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Adoption of Agricultural Innovations in Developing Countries: A Survey*

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Introduction

Adoption of technological innovations in agriculture has attracted considerable attention among development economists because the majority of the population of less developed countries (LDCs) derives its livelihood from agricultural production and because new technology seems to offer an opportunity to increase production and income substantially. But the introduction of many new technologies has met with only partial success, as measured by observed rates of adoption. The conventional wisdom is that constraints to the rapid adoption of innovations involve factors such as the lack of credit, limited access to information, aversion to risk, inadequate farm size, inadequate incentives associated with farm tenure arrangements, insufficient human capital, absence of equipment to relieve labor shortages (thus preventing timeliness of operations), chaotic supply of complementary inputs (such as seed, chemicals, and water), and inappropriate transportation infrastructure.

Many development projects have sought to remove some of these constraints by introducing facilities to provide credit, information, the orderly supply of necessary and complementary inputs, infrastructure investments, marketing networks, etc. Removing these constraints was expected to result not only in the adoption of the improved practices but also in a change in crop composition, which was expected to increase average farm incomes even further. Expectations have been only partially realized. As past experience shows, immediate and uniform adoption of innovations in agriculture is quite rare. In most cases,

EDITOR'S NOTE: Because of the large number of sources and the frequency of citations, brief mention of authors and dates appear in the text in parentheses, rather than with endnotes as is the usual practice of this journal. Formal references are arranged alphabetically in "Literature Cited," at the end of the article.

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adoption behavior differs across socioeconomic groups and over time. Some innovations have been well received, while other improvements have been adopted by only a very small group of farmers.

The purpose of this paper is to survey various studies that have attempted to explain these patterns of adoption behavior either theoretically or empirically. Because the volume of such published research is overwhelming, we will attempt simply to review representative works rather than to present an exhaustive discussion of all work to date. The next section introduces a general conceptual framework for analyzing adoption and diffusion processes and then proceeds to survey the existing conceptual and theoretical literature regarding adoption patterns of agricultural innovations in LDCs within this framework. Section III reviews empirical studies that have attempted to clarify and validate various aspects of adoption processes in the light of the theoretical literature. Section IV provides a critique of methodologies and models used in the empirical literature and suggests new approaches and directions. The implications of the survey are indicated in the last section.

II. A Survey of Adoption Models

A. Overview

It is useful to consider the results of theoretical investigations of the adoption of agricultural innovations in LDCs before reviewing empirical findings, since theoretical studies define adoption variables rigorously, set precise relationships for estimation, and suggest hypotheses that can be tested empirically. Furthermore, theoretical analysis can lead to a better understanding of the interdependence among adoption decisions and thus help in determining the appropriate specification of simultaneous adoption models. Finally, rigorous analysis helps to define in more precise terms the conditions under which certain arguments are valid.

B. Adoption Defined

Rogers (1962) defines the adoption process as "the mental process an individual passes from first hearing about an innovation to final adoption" (p. 17). However, for rigorous theoretical and empirical analysis, a precise quantitative definition of adoption is needed. Such a definition must distinguish between *individual* (farm-level) adoption and *aggregate* adoption. Final adoption at the level of the individual farmer is defined as the degree of use of a new technology in long-run equilibrium when the farmer has full information about the new technology and its potential. This definition corresponds to Schultz's (1975) contention that the introduction of new technologies results in a period of disequilibrium behavior where resources are not utilized efficiently by the individual farm and learning and experimenting lead the farmer toward new equilibrium levels. Note, however, that, when the new technologies are constantly being modified, with some new innovations overlapping (recent technologies such as drip irrigation and automated water and fertilizer control can serve as extreme examples), the equilibrium levels may flow constantly and never be attained. In the context of aggregate adoption behavior, let the diffusion process be defined as "the process of spread of a new technology within a region."[1] Aggregate adoption is measured by the aggregate level of use of a specific new technology within a given geographical area or a given population.

In most cases, agricultural technologies are introduced in packages that include several components, for example, high yielding varieties (HYV), fertilizers, and corresponding land preparation practices. While the components of a package may complement each other, some of them can be adopted independently. Thus farmers may face several distinct technological options. They may adopt the complete package of innovations introduced in the region or subsets of the package. In these cases, several adoption and diffusion processes may occur simultaneously. However, as pointed out by Mann (1978), such adoption processes may follow specific (and predictable) sequential patterns.

The definition of adoption above refers to the degree of use of a new technology as a quantitative measure of the extent of adoption. A distinction needs to be drawn, however, between new technologies that are divisible (such as HYVs or new variable inputs) and innovations that apply to the whole farm and are not divisible at a practical level (e.g., harvesters). The intensity of adoption for the former type of innovation can be measured at the individual farm level in a given time period by the amount or share of farm area utilizing the technology or by the per hectare quantity of input used where applicable. Analogous measures may apply at the aggregate level for a region. For nondivisible innovations, the extent of adoption at the farm level in a given period is necessarily dichotomous (use/no use); but, in the aggregate, the measure becomes continuous (e.g., the percentage of farmers using harvesters). Using these definitions of adoption and its quantitative measurement, the remainder of this section posits a unifying framework for analyses of adoption patterns. Several studies will then be discussed with the aid of this framework.

C. An Analytical Framework

A complete analytical framework for investigating adoption processes at the farm level should include a model of the farmer's decision making about the extent and intensity of use of the new technology at each point throughout the adoption process and a set of equations of motion describing the time pattern of parameters that affect the farmer's decisions. These changes in parameters are the result of dynamic processes such as information gathering, learning by doing, or accumulating resources.

Generally, decisions of the farmer in a given period are assumed to be derived from the maximization of expected utility (or expected profit) subject to land availability, credit, and other constraints.[2] Profit is a function of the farmer's choices of crops and technology in each time period. It therefore depends on his discrete selection of a technology from a mix including the traditional technology and a set of components of the modern technology package.

Given this discrete choice, income is a continuous function of land allocation among crop varieties, the production functions of these crop varieties, the variable usage inputs, the prices of inputs and outputs, and the annualized costs associated with the discrete technological choice. Given the discrete choice and land and variable input values, the perceived income may be regarded as a random variable embodying objective uncertainties with respect to yields (and prices) and the subjective uncertainties associated with the farmer's incomplete information about the production-function parameters.

In many studies, the production function can be assumed to be the only source of (objective and subjective) uncertainty to the farmer. In these cases, maintaining an analytically tractable objective function depends on the specification of the uncertainty in the production function. One convenient and yet fairly general specification of a production function assumes linearity in the random variable:

$$y = f(\mathbf{x}) + g(\mathbf{x})\epsilon, \tag{1}$$

where y denotes output, $\mathbf{x}$ is a vector of inputs, and ϵ is a random variable with zero mean (Just and Pope 1978). This formulation is flexible enough to allow situations where some inputs (such as pesticides) have opposite effects on the mean and variance of yields.

Sandmo's (1971) model of firm behavior under uncertainty allows analysis of adoption choices, assuming any concave utility function when the yield of only one crop behaves according to equation (1) and other crops have deterministic yields. Assuming negative exponential utility with normal yield distributions or quadratic utility allows analysis of cases where several crops have yield uncertainties. Under these assumptions, the farmer's objective function is linear in the means, variances, and covariances of yields and is quadratic in the areas allocated to the different crop varieties.

Most adoption studies assume that the amount of land a farmer can operate each period is given and, thus, that he maximizes his expected utility subject to land availability. Imperfections in the credit and labor markets may also result in credit and labor constraints that affect the farmer's choice.

The solution to the temporal optimization problem at the beginning of each period determines the type of technology the farmer will use in the period, his allocation of land among crops, and his use of variable inputs. At the end of each period, the actual yields, revenues, and profits are realized; and this added information, as well as the experience accumulated during the period and information on outcomes obtained by other farmers, tends to update the parameters the farmer will use in his decision making for the next period.

There are several kinds of equations of motion that reflect changes in the decision-problem parameters over time. In addition to the obvious equations relating to cash resources and wealth accumulation, one must consider equations of motion describing changes in the perceived parameters of the production-function distributions. These changes are the result of a learning process that incorporates prior perception and recent information about yields and inputs uses of farmers in the region. One plausible approach in modeling these changes in perception is to assume that farmers use Bayesian learning rules to update their perceptions. An alternative formulation of these equations of motion may use more ad hoc learning rules and recognize explicitly the effects of extension efforts and human capital differences in changes in perceptions over time.[3] Similar equations of motion may be used to update the farmer's price perceptions.

Another set of equations of motion reflects changes over time in the farmer's effectiveness with new technologies. These changes may be the result of learning by doing. That is, the farmer may become more proficient with his technology as he accumulates information by using it. Measures of experience with a technology include the length of time the farmer under consideration and other farmers in the region have used the technology or the total cumulative amounts of land utilized with the technology by the farmer and other farmers in the region over time. Variables describing extension efforts and human capital may play the same role as measures of learning by doing in the equations of motion of the farmer's production coefficients (see Kislev and Shchori-Bachrach 1973).

Yet another set of equations of motion may reflect changes in prices and costs over time. In particular, these equations may focus on changes in the setup cost associated with the new technologies. Cost and price changes may result from technological improvements in the production of capital goods or in the marketing network of inputs associated with the new technologies. Output prices may be affected by expanded production of the crop if the innovation is adopted on a wide scale. The arguments in these equations of motion may be time, other measures of individual and aggregate experience with the new technology, measures of extension efforts, and the rates of changes in the interest rate.[4]

The behavior of an individual with respect to a new technology (or a group of new technologies) over a period of time can be determined by solving the temporal optimization problem of the individual at each point in time and using the equations of motion to generate the parameters for the optimization problem. To analyze the diffusion of a new technology in a region, aggregate market-clearing relations have to be specified to allow endogenous determination of input and output prices. Thus, at each period, the individual optimization problems and the market-clearing relations will be solved simultaneously to determine price and resource allocation by individuals. Using the equations of motion, this process can be followed to determine the technological choices of all individuals over time. The diffusion patterns of new technologies can then be obtained by aggregation.

D. Review of Models of the Adoption Behavior of Individual Farms

Most of the theoretical studies of the adoption behavior of individual farmers use static analysis that relates the degree of adoption to factors affecting it. These studies investigate the properties of the solution to particular cases of the temporal optimization problem of the farmer. One useful approach is to characterize the problem as one where the farmer has to choose between two technologies: the traditional technology, and a modern technology such as the use of HYVs and the inputs associated with them (fertilizer, irrigation, and pesticides), with or without some form of fixed capital goods. Models following this approach investigate how much land is allocated to modern technology and what are the input-land ratios of modern inputs under different circumstances.

For example, Hiebert (1974) uses a stochastic production function and assumes risk aversion to examine the effects of uncertainty and imperfect information on adoption (and level of use) of fertilizer where only variable costs are incurred in adoption. Imperfect information about yield response is represented by a subjectively random effect of fertilizer in the production function. The results indicate that risk aversion is associated with the use of less land and less fertilizer in production of the modern crop than is risk neutrality. The probability of adoption increases as the stock of information pertaining to modern production increases, say, through extension efforts. If different producers have different abilities to decipher and analyze information, the likelihood of adoption is positively related to producer skills.

As Hiebert (1974) indicates, these theoretical results regarding the effects of extension are consistent with arguments advanced by Nelson and Phelps (1966) and by Welch (1970). In addition, the better the physical environment of the farm, the greater the likelihood of adoption. A more favorable environment (better soil and water availability) increases the expected utility of income from modern production and, hence, increases the probability that a farmer will adopt the new technology.

In another study, Feder (1980) assumed that uncertainty is associated only with the new crop that responds to higher levels of fertilization than does the traditional crop. He uses a constant-return-to-scale version of the formulation in equation (1) to model the stochastic production function of the new crop. He also assumes risk aversion and that adoption of the new crop does not require any fixed initial cost. Using this framework, he finds that fertilizer use per acre (for the new crop) is independent of the degree of risk aversion, uncertainty, and farm size when farmers are not restricted by credit constraints. Under these circumstances, risk affects only the land-allocation decision (between the old and new crops) in a manner consistent with Hiebert's findings. Considering the effect of farm size on relative land allocation, Feder (1980) showed that the share of the modern crop depends on the relationship between relative risk aversion and income.[5] Although there is no definite theory regarding this relationship, when utility is defined over income in excess of a subsistence level, the share of area allocated to the modern crop increases with farm size.

Just and Zilberman (1983) later extended these considerations to all inputs using the production function in (1) and showed that whether modern inputs are used more or less intensively depends on whether the modern inputs are risk reducing or risk increasing and on whether relative risk aversion is increasing or decreasing. Their results also demonstrate that correlation of outputs under alternative technologies plays an important role in determining adoption rates. In particular, if the correlation of outputs under old and new technologies is low or negative and if the modern technology is sufficiently more risky than the traditional technology, then larger farms will devote more land in absolute terms but less land in proportionate terms to the new technology than will smaller farms if relative risk aversion is increasing and absolute risk aversion is decreasing with the farmer's wealth.

A factor that may explain a positive relationship between farm size and the share of the modern crop is the existence of fixed transaction costs and information acquisition costs associated with the new technology, as shown in Just, Zilberman, and Rausser (1980), and in Feder and O'Mara (1981). They demonstrate also that, at a given point in time, there may be a lower limit on the size of adopting farms such that farms smaller than a certain critical level will not adopt the new technology. The critical size increases with higher fixed information costs. But these results will not hold in the absence of uncertainty, given that the new technology is more profitable and that it is neutral to scale.

Whereas the results above were derived assuming concave and well-behaved utility functions, some theoretical studies of adoption behavior use "safety-first" types of models. This approach corresponds to assuming that the utility of income is zero below a certain "disaster" level and is one above it (Pyle and Turnovsky 1971). Using this approach, Roumasset (1976) demonstrates that nonadoption of new HYVs may be the result of higher disaster-level yield probabilities associated with HYVs in rain-fed crops. Using a similar safety-first model, Bell (1972) shows that in a simple case where only the modern production technology is considered smaller farms will apply less fertilizer per acre, because their subsistence requirements per acre are higher than those of larger farms, forcing them to refrain from spending too much cash on fertilizers which may not increase yields if the weather is poor.

However, it should be pointed out that a number of studies have argued (although not in the context of technology adoption) that variable input use may theoretically be higher on smaller farms even when uncertainty prevails (see, e.g., Srinivasan 1972). Empirical evidence shows contradictory patterns, and it is obvious that results depend on other components in the model, such as land quality (irrigated or not) and land-credit relationships. Assuming that a binding credit constraint prevails and that credit availability is proportional to the size of the farm, Feder (1980) showed that increases in uncertainty levels (e.g., areas with rain-fed agriculture versus irrigated areas) are likely to cause lower shares of modern cropland but higher fertilizer-land ratios.[6] Both land allocation and fertilizer-land ratio decisions depend crucially on the relationship between relative risk aversion and income. However, if relative risk aversion is constant, it can be shown in the Feder model that (1) both the fertilizer-land ratio and the land allocated to the modern crop increase with farm size if credit increases more than proportionately with farm size; (2) if the utility is defined over income in excess of a subsistence level, the fertilizer-land ratio is independent of farm size but land allocation to the modern crop increases with farm size.

Yields are the only random variables in most analytical models of adoption behavior under uncertainty. In reality, output and input prices also may be random variables, and their uncertainty may affect technological choices. Some of the implications of output-price uncertainty on adoption behavior can be deduced from models with yield uncertainties by interpreting yield functions as revenue functions. The effect of wage rate and output price uncertainties on adoption decisions is analyzed by Zilberman and Just (1984). They assume that the aggregate supply of hired labor is a random variable (especially in the harvesting season when interregional migrants are a significant part of the labor force). This uncertainty is transformed (through the seasonal labor and output markets) into wage rate and output price uncertainties. The model shows that the likelihood of adoption of a "lumpy" laborsaving technology is increasing as labor supply uncertainty is increasing when the demand for output is elastic, but this is not necessarily so with inelastic ouput demand.

The static individual adoption models that have been surveyed thus far assume that the farmer adopts only one modern technology and has to decide whether and to what extent to adopt it. In reality, quite frequently, modern agricultural technologies are introduced as a package with several components (see Clay 1975; Mann 1978); and, although these components may be complementary, not all of them must be adopted simultaneously. Thus, the farmer makes a choice from among several distinct combinations of modern components in a technological package. A recent study by Feder (1982) analyzes the case where modern technology has two components. One is neutral to scale (e.g., an HYV). The other is a lumpy innovation with a fixed capacity and requires a fixed installation cost regardless of size (e.g., a tube well). The lumpy innovation is beneficial to farmers who use the traditional variety as well as to the adopters of the HYV. Thus, farmers have three packages of new technology from which to choose. They can adopt either the HYV or the lumpy innovation or they can adopt both new innovations. The model assumes that the traditional crop is not risky, while the HYV production function follows equation (1).

The model indicates that, while HYV will be adopted by all farmers (in the absence of fixed adoption costs), there will be a critical farm size such that only larger farms will adopt the lumpy innovation for a given risk aversion. These farmers may devote a larger or a smaller portion of their land to the scale-neutral innovation, depending on the overall degree of complementarity between the innovations. As it turns out, this dependence on complementarity includes not only cross-yield effects of the innovations but also cross-risk effects. If there is a binding credit constraint, an element of substitutability is introduced even though the components are yieldwise complementary. Thus, because the adoption of each component ties up cash resources, policies that enhance the adoption of one component may retard the adoption of the other.

The static models of adoption behavior by individual farms indirectly yield some interesting hypotheses regarding the dynamic properties of the adoption process. Using theoretical or heuristic arguments regarding the behavior over time of the farmer's perceptions of production-function and price-distribution parameters, they can be used to predict dynamic behavior. For instance, Hiebert (1974) argues that as the farmer learns, his perceived distribution of technical parameters shifts over time from a lower payoff to a higher payoff. This induces farmers to increase their use of the new technology. Similarly, in models that incorporate a credit constraint, one can assume that, over time, cash availability to farmers is increased by the increased profits from partial adoption. Since the comparative-static analysis shows that increased credit (or cash) affects adoption positively, it follows that in the case of a single innovation adoption will increase over time. In the case of a package of innovations, the pattern is not clear cut and depends on the degree of complementarity.

O'Mara (1971) was among the first to employ a scientific Bayesian model whereby producers improve their prior beliefs on the basis of observed performance and thus are inclined to increase the share of the modern technology over time. His work was followed by a number of models assuming Bayesian learning that use an explicit formulation for the evolving of perceived distributions of production-function parameters over time. These relations allow more rigorous investigation of the dynamics of the adoption path and, in particular, allow analysis of the evaluation stage of the adoption process before the adopter actually uses the new innovation.

Using such an approach, Lindner et al. (1979) developed an expression for the time lag between initial awareness and actual use. They assume that the farmer is risk neutral and that the innovation is neutral to scale, has fixed technological coefficients and normally distributed yield, and does not require any setup cost. The farmer has a normally distributed prior of the mean profit of the innovation, and the mean of the initial perceived profit distribution is smaller than the expected profit of the traditional technology.

The farmer is assumed to collect information about actual profits derived by other farmers from the innovation. This information updates the prior expected profit in a Bayesian fashion. Actual experimentation occurs when the innovation is perceived as more profitable (on average) than the traditional technology. Lindner et al. (1979) found that the length of time between awareness and adoption is negatively related to the mean profitabilty of the new technology and positively related to the variance of actual profit. Similarly, higher initial perceived mean profit and lower initial variance are associated with a shorter adoption lag.

Fischer and Lindner (1980) extended the model above to allow for differences among farmers (in soil quality, human capital, etc.) that cause differences in the performance of a new innovation on different farms. Farmers are aware of these factors and account for them when updating their perceived expected value of mean profit of the innovation. It is shown that the greater the differences between the farmer and the actual sources of information, the more information (or longer evaluation period) the farmer will require before adopting an innovation.

In another work, Lindner (1980) extends the models above to demonstrate that information may account for the tendency of larger farms to adopt new innovations earlier, even when these innovations are scale neutral. Here he divides the time between the availability of a new innovation and its use into two subperiods: one is the discovery-stage lag (from availability to awareness) and the other is the evaluation-stage lag (from awareness to use). He also assumes that farmers actively engage in search and learning activities to find better technologies. The extent of the effort devoted to search activities is a function of the expected gain from these activities. Since larger farmers will have larger expected (absolute) gains from new innovations, they invest more in search efforts, and their discovery-stage lag is thus shorter. Assuming differences among farms, Lindner shows that a farmer may test a new innovation on the farm even before its perceived expected profit is larger than that of the traditional one because of the informational gain from on-farm information. Again, larger farms need to collect less off-farm information to be persuaded to use a scale-neutral innovation on a trial basis, and thus larger farms have a shorter evaluation-stage lag as well as a shorter discovery-stage lag.

The above works involving Bayesian learning assume risk neutrality, but with some additional restrictions risk-averse behavior can be accommodated as well. Stoneman's (1981) model, although dealing with industrial innovations rather than with agriculture, provides a suitable starting point. The firm is assumed to maximize a mean-variance utility function through the choice of an optimal mixture between an old and a new technology in order to produce a given level of output. Perceptions are assumed to be normally distributed and expansion of the share of the new technology entails adjustment costs. With some specific formulations for the functions in the model, Stoneman shows that the diffusion of the new technology within the firm may follow the frequently observed sigmoid pattern.

Following Stoneman (1981), a paper by Lindner and Fischer (1981) introduces the risk-averse Bayesian learning model in an agricultural decision-making context. The mean-variance utility function of the Stoneman model is retained, but the volume of output is not fixed. Rather, land availability is assumed given. Similar to the findings of Just and Zilberman (1983) the correlation between yields of the old and new technologies is shown to be of great importance in determining adoption behavior. For instance, if the innovation is of higher risk and if the correlation between the risks of the old and new technologies is low, then a higher level of risk aversion corresponds to a shorter time lag for adoption, because of the diversification possibilities offered by the innovation. Interpretation of this result in terms of possible differences in adoption behavior by farmers of different size classes (i.e., different wealth) is not straightforward, because the model implicitly assumes that absolute risk aversion is not affected by wealth. But if one assumes that smaller farmers are more risk averse, the model predicts that certain types of innovations will be adopted faster by smaller farmers than by larger farmers.

E. Models of Aggregate Adoption

Most of the aggregate adoption models are dynamic and derive analytically the behavior of the diffusion process over time. Much of this research has been inspired by, and has attempted to explain, the frequent empirical findings of S-shaped patterns of aggregate diffusion over time (see, e.g., Griliches 1957). Many of these studies stress the role of communication (Rogers 1969), as done in Mansfield's (1961) seminal paper, which derives analytically an S-shaped diffusion path assuming that the driving force of the diffusion process is imitation. A number of works that extend Mansfield's approach specify diffusion behavior similarly and show that diffusion processes can be described quite accurately by compact mathematical formulas such as a logistic curve or other specific sigmoids (see Lekvall and Wahlbin 1973; Hernes 1976; Lerviks 1976). The parameters associated with these functions are determined by factors characterizing the distribution of certain properties (e.g., risk aversion, wealth) over the population of decision makers as well as by economic factors pertaining to the innovation and the environment in which it is being introduced (adoption costs, input prices, cost of alternatives, product prices, etc.). As emphasized by Hernes (1976), it is important to use a mathematical formulation flexible enough to allow for asymmetry in behavior over time. By introducing heterogeneity in the population both statically and dynamically, Hernes shows that the cumulative distribution of adoption may be skewed either rightward or leftward when external influences follow the usual exponential function or when internal influences follow the usual logistic function. From these results, he concludes that the shape of the growth curve in itself provides little information about which underlying process is applicable.

Mansfield's (1961, 1966) work has been criticized by Davis (1979) and by Gutkind and Zilberman (1981) for lacking a solid microeconomic model of the behavior of the individual firm and by Stoneman (1981) for the ad hoc specification of the learning process. The critics offer a new line of work on the dynamics of diffusion more in tune with traditional microeconomics and with the general framework presented here.

For example, Davis (1979) shows analytically and empirically (for industrial innovations) that if a new technology has scale elements and the farm-size distribution is lognormal, processes of learning by doing and information gathering will result in a sigmoid diffusion curve over time. This diffusion curve follows a cumulative normal time path for major (and technically complex) innovations or a cumulative lognormal time path for simple and less expensive innovations. Gutkind and Zilberman (1981) obtain more general results for cases where the new technology is embodied in a lumpy capital good and the diffusion process is driven either by the decline of the relative price of the capital good over time or by a process of learning by doing that reduces variable input requirements over time. They show that for unimodal and negatively skewed farm-size distributions these processes are likely to result in sigmoid diffusion curves. Moreover, given farm-size distribution, the inflection point of the diffusion curve corresponds to a larger aggregate adoption level when the relative price of capital declines at a constant rate over time than when it declines at decreasing rates over time.

Feder and O'Mara (1982) derive the aggregate diffusion curve of a scale-neutral risky innovation with risk-neutral farmers, equal-size farms, and normally distributed prior belief regarding the mean yield of the new technology. Assuming a Bayesian learning process, they show that aggregate adoption at each point in time is a function of cumulative aggregate adoption prior to that moment and that the resulting diffusion curve can be sigmoid. Their results provide justification for the use of cumulative adoption as an index of learning and experience in formulating a perceived production function in lieu of specifying a full-fledged Bayesian learning model.

Cochrane's (1958) "technological treadmill" model offers another possible approach to analyzing the diffusion of innovations in agriculture. It incorporates some of the notions developed in rural sociology studies of adoption behavior into a dynamic model of a competitive industry. Following Rogers (1957), it assumes that farmers are divided into three groups according to their tendency to adopt: "early adopters," "followers," and "laggards." It also assumes that farmers face a sequence of innovations which are adopted one at a time. This approach emphasizes the possible reduction in gains from adoption over time due to negatively sloped demand (which causes price reduction when supply expands with adoption).

A rigorous formulation of this approach appears in Kislev and Shchori-Bachrach (1973). Their model describes an "innovation cycle," where a new product or a new production technology becomes available to a competitive industry. The more skilled producers are assumed to have a higher opportunity cost for their resources and are also more efficient in their acquisition of technical knowledge (and are the "early adopters"). Knowledge is also affected by communal learning by doing, which is represented through the cumulative aggregate output of the industry. The level of knowledge affects the production function of each firm; and it is shown that, initially, the higher-skilled producers will adopt the new technology while the lower-skilled producers will wait until sufficient experience has developed at the industry level. Industry's output expands, and with the joining of less skilled producers the price drops (demand is stationary); it is quite possible that the higher-skilled producers will switch to alternative activities, since the opportunity cost for their resources is high.

Feder and O'Mara (1981) incorporate risk-reducing learning (measured by cumulative use of the innovation) in a model where individual farmers maximize expected utility by optimal choice of a mix of old and new technologies and adoption involves a fixed setup cost. Through numerical simulation, the aggregate adoption pattern is shown to follow the familiar sigmoid shape.

The work of Day and Singh (1977) constructs another dynamic model of aggregate adoption where farmers' behavior is characterized as "cautious optimization." With the passage of time, farmers' self-imposed constraints due to risk aversion are gradually removed (through learning by doing), and financial constraints are relaxed (through buildup of surplus cash generated by profitable adoption in previous years). Subject to these constraints, the extent of adoption of modern HYVs is determined in a linear programming model. The gradual relaxation of constraints over time leads to higher levels of adoption, which in turn lead to an even faster removal of constraints; and aggregate adoption proceeds until some upper limit is reached.

F. Adoption Behavior and Tenurial Arrangement

The framework presented above and the studies reviewed thus far assume that each farmer controls a given amount of land, without specifying landownership and rental arrangements. Several studies, however, argue that tenurial arrangements may play an important role in the adoption decision. Views are not unanimous, however, and the subject is one of considerable controversy.

For example, Bahduri (1973) develops a model showing that a landlord's double role as a provider of credit and as landowner (quite common in India, the country on which Bahduri focuses) creates a situation such that the landlord may not permit adoption of yield-increasing innovations. This is because adoption will reduce the tenants' indebtedness to the landlord, and the income from lending will decline more than the output share will increase. In a similar vein, although using a more complicated model (incorporating uncertainty and a mean standard deviation utility function), Scandizzo (1979) concludes that landlords will be reluctant to adopt land-augmenting innovations if interest earnings and price margins are high (owing to the fact that landlords market their tenants' output). The response to labor-augmenting innovations may be similar, although the likelihood of resistance is smaller.

Bahduri's analysis was criticized by a number of authors. Newbery (1975), for example, argues that if the landlord has sufficient monopoly power to exploit the peasant and withhold the innovation, then he should have sufficient power to extract the extra profit generated by the innovation. Similarly, Ghose and Saith (1976) object to Bahduri's simplified assumptions of the model and, under an alternative formulation, conclude that landlords will favor adoption of yield-increasing technologies. Srinivasan (1979) has refuted Bahduri's calculations; in fact, empirical evidence from India (Bardhan and Rudra 1978) does not support the assumptions underlying his model. A number of factual and methodological objections concerning Scandizzo's (1979) model are also raised by de Janvry (1979). In particular, the assumption of fixed crop-sharing parameters is criticized for essentially the same reason as that mentioned by Newbery. Rather than being a means for extracting profits, usurious interest rates serve to tie the tenant to the land and weaken his bargaining position. Thus, under semifeudal conditions, landlords will not be reluctant to adopt yield-increasing innovations subject to the usual profitability and risk considerations.

While the landlord-moneylender link does not seem to provide sound hypotheses on the relationship between the land-tenure system and innovations, Newbery (1975) constructs a model that implies that sharecropping could hinder adoption of innovations. The essential assumptions are that both production and labor markets are subject to uncertainties and that the new technology (unlike the traditional one) makes it impossible to supervise tenants' inputs (in particular, labor). This implies that the innovation increases the moral hazard and thus is unacceptable to the landlord unless he can increase fixed charges and reduce the share he receives of the crop; but such changes are likely to be rejected by tenants. It is claimed that, under such circumstances, the landlord may prefer to evict his tenants and resort to the use of hired labor with the new technology; however, if supervision costs are high, such an outcome is doubtful.

The tenurial contract may change as a result of technological change as demonstrated by Bell (1972) in his detailed analysis of the choice of lease arrangements. Tenants' attitudes toward adoption are shown to depend not on the form of the existing lease but on the profitability and riskiness of the new technology. Whenever the innovation is attractive to the tenant, it will also be attractive to the less risk-averse landlord. The latter will also be inclined to share in the variable costs if he was not doing so already.

Further hypotheses regarding tenure systems and the impact of technological change are formulated by Bardhan (1979). He constructs a model with endogenous wage determination as well as allocation of land between sharecropping and self-cultivation. The analysis yields a number of results, including the following: (1) the percentage of area under tenancy will increase if a land-augmenting technological change is introduced; (2) a larger degree of imperfection in the market for inputs complementary with HYV cultivation technology leads to a lower percentage of area under tenancy; and (3) a higher labor intensity of the crop induces a higher incidence of tenancy.[7]

III. Empirical Studies of Adoption

The theoretical models discussed thus far suggest many important hypotheses relating adoption of new technologies to key economic and physical parameters, in static and dynamic contexts and on micro and macro scales. Parallel to the development of these conceptual frameworks, a large empirical literature has evolved that attempts to analyze observed adoption patterns mostly by focusing on the relationships of key variables to adoption behavior. The results reveal the present state of knowledge about the adoption process. The contribution of these empirical models is enhanced if we interpret their implications against the backdrop of the conceptual models considered above. That is, the empirical results can confirm or reject some of the theoretical explanations in specific cases and can suggest important new avenues of conceptual work. Here we review some of the empirical works on adoption of agricultural innovations.

For the purposes of this paper, the Green Revolution and farmers' responses to it are relevant as examples of innovations that are divisible and thus neutral to scale (provided no credit and tenure constraints are present). There are scores of empirical studies related to the Green Revolution, and it would be impractical to mention each in this review. However, Ruttan (1977) has drawn several generalizations from this large body of literature:[8]

1. The new HYVs were adopted at exceptionally rapid rates in those areas where they were technically and economically superior to local varieties.
2. Neither farm size nor tenure has been a serious constraint to the adoption of new HYVs of grain. While smaller farmers and tenants tended to lag behind larger farmers in the early years following the introduction of HYVs, these lags have typically disappeared within a few years.
3. Neither farm size nor tenure has been an important source of differential growth in productivity.
4. The introduction of HYVs has resulted in an increase in the demand for labor.
5. Landowners have gained relative to tenants.

Ruttan acknowledges that there are many exceptions to these generalizations because innovations have been introduced in environments with different economic, social, and political institutions. Similar issues have been raised in analyses of adoption of other types of agricultural innovations.

Ruttan's generalizations, as well as the theoretical work considered in the preceding section, suggest several factors affecting the adoption process. To summarize the vast amount of empirical literature on adoption systematically, we organize the review of empirical work according to the key explanatory factors affecting adoption.

A. Farm Size

Farm size is one of the first factors on which the empirical adoption literature is focused. Farm size can have different effects on the rate of adoption depending on the characteristics of the technology and institutional setting. More specifically, the relationship of farm size to adoption depends on such factors as fixed adoption costs, risk preferences, human capital, credit constraints, labor requirements, tenure arrangements, and so on. The role of some of these factors points to the need to sort out confounding effects. The possibilities are discussed in the remainder of this section.

An often-mentioned impediment to adoption of new technology by smaller farms relates to fixed costs of implementation. The theoretical literature suggests that large fixed costs reduce the tendency to adopt and slow the rate of adoption by smaller farms. These conclusions are supported by Weil (1970), who found in Africa that adopters of ox cultivation cropped larger areas and operated significantly larger farms than those using hand cultivation. Several studies reviewed by Binswanger (1978) have found a similarly strong positive relationship between farm size and adoption of tractor power in south Asia. Other empirical studies have shown that inadequate farm size also impedes an efficient utilization and adoption of certain types of irrigation equipment such as pumps and tube wells (Hodgdon 1966; Dobbs and Foster 1972; Gafsi and Roe 1979).

It is important to note, however, that the relative lumpiness of technology is somewhat mitigated by a larger variety of designs and by the emergence of markets for hired services (Staub and Blase 1974). For example, Greene (1973) found that smaller farms in Thailand overcame an initial lag fairly fast and eventually used (hired) tractor services as much as did larger farms. Similar findings are reported for the Philippines by Alviar (1972). In some areas, governmental tractor hire stations have been established, but quite often these programs have failed (e.g., in northern Nigeria) because of poor maintenance.

The study by Weil (1970) further indicates that the negative relationship between adoption of lumpy technology and farm size may be caused by credit constraints. He suggests that capital may be more available for large farms, so that even though all farms may wish to adopt (and may increase short-run profit by adopting), larger farms are more likely to do so.

Many empirical studies also suggest that the use of HYVs and some modern variable inputs initially tends to lag behind on smaller farms. For example, Parthasarathy and Prasad (1978) found a significant positive relationship between size and HYV seed adoption in an Andhra-Pradesh village in 1971–72 (about 7 years after HYV introduction). Additional evidence of such instances is cited in the surveys by Vyas (1975) and by Perrin and Winkelmann (1976). Jamison and Lau

(1982, p. 208) have found a positive relationship between the adoption of fertilizers and farm size in a study of Thai farmers. Seemingly contradictory evidence is cited by Hayami (1981) from Barker and Herdt's (1978) study of 30 villages in five Asian countries. The relationship between adoption of modern rice varieties and absolute farm size for a cross-country pooled sample is negative. However, absolute farm sizes may be noncomparable across countries or regions because of differing agroclimatic conditions. Indeed, when farmers were defined as large or small on the basis of median farm size in their village, the results indicated that larger farmers demonstrate a higher adoption rate, although in most cases the difference is not significant (Barker and Herdt 1978, p. 94). Thus, the majority of evidence indicates that the incidence (as opposed to intensity) of adoption of HYVs is positively related to farm size. Since HYV technology is seemingly scale neutral, these results may appear to be at variance with economic intuition. However, as some theoretical studies suggest, even seemingly neutral technologies such as HYV may entail significant setup costs in terms of learning, locating and developing markets, and training hired labor. When these factors are considered as fixed expenses, the theoretical models imply that they tend to discourage adoption by small farms.

A number of empirical studies also support Ruttan's (1977) contention that smaller farms that initially lag behind larger ones in adopting HYV eventually catch up; and, moreover, some evidence is consistent with and validates the theoretical finding that the intensity of HYV adoption on small farms exceeds that of larger farms. For example, Muthia (1971), Schluter (1971), and Sharma (1973) found that small- and medium-size farms in India adopted HYVs on a larger proportion of acreage than did large farms. Schluter further found that the degree of this relationship increased with the length of time since the introduction of the new varieties.

The studies regarding intensity of fertilizer and pesticide use per unit of land show a more confusing pattern of behavior. While many studies indicate no significant difference in chemical input use per acre between farms of different size (see, e.g., Lipton 1978; Parathasarathy and Prasad 1978; Burke 1979; Singh 1979), others indicate a positive relationship between the amount of fertilizer applied per hectare of fertilized land and farm size. Perrin and Winkelmann (1976, p. 893) report that there were significant size effects in about half of the studies covered by their survey. Similar findings are reported by Clawson (1978) and in a number of other studies cited by Singh (1979). On the other hand, some empirical studies find negative relationships between intensity of use of modern inputs and farm size. However, Van der Veen (1975), who studied Philippine rice, suggested three possible explanations for this observed phenomenon. First, small farms may farm land more intensively to meet subsistence needs; second, small farms may irrigate more efficiently; and, third, small farms use relatively more low-cost family labor. Srinivasan (1972) has shown analytically that some of these factors explain the higher use of variable input per hectare by smaller farms. Theoretical studies on these types of inputs also show that the relationship between farm size and intensity of use depends critically on risk preferences of farms and on the risk effects of the input. With constant relative risk aversion or a risk neutral input, the theoretical studies imply no relationship between farm size and intensity, while a positive relationship is implied by increasing (decreasing) relative risk aversion for a risk-increasing (reducing) input.

The relationship between credit and farm size may be another factor underlying the conflicting observed patterns of modern input use by farmers of different size classes as suggested by some of the theoretical studies reviewed in the preceding section. Credit constraints may or may not be binding in some areas and in some size classes; but when credit is binding, use may be positively related to size.

Although many of the empirical findings on the relationship between farm size and adoption are compatible with the implications of theoretical studies, several observations from empirical studies are apparently explained by factors not yet considered in the theoretical literature. For example, an additional reason given by Weil (1970) for adoption, beyond the profit motive, is that farmers apparently prefer to replace heavy demands on human power with ox cultivation to improve working conditions. This observation suggests that theoretical models should be further developed to consider the labor/leisure and income/quality-of-life trade-offs in technology adoption. Moreover, in some cases, land-quality differences combine with farm-size differences to affect adoption decisions. For example, Burke (1979) found that adopters of Green Revolution technology are more land intensive when soil quality is taken into account and less land intensive if land quality is not considered and land intensity is simply measured by the land-labor ratio. Gladwin's (1979) findings in Mexico further suggest the importance of considering land quality in explaining adoption decisions.

The wide variety of empirical results, interpreted in the context of the theoretical literature, suggests that size of holding is a surrogate for a large number of potentially important factors such as access to credit, capacity to bear risks (see discussion below), access to scarce inputs (water, seeds, fertilizers, insecticides), wealth, access to information, and so on. Since the influence of these factors varies in different areas and over time,[9] so does the relationship between holding size and adoption behavior. Because the theoretical literature and analytical interpretation of the empirical results suggest that several intervening factors lie at the root of observed farm-size/adoption relationships, the remainder of this section turns to consideration of the observed role of such factors.[10]

B. Risk and Uncertainty

Innovations entail, in most cases, a subjective risk (that yield is more uncertain with an unfamiliar technique) and quite often objective risks also (due to weather variations, susceptibility to pests, uncertainty regarding timely availability of crucial imputs, etc.). However, empirical studies have very rarely treated this factor, because it is difficult to measure. One example is Gerhart's (1975) study of maize adoption in Kenya, which used the presence of drought-resistant crops as an indication of especially high risks and found this variable statistically significant in explaining adoption performance. However, this procedure is potentially misleading, because the decision to plant drought-resistant crops is an endogenous variable and should not, in general, be included on the right-hand side of the equation. A more appropriate procedure, used in a number of studies that obtained observations from different climatic or topographical areas, is through location-specific dummy variables that are shown to be significant (see, e.g., Colmenares 1976; Cutie 1976). It should be noted that such dummy variables could also represent other factors relating, for example, to fertility (rainfall, soil quality, etc.) or access to markets.

Another approach is to ascertain farmers' perceptions through direct interviews. The only works following this procedure in the context of innovation adoption are reported by O'Mara (1980) and Binswanger et al. (1980). O'Mara derived for a sample of Mexican farmers the corresponding sets of subjective yield distributions associated with HYVs. These were shown to be related to the adoption decisions actually taken, and they were modified over time on the basis of new information. Other suggested possibilities relate to proxy variables measuring rainfall variability or indices related to the incidence of major disasters (major infestations, severe droughts, floods, etc.). Binswanger et al. obtained a measure of farmers' risk aversion (for a sample of farmers in India) through gambling experiments. These measures were then used as an explanatory variable in a multivariate analysis of fertilizer adoption with mixed results in terms of statistical significance.

Farmers' technology choices are based on their subjective probabilities and, hence, on their exposure to information regarding new technology. As Gafsi and Roe (1979) show for Tunisia, domestically developed new varieties will be received more favorably by farmers than unfamiliar imported varieties. A related hypothesis is that more exposure to appropriate information through various communication channels reduces subjective uncertainty. As before, the problem lies in measuring the extent of information to which the farmer is exposed. A common proxy variable is whether the farmer was visited by extension agents (e.g., Gerhart 1975; Colmenares 1976) or whether he attended demonstrations organized by the extension service or other agencies (e.g., Demir 1976; Perrin 1976). Some studies used both variables because they represent different exposure sources. Other studies consider exposure to mass media (newspapers, radio, leaflets), literacy, level of education, and period of time spent out of the village as appropriate proxies.

While these studies are motivated by the conceptual work of Rogers (1957, 1962) on stages of experimentation, few of them (e.g., O'Mara 1980) apply the more sophisticated Bayesian models of learning such as the one proposed by Lindner (1980). It is observed that in many cases farmers experiment with new technologies or new practices on a small portion of their land. This suggests that some Bayesian learning processes are taking place. Results of studies using information proxies are mixed, as "information" variables are not always found statistically significant, and no general conclusions can be derived. The problem may lie simply in the fact that, in some instances, the proxy does not measure what it is supposed to approximate. For example, literacy may not have much to do with available information if the extension service organizes an effective demonstration pilot program at the village level (Vyas 1975). Or, in cases where the extension service has failed in the past to solve a major farm problem (thus eroding farmers' confidence), the most dominant factor may be the information gained by observing the procedures and performance of neighbors, friends, and relatives who have experimented with the innovation as the Indian study by Harriss (1972) indicates. However, in some cases, both demonstration and imitation effects may fail to exert influence as indicated in Ojo's (1963) study of the western region of Nigeria. In any case, most of the empirical work on the role of subjective risk is not yet rigorous enough to allow validation or refutation of available theoretical work.

C. Human Capital

By contrast to the subjective (learning) risk literature, the human capital empirical literature relating to adoption is well integrated with theory. This literature was inspired by the writings of Schultz (1964), who argues that frequent introduction of new technologies results in disequilibrium suboptimal use of inputs and technologies even though, in traditional static agriculture, resource allocation is efficient. Thus, changes in the technological environment increase the value of farmers' entrepreneurial ability, where such ability is defined as "the ability to perceive, interpret, and respond to new events in the context of risk" (Schultz 1981, p. 25). Welch (1978), who has extended and applied Schultz's concepts, suggests that the contribution by the human factor to the returns from agricultural production can be attributed to worker ability and allocative ability. Both abilities improve as experience and health improve.[11] Formal schooling, however, is hypothesized to play a much more important role in determining allocative ability than worker ability. This hypothesis has been supported by several studies. Ram (1976) found that farm operators' contributions to production are positively related to their education, whereas workers' contributions are not. Chaduri (1968) found that differences in education explain variation in cropping among regions in India but not variation in yields. Sidhu (1976) found that although farmers' education has some effect on yield, it had relatively greater effect on gross sales by farmers in the early stages of the Green Revolution in the Punjab.

Because allocative ability is especially valued in dynamic technological environments, Welch (1970) hypothesized that the value of education increases with technological change. He also hypothesized that extension services may substitute for education in an allocative choice in a changing environment and that the productivity of education in allocative choices is augmented by the size of farm operations. Welch (1970) verified these hypotheses in a study of wage patterns of American farm workers with different educational backgrounds in response to varying agricultural research levels (used as a measure of technological change) and extension activities. Ram (1976) found that the returns to farm managers' education are higher in "progressive" districts of India than in "backward" districts. Studies on South America surveyed critically in Welch (1978) indicate that education has no impact on productivity in regions with traditional agricultural practices but is related positively to education in some regions that are in the midst of modernization.

Several studies have investigated the effects of education on dynamic adjustment to changes in prices. The work of Huffman (1977) on the use of nitrogen by corn producers in the United States shows that farmers with better education adjusted their nitrogen use better to a decline in price than less educated farmers, and that their input levels approached optimal levels faster than did those of the less educated. Extension efforts are shown to substitute for education in the adjustment process. Petzel (1976) shows for the United States that education and scale of farm operations accelerate the adjustment of land use in soybean production to changes in output and input prices.

The results above suggest that farmers with better education are earlier adopters of modern technologies and apply modern inputs more efficiently throughout the adoption process. Moreover, several empirical studies have explicitly verified the link between early adoption and education. Some of the evidence has been presented in Evenson (1973) and Villaume (1977). Some recent studies used panel data and discrete choice models to analyze the effect of human capital on adoption probabilities. Gerhart (1975) found that the likelihood of adoption of hybrid maize in Kenya was positively related to education. Using estimatable forms derived from an optimization model that explicitly considers the cost of acquiring and processing information, Rosenzweig (1978) found that the probability of adoption of high-yield grain in the Punjab is positively related to education and farm size. Jamison and Lau (1982) applied a discrete-choice optimization model and a logit estimation technique to analyze adoption of chemical inputs in Thailand. They found that education affects the probability of adoption positively only above a threshold level (4 years). They also found a positive relationship between the likelihood of adoption and both age (which may represent experience) and extension activity.

D. Labor Availability

Labor availability is another often-mentioned variable affecting farmers' decisions about adoption of new agricultural practices or inputs. Some new technologies are relatively laborsaving, and others are labor using. For example, ox cultivation technology is laborsaving, and its adoption might be encouraged by labor shortage. On the other hand, HYV technology generally requires more labor inputs, so labor shortages may prevent adoption. Moreover, new technologies may increase the seasonal demand of labor, so that adoption is less attractive for those with limited family labor or those operating in areas with less access to labor markets.

Hicks and Johnson (1974) have found that higher rural labor supply leads to greater adoption of labor-intensive rice varieties in Taiwan, and Harriss (1972) has found that shortages of family labor explain nonadoption of HYVs in India. Most of the studies seem to agree that the operative constraint in African farming systems is the peak-season labor scarcity (see, e.g., Helleiner 1975). Specific evidence to that effect for the North Central region of Nigeria is provided by Nordman (1969). The seasonal peak labor shortage may be overcome, however, if neighboring regions peak at different times thus allowing temporary labor migration.

One of the major purposes of farm mechanization is to alleviate labor bottlenecks. For example, ox power and tractor power can make possible more timely farming operations and allow increased production and reduced labor demand and, sometimes, more double and multiple cropping. These arguments are confirmed by the empirical works of Weil (1970) in Gambia, Alviar (1972) in Laguna, and Spenser and Byerlee (1976) in Sierra Leone. These results support the theoretical work on labor bottlenecks and labor supply uncertainty suggesting that uncertainty regarding the availability of labor in peak seasons can explain adoption of new laborsaving technology.

E. The Credit Constraint

Several of the theoretical studies mentioned earlier argue that the need to undertake fixed investments may prevent small farms from adopting innovations quickly. Capital in the form of either accumulated savings or access to capital markets is required to finance many new agricultural technologies. Thus, differential access to capital is often cited as a factor in differential rates of adoption. This is the case with indivisible technology, in particular, such as tractors or other machinery that requires a large initial investment. These implications have been confirmed by descriptive and empirical work on the role of credit as well (e.g., Lowdermilk 1972; Lipton 1976; Bhalla 1979).

On the other hand, others have argued that lack of credit alone does not inhibit adoption of innovations that are scale neutral. Schutjer and Van der Veen (1977) cite a number of scholars who point out that the profitability of HYV adoption will induce even small farms to mobilize (from whatever sources to which they have access) the relatively small cash requirements for necessary inputs. Von Pischke (1978) similarly questions the assertion that credit availability is a precondition for adoption.

A number of studies, however, have found that lack of credit does significantly limit adoption of HYV technology even where fixed pecuniary costs are not large. For instance, in a study of Indian agriculture Bhalla (1979) reported that small and large farms gave different reasons for not using fertilizer in 1970–71. Lack of credit was a major constraint for 48% of small farms and for only 6% of large farms. Bhalla concludes that "access to credit may be responsible for the gain in income (and HYV area) made by the large farmers" (1979, p. 143). Similarly, many other studies have found that a majority of small farms reported shortage of funds as a major constraint on adoption of divisible technology such as fertilizer use (e.g., Frankel 1971; Wills 1972; Khan 1975).

External off-farm income sources are also relevant since they enable the farmer to undertake agricultural practices that may otherwise jeopardize his subsistence income. Off-farm income can help to overcome a working capital constraint or may even finance the purchase of a fixed-investment type of innovation. These effects have been verified empirically by Gerhart (1975), Rochin and Witt (1975), Demir (1976), and Perrin (1976), among others, through the introduction of a measure (or a dummy variable) of such income.

The study by Scobie and Franklin (1977) also concludes that access to credit may not encourage adoption if it entails restrictions on input use (e.g., lower limits on fertilizer and pesticide applications). In fact, evidence suggests that rational farmers will evade the restrictions. In areas where adoption of divisible innovations (such as HYVs) depends on (or is greatly enhanced by) complementary indivisible investment (such as tube wells), lack of credit can impede the uptake of the divisible innovation by smaller farms (Clay 1975). These results are fully consistent with the theoretical explanation advanced by Feder (1982) of the role of credit and risk in explaining adoption of interrelated agricultural innovations. One policy advanced to minimize the adoption-discouraging effects of credit scarcity is a subsidization of credit. But Lipton (1976) argues that subsidization of credit does not necessarily circumvent the problem for smaller farms since in many cases the larger and more influential farms manage to get the bulk of such credit.

F. Tenure

A number of empirical and descriptive studies have considered the effects of tenure arrangements and the proportion of farms rented on the adoption of HYV technology. For example, Parthasarathy and Prasad (1978) conclude that tenants had a lower tendency to adopt HYVs than owners. On the other hand, nitrogen fertilizer use was the same for tenants and owners. But less familiar fertilizers, such as phosphates, and insecticides were used less by both smaller farms and tenants. The evidence is somewhat confusing since, as the authors emphasize, the landlord is the decision maker regarding the variety of crops to be grown on leased land. Similarly, other empirical studies do not find a clear relationship between tenure and adoption. Vyas (1975) cites studies referring to HYV wheat adoption in India that show that tenants were not only as innovative as landowners but sometimes used more fertilizer per hectare than did owners. It has been pointed out by some observers, however, that a distinction should be drawn between pure tenants (who own no land) and tenant-owners (who own at least some of their land)—the latter can be expected to be more receptive to innovations. One reason for this behavior may be that tenant-owners are less affected by credit constraints than are pure tenants.

The work of Schutjer and Van der Veen (1977) further suggests that any observed effect of tenancy may be indirectly due to the implied relationships between tenure and access to credit, input markets, product markets, and technical information. If these relationships differ in different sociocultural environments, empirical results may seem to conflict if the underlying factors are not considered directly. Thus, clear empirical results on the relationship between tenure and adoption may be lacking because many factors are yet to be considered appropriately.

The conflicting empirical results regarding the relationship of tenure and adoption are in accordance with the unsettled debate in the theoretical literature over the relation between tenancy and adoption (see Sec. II*F*). The discussions point out the need to specify the terms of tenurial agreement explicitly for empirical work.

G. Supply Constraints

An important factor in explaining adoption patterns is the availability of complementary inputs. It is obvious that HYV seeds will not be adopted by most farmers unless both seeds and some fertilizers are available; in most cases, the high-yield potential of the seed can be realized only if at least some fertilizers are applied. Thus, a sound study should determine whether behavior is supply constrained. But other inputs are also complementary to different degrees, for example, water and storage facilities (for perishable crops).

The latter point again raises the issue of complementary innovations mentioned earlier. That is, some innovations (which may or may not have been introduced simultaneously) are complementary to a certain degree. The HYV fertilizer package is more profitable and less risky if means of developing an assured and regulated water supply are also provided (see Dalrymple 1978; Burke 1979, pp. 135–54). The studies by Clay (1975), Vyas (1975), and Duff (1978) provide detailed descriptions of innovation complementarity and suggest the importance of jointly examining such adoption decisions.

H. Aggregate Adoption over Time

The early empirical studies of the dynamics of diffusion in agriculture conducted in the United States during the 1940s and 1950s established some of the basic notions regarding adoption behavior over time in agriculture—especially at the aggregate level. Studies conducted by rural sociologists have documented sigmoid diffusion curves over time for several agricultural innovations (e.g., Beal and Buhlen 1957; Rogers 1957). Many of these studies have focused on the role of communications in determining the pace of the diffusion process and the shape of the diffusion curve. For example, Rogers discusses empirically the existence of different stages of the adoption process for different categories of adopters of hybrid corn in the United States. He found that the awareness gap and the experimentation period are shorter for the early adopter than for followers. Using data on diffusion of weed spraying in Iowa, Rogers constructed an aggregate adoption measure and an aggregate awareness measure and studied how these measures changed over time. Both functions are S-shaped, but the horizontal gap between them becomes greater with time, implying shorter awareness and experimentation gaps for early adopters. As Section II indicates, there are several theoretical models that explain the shape of the diffusion curve. But the dynamics of aggregate awareness and the experimentation period have not been addressed analytically. Nevertheless, the framework developed by Fischer and Lindner (1980) for analyzing the allocation of resources to search for technology seems to offer a promising point of departure.

The first econometric study of aggregate adoption over time was conducted by Griliches (1957), who introduced economic variables to explain the diffusion of hybrid corn in the United States. He estimated the fraction of land utilized by hybrid corn as a logistic function of time for 132 corn-growing districts. The logistic function,

$$P(t) = K\,[1 - e^{-(a+bt)}]^{-1}, \tag{2}$$

is a sigmoid function of t where K is the long-run upper limit on adoption aggregate; the slope coefficient, b, is a measure of the rate of acceptance of the new technology; and the intercept, a, reflects aggregate adoption at the start of the estimation period. Griliches found variation in the diffusion curve parameters among districts. Further investigation showed that a substantial share of the variation in rate of acceptance and the long-run upper limit on adoption of hybrid corn are explained by differences in the profitability of the technology in different districts.

Using Griliches's approach, Martinez (1972) obtains similar results for the adoption of hybrid corn in Argentina. Jarvis (1981) estimates and predicts the diffusion of improved pastures in Uruguay using a nonlinear regression technique for a modified logistic curve that includes beef and fertilizer prices as explanatory variables. Both prices (and hence the relative profitability) significantly affect the rate of acceptance and the long-run upper limit of aggregate adoption. Jarvis also shows that the long-run aggregate adoption level is affected by the amount of land suitable for the new grass varieties.

The results of these studies highlight the location specificity that characterizes many new agricultural technologies. This aspect of agricultural technology has an important effect on the possibility of transferring technologies generated by research in other regions or other countries. Ruttan and Hayami (1973) cite examples of biological and mechanical technologies that demonstrate three distinct phases in the process of technology transfer. First, new materials (such as seed, plants, animals, machines, and the technologies associated with them) are imported without a systematic adaptation to local conditions (the "material transfer" stage). This is followed by a "design transfer" phase, in which technology is primarily in the form of blueprints, formulas, and books. A systematic approach to the testing of foreign materials gradually evolves. Finally, a local production capacity is created, adapted to local conditions on the basis of a prototype technology that originated abroad (the "capacity transfer" stage). Evenson and Binswanger (1978) demonstrate, however, that these stages may not always follow in the order described. They argue that countries have three main options for improving the productivity of the agricultural or any other sector. Under the "direct transfer" option, the best foreign techniques are screened and adopted without adaptation. The second option is the selection of foreign techniques that are subsequently modified to suit local conditions through adaptive research. The third option involves the screening of technology, as well as basic scientific knowledge, in order to try to generate technology through comprehensive local research.

The observed pattern of technology diffusion will depend on the extent to which the technology suits the conditions under which most farmers operate and on the pace of adaptive research. The shape of the aggregate diffusion profile is, therefore, a function of factors related to technology generation, as well as of factors related to farmers' behavior.

Several theoretical models discussed earlier explain the empirically observed sigmoid diffusion curves and the sensitivity of the parameters to the relative profitability of a new technology. One of the theoretical models, however, is directly backed by empirical application. Kislev and Shchori-Bachrach (1973) analyzed the diffusion of plastic covers among different groups of vegetable growers in Israel. They estimated a diffusion curve for each group and explained differences in coefficients among groups by human capital differences (measured by average schooling). Skill-intensive groups were the earlier adopters and thus the intercepts of their diffusion curves are larger. Labor-intensive producers, who eventually become the main users of the technology, are late adopters and have low intercepts but high rates of acceptance in their diffusion curves. The predicted long-run aggregate adoption level was found to be larger than the actual one, and this is explained by a reduction in vegetable prices resulting from extensive adoption of the technology. The reduction of prices results in unfulfilled expectations for profit—especially for the low-skilled followers and laggards who are the main users of the new technology in the long run. The skill-intensive early adopters were most likely to switch to the next stage in the new technology package. These results are consistent with Cochrane's (1958) technological treadmill hypothesis.

Another component of Cochrane's model is documented in Mann's (1978) description of a sequential pattern of adoption of innovations for Green Revolution technologies in Turkey. Also, Falcon (1977) notes that the "phenomenal" increase in food supply and the resulting price reductions are the main characteristics of the diffusion of Green Revolution technologies in Asia. Similar findings are reported by Scobie and Franklin (1977) for Colombia. These studies thus suggest that output-price effects and the role of adoption sequences should receive more attention in future studies of the diffusion processes.

IV. Evaluation of Previous Work and New Directions in Empirical Research

A. Some General Remarks

The sections above review the conclusions of a great number of empirical studies of adoption and possible theoretical explanations of them. It is worthwhile also to discuss the validity of the empirical methodology. Much of the empirical work has lacked a theoretical basis on which to specify structural relationships and interdependencies. Thus the functional forms which have been estimated may not correspond to any reasonable underlying decision behavior. More important, many models often fail to meet the statistical assumptions necessary to validate the hypothesis tests on which the conclusions are based. Many studies provide only qualitative rather than quantitative information about the adoption process. Finally, endogenous variables have often been used as explanatory variables without regard for the simultaneous equations bias that can result. We will consider these issues in the following sections.

B. Dichotomous and Continuous Adoption Variables

In most studies, adoption variables are categorized simply as "adoption" or "nonadoption." However, knowing that a farmer is using HYVs may not provide much information, because he may be using 1% or 100% of his hectarage. Similarly, with respect to the adoption of new types of fertilizers, a farmer may be applying a small amount or a large amount per hectare. Indeed, on the basis of a comprehensive review of adoption studies, Schutjer and Van der Veen (1977, p. 14) conclude that "the major technology issues relate to the extent and intensity of use at the individual farm level rather than to the initial decision to adopt a new practice." Adoption apparently cannot be represented adequately by a dichotomous qualitative variable in many cases.

Given the need for quantitative analysis, we find it disturbing that many of the econometric studies of adoption have focused on the directional impacts of certain explanatory forces rather than their quantitative importance. For example, several studies of adoption have been undertaken using χ^2 contingency tables to perform nonparametric hypothesis tests of the importance of certain explanatory variables (Rochin and Witt 1975; Parthasarathy and Prasad 1978). While the outcome of these tests may suggest a significant effect in statistical terms, there is no way of knowing from this type of analysis whether the economic importance of the effect is worth considering.

Several other studies have used correlation analysis to examine the interrelationships of several factors affecting adoption (Rogers 1969). However, this approach also produces only qualitative information regarding the effect of various explanatory factors; no information regarding the quantitative importance of various factors is obtained. Furthermore, the simple correlations between some variables may be greatly influenced by other variables so that each correlation may include the spurious effects of the other variables.

In those studies which have attempted to determine econometrically the quantitative importance of various explanatory variables, ordinary regression methods have been in most common use. However, many such studies have attempted to explain only the decision of adoption versus nonadoption rather than the extent or intensity of adoption. For example, a common practice has been to explain adoption empirically by an ordinary least squares (OLS) regression of a zero-one adoption variable (say, use of an HYV) on explanatory variables such as farm size, tenure, location, or topography (see, e.g., Colmenares 1976). However, normality of disturbances is obviously inappropriate for such regressions; and thus the estimated standard errors and *t*-ratios produced by an OLS regression are not appropriate for investigating hypotheses about the role and importance of various factors in the adoption process.

Second, ordinary linear-regression estimates produce predictions other than zero or one for the dependent variable; if these predictions are considered as probabilities, then predictions less than zero or greater than one are nonsensical. Some studies recognize that normal hypothesis testing procedures are invalid in this approach but still claim the unbiasedness of their estimated equations (e.g., Cutie 1976). These claims are also not appropriate, as the recent econometric literature on limited dependent variables makes clear (see, e.g., Pindyck and Rubinfeld 1976).

Turning to the econometric literature, one finds that appropriate estimation methodology has been developed for investigation of the effects of explanatory variables on dichotomous dependent variables (see, e.g., Amemiya 1973). The most commonly used qualitative response models are the logit model, which corresponds to a logistic distribution function, and the probit model, which assumes an underlying normal distribution. These models specify a functional relation between the probability of adoption and various explanatory variables. Examining the empirical studies in the literature, however, reveals that very few have actually adopted procedures that explicitly account for the qualitative nature of the dependent variable. Gerhart (1975) used a probit analysis to explain adoption rates of hybrid maize in three different regions in Kenya (unfortunately, this study is subject to the other biases discussed below). Jamison and Lau (1982) applied logit analysis to investigate factors affecting the adoption of chemical inputs among Thai farmers. Nerlove and Press (1976) used logit analysis to study adoption of several innovations in Philippine agriculture (more will be said below about this study).

With the backdrop of probit and logit models, it is also worthwhile to discuss another approach that has found its way into the adoption literature; discriminant analysis is a procedure for classifying observations in one category or another based on several explanatory variables (see, e.g., Yapa and Mayfield 1978). The usefulness of discriminant analysis, however, is often confused with that of logit analysis (e.g., McFadden 1976*b*). The relative odds of correct binary classification are given by the logit formula for this case, but the discriminant estimator is not generally a consistent estimator of the parameters of the logit model when selections are generated thereby (see, e.g., McFadden 1976*a*; Press and Wilson 1978). Hence, the probit-logit methodology appears to be preferable to discriminant analysis for analyzing the adoption decision.

C. Continuous But Limited Adoption Variables

Next consider the possibilities for studying econometrically the degree or intensity of adoption as well as the decision of adoption versus nonadoption. Actually, many of the same empirical problems discussed above also carry over into problems where adoption is represented by continuous but limited variables. For example, many studies seek to explain the *percentage* of adoption on the basis of various explanatory variables. The dependent variable is continuous but limited to the interval (0, 100); hence, this approach entails obvious specification bias when linearity is used and occasionally produces nonsensical predictions outside of the interval (0, 100) (see, e.g., Anden-Lacsina and Barker 1978). Other problems with limited dependent variables are created by adoption of inputs, such as new types of fertilizers, where there is an obvious lower limit of zero on the amount applied but no clearly defined upper limit. Here again, some studies have simply regressed fertilizer use linearly on various explanatory variables without considering the lower boundary (e.g., Cutie 1976). This approach is subject to the same criticism as above if some zero responses for fertilizer use are observed.

Other studies avoid the problem of obtaining negative predictions for fertilizer use by using the logarithm of fertilizer use as the dependent variable (e.g., David 1978; David and Barker 1978); thus, any finite explanatory variables lead to positive predictions for fertilizer use as long as finite coefficient estimates are obtained. Although this approach is more acceptable, there may be many farms on which fertilizer is not used, and such predictions would not be possible in the logarithmic or semilogarithmic framework (given finiteness of variables and coefficients). Again, there is an obvious problem of specification bias, although perhaps not as serious as those above.

It seems, therefore, that, for most adoption problems, valid hypothesis testing and unbiased estimation of parameters of the adoption process require explicit treatment of the limited nature of dependent variables that reflect adoption intensity. The probit-logit methodology is one possibility when the adoption process is dichotomous. But a strictly dichotomous variable often is not sufficient for examining the extent and intensity of adoption. For some problems, such as fertilizer use, sufficient modeling detail might be attained in a two-stage investigation, where first the probability of fertilizer use is explained in a dichotomous choice model and then the quantity of use given adoption could be explained in a conditional model with the logarithm of fertilizer as a dependent variable. However, other adoption variables, such as the percentage or proportion of cropland used for HYVs, may require specific considerations of limited dependent variables. The general logistic specification is, again, a feasible functional form for reflection of variables in the open-unit interval where ordinary estimation methods suffice for a suitable transformation. Furthermore, for the more general limited dependent variable problem, significant progress in estimation has been made by Amemiya (1973), Hartley (1977), and others, so that consideration of more general functional relationships including interval end points is feasible.

D. Simultaneous Equations Considerations

Another critical issue in econometric studies of factors affecting adoption is the possibility of simultaneous equations bias. Among the empirical studies reviewed, one finds a number of cases where this issue has not been considered. For example, some studies attempt to explain the quantity of fertilizer used by an ordinary regression on the use of HYVs, among other things (e.g., David and Barker 1978). However, the decision to use more fertilizer and the decision to use HYVs are generally simultaneous and thus probably subject to the same random disturbances—for example, misrepresentation of the role of extension in learning about both practices. Hence their results are apparently subject to simultaneous equation bias and inconsistency. One study by Sison (1978) also used ordinary regression to determine the effect of the rice production technology choice (and other factors) on the amount of land used for rice production. Both of these variables are probably simultaneous choice variables also, so that results are biased and inconsistent.

Some studies that have correctly considered the qualitative nature of their dependent variables have also been subject to this type of bias (e.g., Gerhart 1975; Yapa and Mayfield 1978). While simultaneous estimation of linear and even nonlinear systems of equations is a common econometric problem, the estimation problems offered by these cases are somewhat more difficult. Nerlove and Press (1973, 1976) appear to have been among the first to discuss the logit model in a truly simultaneous equation framework. In the context of simultaneous estimation of several adoption decisions, it becomes possible to uncover interactions that can be extremely useful in attempts to manipulate the adoption process. For example, suppose several new technologies or practices are introduced in an attempt to modernize production (e.g., hybrid seed, chemical fertilizer, modern weeding practices, and modern land preparation practices). In this case, it may be that a farmer is more likely to adopt fertilizer if hybrid seed is adopted, but not necessarily vice versa. These results, if forthcoming, would suggest that extension work might concentrate more on hybrid seed adoption, since fertilizer use is likely to follow. Nerlove and Press, in fact, introduced a technical framework for investigating these kinds of interactions in a simultaneous multinomial log-linear probability model and have further applied the framework to simultaneous investigation of these four adoption decisions in Philippine agriculture. The analysis is quite brief and is provided only as an example but, nevertheless, begs for further application of multinomial logit or probit models in the study of adoption.

Another recent approach to empirical work on adoption, which shows promise particularly for multiequation modeling, is based on duality.[12] Using the dual approach, one can specify flexible equations describing choices for several decision variables in such a way that estimates of different equations can be constrained to relate to a common underlying producer decision problem. Because different equations relating to the same farmer have common parameters representing preferences and technology, constrained estimation leads to greater efficiency in estimation. A particular advantage gained through this approach is the ability to examine distributional implications of new policies or technologies by exploiting the model structure. These advantages in examining distributional implications of policies for developing agriculture are exemplified in studies by Lau, Wun-Long, and Yotopoulus (1978) and by Lau et al. (1981). The methodology for extending this approach to the case where some decisions are discrete has been developed in the works of McFadden (1982) and, in some cases, led to multinomial logit models similar to the Nerlove-Press studies above. It remains, however, to apply the more general methodology in examining technology adoption in developing agriculture.

V. Conclusions and Implications for Further Adoption Research

The adoption research reviewed here seems to support the following major conclusions. First, most adoption research has thus far viewed the adoption decision in dichotomous terms (adoption or nonadoption). But for many types of innovations, the interesting question may be related to the intensity of use (e.g., how much fertilizer is used per hectare or how much land is planted to HYVs). Future studies can rectify this problem by properly accounting for a more varied range of responses and by employing statistical techniques suitable for the variables considered.

Second, empirical research of adoption behavior should recognize that in many cases several innovations which have various degrees of complementarity are introduced simultaneously. It follows that adoption decisions for various innovations are interrelated. Analysis of this issue is further complicated by the fact that various interrelated innovations are often introduced over time in a partially overlapping manner, thus creating a lasting disequilibrium. The dearth of research on this aspect is probably related to the complexity of the issue, but these interrelationships should be considered in the econometric procedures. To do otherwise may introduce biases and detract from the validity of the conclusions reached.

Third, many adoption models consider a rather simple economic model where the industry is a price taker in perfect competition with homogeneous inputs. As Falcon (1977) notes, however, price effects in input and output resulting from technology adoption may affect the progress and the direction of the diffusion process by affecting the relative profitability of alternative technologies and by changing the income distribution. Similarly, the "nonexistence" of government policies in most adoption models is bothersome. Price support schemes, food taxes and subsidies, and input and output quotas are an important part of the reality of many developing countries and affect technological choices and diffusion processes.

Fourth, the conflicting conclusions sometimes indicated by studies from different regions or countries may in many cases be the result of differing social, cultural, and institutional environments (aside from "pure" economic factors). It is thus essential to provide detailed information about the interactions among the various factors that generate the observed behavioral patterns. Furthermore, in consideration of the dynamic aspects of adoption, descriptive studies suggest that a given farmer may follow a sequential process of adopting several related production practices. Further work is needed to understand any order and regularity in such chain processes.

Finally, differential adoption rates of Green Revolution technology by different socioeconomic groups (classified, e.g., by tenure status or holding size) are often found to disappear once the process is sufficiently advanced (e.g., Ruttan 1977). But even if this is the case, the early adopters (usually the larger and wealthier farms) can accumulate more wealth and use the differential in the subjective value of land to acquire more land from the laggards. The acquisition of new wealth enables further adoption and thus affects the dynamic pattern of aggregate adoption. Thus, special attention to changes in landholding patterns and wealth accumulation (as well as tenancy arrangements) is warranted.

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Notes

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1. The terms, "adoption process" and "diffusion process," as defined here, correspond to interfirm and intrafirm diffusion in Mansfield (1966).

2. Most adoption models assume that the utility function of the farmer has one argument, e.g., perceived income or perceived consumption; but in some situations the utility function is assumed to have other elements, such as leisure time. Of course, maximization of temporal expected utility represents an oversimplification of the dynamic considerations that could be made by a sophisticated planner. But intuition suggests that this "myopic optimization" approach may be a reasonable representation of decision making by peasant farmers. In point of fact, it has been proved analytically that, under reasonable circumstances, the myopic optimization outcomes are good approximations of the outcomes of the more complex intertemporal optimization problem (see Tesfatsion 1980).

3. This approach is used in Lindner, Fischer, and Pardey (1979).

4. Equations of motion of this type are considered in Gutkind and Zilberman (1981).

5. Absolute risk aversion measures the insistence of a risk-averse individual for more-than-fair odds when faced with a bet whereby he can win or lose a given sum of money. Relative risk aversion measures the same insistence when

the bet is such that a given proportion of wealth or income can be won or lost. It is generally accepted that absolute risk aversion declines as wealth increases; see Arrow (1971).

6. While the assumptions of the paper are restrictive and possibly do not hold in many situations, they provide the means of understanding the implications of imperfect capital markets for adoption; see Feder (1980).

7. While the first of the hypotheses above is in contradiction to the conclusions obtained by Newbery (1975), Bardhan's model does not consider the presence of uncertainty and risk aversion. Furthermore, the specification of the landlord's decision problem ignores the fact that although the landlord cannot supervise the tenant's labor input he takes into account the tenant's reaction function, which is affected by the amount of land allocated to him.

8. Ruttan (1977) lists two other generalizations which relate to the effects of new technology on wages, income, and prices. These generalizations are not included here because the focus of this paper is on explaining the adoption process itself rather than its effects.

9. For example, preferential access to limited supplies of fertilizers may be of importance only during the initial years before distribution channels are properly organized.

10. Similar conclusions were obtained by Schutjer and Van der Veen (1977).

11. Evidence of the importance of health in determining farmers' productivity is presented by Schultz (1981).

12. For a review of this econometric approach in production, see Fuss and McFadden (1978).