sold, (2) Heifers to be sold, (3) Heifers to be bred,i.e., placed in the reproductive herd, and (4) Cows from the reproductive herd to be sold for slaughter. Given prices for steers, heifers, and cows, gross revenues are a linear function of the numbers sold in each category provided we assume, as a first approximation, that price is independent of age; however, in our formulation we also introduced quadratic terms reflecting "aging costs" for each of the three categories, so that longer retention of an animal results in a lower "net" receipt. The decision variables are conditioned by the stocks of steers and heifers on feed, by the size of the reproductive herd, and by births 9 months ago. The decision variables and conditional variables are constrained by a set of linear identities expressing our assumptions about the nature of the lags involved. In addition to aging costs, we assume quadratic costs for maintaining animals on feed or in the reproductive herd, different for steers, heifers and cows, and an additional quadratic cost for maintaining calves each period prior to the time at which they can be allocated to one of the stocks or slaughtered. We also assume a "breeding" cost over and above the cost of maintaining a cow in the reproductive herd. Feeding costs plus aging costs are assumed to reflect variations with age both in the ability of an animal to transform feed into flesh and the decreasing value, <u>ceteris paribus</u>, of older animals. We assume that the cattle producer makes his choices so as to maximize the expected discounted present value of future net revenues from sales of steers, heifers and cows to some finite, but distant horizon (retirement), subject to uncertain future sales prices but <u>known constant</u> aging, feeding, breeding and maintenance costs and a constant rate of discount. Because of the structure of the problem, the finiteness of the horizon, in fact, turns out not to matter.

Since our objective function is quadratic in the decision variables and the uncertain prices and since all the constraints among these variables are linear (see Nerlove, Grether, Carvalho, 1979, pp. 335-337), there exist certainly equivalents for the unknown future prices, namely their conditional expectations at decision time, given past values of these variables, which, in the present problem, we assume are all the information at the disposal of the cattle producer. (In a more complete and complex model we might also wish to consider demands for various types of cattle as well as the market for feed and other inputs; in this case the distinction between rational and quasi-rational expectations would become important.) The existence of certainty equivalents means we can replace prices by their conditional expectations and proceed as if we were dealing with a problem of decision making under certainty. The problem as formulated is now a relatively simple dynamic programming problem which, if numerically specified, could be solved by standard methods. However, as we have set the problem up, it is <u>not</u> numerically specified: the discount rate and aging, feeding, and maintenance costs are all behavioral or technolgical parameters, or some combination thereof, to be determined by <u>estimating</u> the model. What equations do we estimate? Presumably one each for each of the four decision variables:

The stocks of steers and heifers, the size of the reproductive herd, and new gross investment, i.e., the number of heifers added to the reproductive herd. Alternatively, equations determining any four equivalent variables related to the foregoing by the identities referred to above may be estimated. To find these equations, we must solve the dynamic programming problem algebraically in the usual recursive manner, backwards from the end of the horizon; the solution will generally differ depending on the number of periods to go to the end of the horizon; however, because of the nature of the lags involved, the solutions "stabilize" after a certain number of periods back. The number of periods differ for the different variables: It is only one quarter for steers, but five periods for heifers and additions to the reproductive herd, and four periods for cows. (See Nerlove, Grether, Carvalho, pp. 345-366, for an intuitive explanation.) When we say the solution stabilizes we mean that it is the same after, say, six periods as it is after five. A stable solution equation thus characterizes current producer behavior and provides a basis for estimation.

The characteristics of the stable solutions are as follows: The "own-demand for the stock of steers" depends upon the current price of steers in relation to the price expected next period and the size of the reproductive herd 4 periods ago. The "own-demand for the stock of heifers" depends on the current price of heifers in relation to the expected prices, 1, 2, 5, 6 and 7 periods from now, the current price of cows in relation to the expected prices 1 through 4 periods from now, the expected prices of steers 5, 6, and 7 periods from now, and the current and past 4 values of the size of the reproductive herd. Similarly, gross additions to the reproductive herd and the own-demand for the stock of cows depend on the current and expected future prices of heifers and cows, the expected future prices of steers, and certain past stock variables. If we now formulate time-series models, in principle multivariate but possibly univariate, in order to obtain quasi-rational expecations as minimum-mean-square-error forecasts, the latter may now be substituted for the unknown conditonal expectations of future prices. In this way, implicit distributed lag relationships are obtained; however, it should be emphasized that the behavioral relationships deduced in this manner do not explicitly involve any distributed lags. If the exogenous variables which drive the system, in this case the prices of steers, heifers, and cows were suddenly to become fixed at certain levels and thereby cease to follow the time-series models we had estimated for them, but cattle producers, implausibly, continued to assume that they did, the system would proceed over time to an equilibrium solution in which all variables remained unchanged forevermore. The same equilibrium would be reached, although the path to it would be different, if the same levels of prices were announced and believed with certainty. But this equilibrium is only implicit in the dynamic structure; it does not, in any sense, correspond to a long-run equilibrium position which is continually changing and toward which cattle producers are continually adjusting.

Although it is undoubtedly grossly over-simplified as a model of U. S. cattle production, we have estimated the model partially for the period 1944-69 using quarterly data. The results are reported in Carvalho (1972) and modified results in Nerlove, Grether, Carvalho (1979, pp. 348-353). The reader is referred there for the empirical detail. My discussion here serves primarily to illustrate how econometrically relevant dynamic models of behavior can be constructed on the basis of optimizing behavior without recourse to the many arbitrary or ad hoc assumptions. Some of the latter must, of necessity, remain in any practical formulation, the most crucial of these being the assumptions necessary to obtain a problem in which relatively simple certainty equivalents exist.

In the absence of substantial technical change and/or rapid developments in infrastructure or markets, such as frequently characterize agriculture in developing countries, perennial crops are also susceptible to analyses similar to the one described above for livestock, but certain features of perennials make the existence of relatively simple certainty equivalents doubtful.

Both because of the longer time horizon involved and a number of other characteristics, the analysis of supply response for perennial crops is likely to be more difficult than for livestock. First, the decision to plant such a crop is normally made far in advance of the expectation of any output. Even after output is forthcoming, the yield typically varies over the lifetime of the plant reaching a peak some years after initial output, maintaining a roughly constant level for a number of years, and then beginning a slow decline to eventually uneconomic levels. The pattern of yield may be varied somewhat by other inputs, but more importantly by choice of variety. During the initial phase of no output, and sometimes even beyond this period, the perennial may be interplanted with other crops. Second, whereas in the case of annuals the decision to harvest or not usually represents an insignificant aspect of supply response (but see Nerlove, 1958, pp. 112-121), harvesting costs typically represents a major part of the costs of production in the case of a perennial, so that knowledge of the age-distribution and yield profile of the existing stock of plants provides only an upper bound to potential output. Third, the stock of plants may be depleted over time not only by deliberate action of the producer to cull unproductive plants in the older age groups, to replant or replace existing plants with higher yielding varieties, or to plant alternative crops, but also by the differential effects of weather and disease. One cannot deduce the age distribution of the stock from a knowledge of past plantings alone.

Moreover, the effects of poor weather or disease upon yields may be spread over a number of years.

As in the case of livestock, it is possible to formulate a dynamic programming model which can take into account the main features of perennial production. Apart from data limitations, which are typically very serious in the case of most perennials (Hartley, 1979), the chief difficulties appear to be the nonlinear constraint introduced by the bounding of harvested output by potential output and the additional uncertainty, beyond the uncertainty of future prices and costs, of yields due to weather and disease, but, more importantly, also as to the introduction of new plant material with higher yields. For example, in the case of rubber, research in Malaysia on the agronomy of natural rubber in the past 25 years has led to a more than three-fold increase in commercial yields as new clonal materials have replaced previously unselected seedlings or inferior stock. I will return to the question of how new technology affects the dynamics of supply in the next section, but note here that its possibly discontinuous nature and uncertainty regarding when a new variety or new material may be available introduces a whole new dimension in the case of a long-lived perennial which is not present in the case of an annual crop. Unless harvests are normally well below potential always, a very implausible circumstance since one could not then explain why so much of the crop had been planted in the first place, the nonlinear boundary condition in itself would preclude the formulation of a dynamic optimization model having single-valued cerainty equivalents. Even approximate certainty equivalents would be ruled out in this case (Malinvaud, 1969). The discontinuous nature and uncertain timing of technological change and the effects of weather and disease on yields would also seem to rule out single-valued certainty equivalents. Without such certainty equivalents, the dynamic programming model formulated and solved as if future prices, costs and yields were known with certainty no longer represents a structure into which we can introduce quasi-rational or rational expectations based on time series of past prices, costs and yields. No doubt, as additional work on perennials is undertaken, these issues will be resolved initially in an ad hoc manner with different analysts concentrating on different aspects of the problem.

4. Supply Response during Agricultural Transformation

In Transforming Traditional Agriculture, T. W. Schultz (1964), argued that farmers in traditional agricultural settings, while they may differ for reasons of schooling, health and experience in their ability to perceive, interpret and respond to new events as these impinge on their farm enterprises, do in fact allocate the limited resources at their disposal in a highly efficient manner. But within a traditional agricultural setting few adjustments are required and those which do occur are typically not large.

One can imagine an agricultural sector in which no changes in technology, infrastructure, markets and so forth, have occurred for a very long time. Under such "stationary" conditions, farmers may be poor, uneducated, and slow to perceive or respond to change. They may, nonetheless, be in virtually perfect adjustment to their environment and attain a very efficient allocation of resources. In the case of a largely subsistence agriculture there may be few price signals to which to respond. Efficient allocation of resources largely consists then of proper allocation of time, land, and whatever limited physical capital exists in various household activities which include, not only farming, but other types of household production and consumption, the rearing of children and such limited gross investment in human and physical capital as may be necessary to maintain existing stocks. If farmers have limited needs for goods they themselves cannot produce and limited opportunities for off-farm employment, markets and the infrastructure of communications and transport may be poorly developed or virtually non-existent. In this case, one can learn very little about potential supply response to price or other changes by observing past behavior. One might infer little supply response to prices observed in central markets, for example, simply because such prices are largely irrelevant to the allocation problems which these farm households resolve.

Even when farmers sell a substantial fraction of their output of certain crops and buy other goods they need, fluctuations in market prices may induce little response simply because such changes are due to weather or other temporary factors which have little long-term significance for the allocative decisions being made.

Schultz (1975, pp. 831-32) puts the matter well and succinctly:

> "Farm people who have lived for generations with essentially the same resources tend to approximate the economic equilibrium of the stationary state. When the productive arts remain virtually constant over many years farm people know from long experience what their own effort can get out of the land and equipment. In allocating the resources at their disposal, in choosing a combination of crops, in deciding on how and when to cultivate, plant, water and harvest, and with what combination of tools to use with draft animals and simple field equipment -- these choices all embody a fine regard for

> marginal costs and returns. These farm people also know from experience the value of their household production possibilities; in allocating their own time along with material goods within the domain of the household, they too are finely attuned to marginal costs and returns. Furthermore, children acquire the skills that are worthwhile from their parents as children have for generations under circumstances where formal schooling has little economic value."

It is doubtful whether such a stationary state now exists or has ever existed, although it may have been approximated in certain times and places (a point made very clearly by Schultz, 1964). In modern agriculture, or in an agricultural sector in the course of modernization, constant changes are occurring. These changes are typically large, frequently discontinous, and require major reallocation of resources both within the agricultural sector and between agriculture and the rest of the economy. Moreover, more often than not these changes are not reflected in "visible" prices, although in market-oriented economies major shifts in the demand for various agricultural commodities or in the supply of inputs used in agricultural production, do take the form of price changes. In the supply response studies discussed earler in this paper, and, indeed, in my discussion of models of response based on dynamic optimization, I tacitly assumed that "visible" prices convey all of the information to which farmers find it necessary to respond. This is certainly not true even in recent times in a highly developed economy such as we have in the United States.

In the last fifty years we have experienced two major changes in U. S. agriculture, as well as, of course, a continuing sequence of lesser changes due to shifts in demand and supply and on-going agricultural research. The first of these was the development and spread of hybrid corn, so well documented by Griliches (1957). While it may be true that the differential spread of hybrid corn in the U. S. can be explained in terms of differing costs and returns and farmers' perceptions of these differences, such a formulation is not particularly useful in understanding the complex of forces related to the supply of research and discovery which brought about the change and which governed its rate of spread. On the other hand, the second major change, the remarkable fall in the cost of nitrogen fertilizer, which took place in the 'fifties and early' sixties and which resulted in a significant increase in the optimal amount of such fertilizer applied to a variety of crops, was essentially a price phenomenon. Yet, as I think is shown by the studies of Wallace Huffman (1972, 1974, 1977), the changes which took place cannot be explained dynamically solely in terms of relative prices. There is virtually nothing in the production process for corn, for example, which would have prevented an almost instantaneous complete adjustment, yet the adjustment did take time and the speed with which it occurred varied substantially in different parts of the Corn Belt. Using county data for the period 1959-64, during which prices of nitrogen relative to corn fell about 25%, Huffman computes a partial adjustment coefficient showing actual changes during the five-year period as a fraction of the changes by county necessary to achieve an optimum as determined from a production function for corn estimates from agronomic data. His major finding is that the speed of adjustment varies systematically across counties with respect to average levels of extension services provided, farmers' education, and farm size. One could not have predicted such results on the basis of the type of dynamic model discussed in the preceding section of this paper. If the production function is shifting and not completely known by producers, processing and dissemination of information and its incorporation into the optimization process constitute a more important part of the dynamics of supply than the issues we have raised thus far.

Two additional points are worth making in this connection: The research process, especially in the U. S., has become institutionalized to such a degree, that it itself and farmers' continuing responses to the wide range of new opportunities constantly opening up to them have become a central characteristic of the dynamics of supply in modern agriculture. Second, developments in the industries supplying inputs to agriculture are not unrelated to other types of research, such as the continued development of new varieties of plants which use fertilizer and water more effectively or lend themselves more readily to mechanized cultivation and/or harvesting: The impact of the fall in fertilizer prices would have been far less without the hybrid varieties, and, conversely, the profitability of the new varieties would have been less great with higher fertilizer prices.

What lessons does the U. S. experience hold for understanding agricultural supply response in developing countries today? I return to the theme on which I touched at the very beginning of this paper: To understand the essential dynamics of supply in developing economies, we must consider the causes of change in the agricultural sector, the complex of forces set in motion by technological improvement, public investment in infrastructure and public health, the development of markets and the differential abilities of economic agents to deal with disequilibria. From what I know of agriculture in developing countries, I would suggest several major sources of change in agriculture during modernization:

(a) As investments are made in better communications, transportation, and other types of infrastructure, there are greater opportunities for markets of all kinds to develop. In consequence, price signals are likely to become more important, not less, as farm people become less isolated. Moreover, the markets and prices which are important in understanding the dynamics of supply are not limited to product markets and prices. Clearly, inputs such as fertilizer, farm implements, herbicides and insecticides, better seeds, and so forth, are increasingly purchased and used. But labor markets also develop more fully and farm people begin to respond to opportunities for off-farm employment, part-time, seasonal, and permanent. The impact of changes in the labor market on supply response may be at least as great as the impact of changing product prices.

(b) The process of technical change in agriculture accelerates and becomes increasingly institutionalized and indigenous. Improvements in varieties of plants and animals and in the other inputs which are necessary to make these varieties more productive become an increasing source of supply response. The dynamics of supply under these circumstances can be understood only by understanding the determinants and manner of adoption of new agricultural technology and how it comes to be produced on a continuing basis. The so-called "green revolution," the rapid adoption of new, highly productive wheat varieties by the small, financially poor, uneducated farmers of the Punjab is perhaps somewhat misleading in this connection.

To be sure, this event,others like it the world over, and the development of international agricultural research centers, have had a major impact on supply. Continued change, however, is likely to rest more on a series of smaller, less dramatic developments, the perception of which will require improvements in the abilities of farm people to adapt to maintained disequilibria. Improvements in rural educational facilties, especially literacy and extension services, and in other infrastructures such as facilities for irrigation, drainage,and other forms of water control, must play an important role in these developments. Many of these require major public investments, but the ability and willingness of farm people to take advantage of the increased availability of educational and extension services or the public provision of certain types of infrastructure can come about only through changes in the nature of private investment, especially in human capital but also in on-farm physical capital.

(c) Demographic change which accompanies the process of agricultural transformation and economic development is a crucial element in agricultural supply response. To an important extent these changes are initiated by improvements in public health which result in sharply decreased mortality, particularly infant and child mortality, and in control and/or eradication of debilitating diseases which make human labor less productive than it would otherwise be. However, many of the demographic changes which occur have their roots in the individual decisions of farm people to make greater investments in human capital in the form of greater education and better nutrition for their children and

and to have fewer children, as other forms of saving and provision for old age become available, as labor markets improve, and as there is an increased awareness of opportunities outside of the agricultural sector. Such demographic changes alter the nature of agricultural production, lead to increased use of nontraditional inputs, and to a greater reliance on markets, and thus alter the nature of supply response to prices and other factors.

(d) Naturally the role of government in this process is important, and there are many areas in which, and points at which, government intervention is both necessary and desirable. But this should not be allowed to obscure the fact that governments are continually tempted to intervene when they should not and in ways which may seriously impede agricultural development and distort the incentives and signals which prices provide in modern agriculture. Marketing boards which supposedly regularize the flow of product from producer to market or stabilize extreme price fluctuations frequently hold down the prices producers receive; protection of domestic industry, such as fertilizer, serves to make more costly the things that farm people buy; taken together, serious consequences may follow, as the infamous case of rice production in Thailand serves to indicate.

While all of these arguments suggest that increased production is more dependent upon factors other than price, does not mean, as Gale Johnson has so congently pointed out (1978, pp. 210-213), that prices don't matter very much and that they can be used to accomplish other goals and objectives.

distributional, political, with respect to trade, control of inflation, and so forth. As he says (1978, pp. 211-212):

"Prices do matter. Prices affect decisions made by Farmers -- how much fertilizer to use, how to allocate this land and labor among crops and whether it pays to invest in tube wells or in improvements of irrigation systems. But prices also matter to others who have direct relationship to agriculture -- research institutions, producers of farm inputs, credit agencies, and extension agents. Where the price of fertilizer is five to ten times the price of grain, there is little point in research institutions undertaking research on methods of applying fertilizer or on crop varieties that will give a significant response to fertilizer. Firms will be reluctant to produce farm inputs for which demand is restricted by low farm-product prices. Similarly, the supply of credit -- as well as the demand for it -- is affected by farm output prices.

"If there is continuing investment in reseach resulting in a flow of new varieties, new methods of protecting plants from diseases, insects and rodents, investments and improvements in irrigation, and readily available supplies of modern inputs at reasonable prices, and increase in [product] prices will evoke much larger increases in output than if some or all of these conditions are not met. . . But this in no way implies that prices are not important."

Because of the inevitable tendency of governments to interfere with markets and prices, however, the problems of untangling supply responses are made doubly difficult. In the short run price uncertainties may be reduced by such interventions, but reduced uncertainty is not at all clear in the long run. Uncertainties with respect to the behavior of government may be far greater than uncertainties with respect to the behavior of weather and markets. Supply response occurs in a complex and interrelated system of which government is one element. Prices and other factors such as those discussed above affect not only farm people but also numerous institutions related to agriculture and agricultural development. The dynamics of supply in developing nations and in agriculture in the process of transformation cannot be fully understood without taking these complex interrelationships into account. It is doubtful whether studies based on historical relationships of the output of a single crop, or the area devoted to its cultivation, in relation to past prices can shed much light on these issues or even on the role and importance of prices and markets.

5. Prospect

Since the publication of my own work on the subject -- aeons ago it now seems to me -- there have been numerous well-done studies of supply response to price in both developed and developing countries. Real interest, however, centers on the dynamics of supply in agricultural sectors undergoing the transformation from traditional to modern agriculture. In this paper, I have emphasized the simplistic and relatively *ad hoc* nature of the basic model I used so long ago to study the response of U. S. farmers to price in the production of corn, cotton and wheat in the period prior to the introduction of price supports and acreage allotments. It is inadequate, despite the many ingenious modifications and additions others have made to it, either to model dynamic optimization in response to changing prices or to understand the true nature of dynamic supply response in the context of a developing economy.

To overcome the first sort of inadequacy is a challenging intellectual problem from both a theoretical and an econometric point of view. I have, perhaps, dwelt overly long on some of the ways in which distributed lag models of supply response based on dynamic optimization under uncertainty can be developed for livestock and perennial crops. In defense, I plead current involvement in research on these problems, rather than a sense of their importance relative to the second group of difficulties I have discussed here. Given a sufficiently adequate data base and enough intellectual effort and ingenuity, I am confident that the former can be satisfactorily resolved.

The inadequacy of the basic supply response model to disentangle the forces shaping agricultural supply in the context of a developing economy is far more serious. We are lacking both the necessary theoretical and econometric tools and the basic data. To be sure there exist time series data and other information in scattered instances for individual crops in particular areas which make it possible to do the more standard types of analysis with or without modifications along the lines suggested in my discussion of livestock and perennials. Along these lines perennials, so important to the economies of many developing countries, appear to offer the greatest opportunities for fruitful research. But, at best, such studies can yield only a partial and limited understanding of the dynamics of supply in developing countries. These dynamics are the result of a complex interaction of household and economy, which extends beyond the demographic-economic interactions I discussed in an earlier paper (1974). A variety of institutions, markets, and other phenomena must be related to one another in a process which extends over both time and space. Neither the data nor the theory are at hand in any very complete form.

What hope have we then for understanding the dynamics of agricultural supply in developing nations and what are the prospects for fruitful research? Notwithstanding my pessimism about the current state of affairs, I am optimistic with respect to the future. Economists have become increasingly involved in the collection and analysis of basic data at the microlevel of household or firm by special surveys or using census instruments. More often than not surveys are the only way to collect information on household time allocation, adoption of modern agricultural practices, fertility and labor force participation, and, for firms, on expectations, plans and realizations. The last decade has witnessed a resurgence of interest in the "new home economics" and the development of new theoretical and analytical tools which can be applied equally to farm households in developing nations. New econometric techniques for the analysis of microdata, particularly categorical data from surveys, are being adapted from earlier uses in biostatistics and sociometrics (e.g., Nerlove and Press, 1976; Koenig, Nerlove, Oudiz, 1979). We can, by special surveys and these methods of analysis, gain considerable insight into many of the basic phenomena underlying supply response in transitional and developing agriculture, particularly with respect to the adoption of new techniques and the demographic-economic interactions at the microlevel which are so crucial. The tangled web of the effects of government interventions, investments in infrastructure and the development of markets may be less susceptible to purely econometric analysis, but considerable progress can be made in understanding these phenomena by in depth case studies and clear, if simple, economic reasoning. Sophisticated econometric techniques and high-powered economic theory are complementary, not antithetical, to case studies and common sense.

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