Adoption of agroforestry innovations in the tropics: A review

D.E. Mercer

Southern Research Station, USDA Forest Service, 3041 Cornwallis Road, P.O. Box 12254 Research Triangle Park, NC 27709; USA; e-mail: emercer@fs.fed.us

Abstract

The period since the early 1990s has witnessed an explosion of research on the adoption of agroforestry innovations in the tropics. Much of this work was motivated by a perceived gap between advances in agroforestry science and the success of agroforestry-based development programs and projects. Achieving the full promise of agroforestry requires a fundamental understanding of how and why farmers make long-term land-use decisions and applying this knowledge to the design, development, and 'marketing' of agroforestry innovations. This paper reviews the theoretical and empirical literature that has developed during the past decade analyzing agroforestry adoption from a variety of perspectives and identifies needed future research. Much progress has been made, especially in using binary choice regression models to assess influences of farm and household characteristics on adoption and in developing ex-ante participatory, on-farm research methods for analyzing the potential adoptability of agroforestry innovations. Additional research-needs that have been identified include developing a better understanding of the role of risk and uncertainty, insights into how and why farmers adapt and modify adopted systems, factors influencing the intensity of adoption, village-level and spatial analyses of adoption, the impacts of disease such as AIDS and malaria on adoption, and the temporal path of adoption.

Introduction

No matter how elegant, efficient. productive, and/or ecologically sustainable, agroforestry systems can contribute to sustainable land use only if they are adopted and maintained over long time periods (Raintree 1983; Scherr 1992; Sanchez 1995). Although there arc some examples of significant adoption over the past two decades (Current et al. 1995; Buckles and Triomphe 1999; Barrett et al. 2002; Franzel and Scherr 2002), many have lamented the fact that adoption and diffusion have lagged behind the scientific and technological advances in agroforestry research reducing the potential impacts of agroforestry-based development projects (Adesina and Chianu 2002; Alavalapati et al. 1995; Bannister and Nair 2003: Lapar and Pandey 1999; Nair 1996: Sanchez 1995; Thacher et al. 1997). As a result, research on adoption of agroforestry innovations has attracted much attention and generated a relatively large literature during the past decade.

Approaches to analyzing agroforestry adoption tend to follow the vast literature on adoption of agricultural production technologies, most of which focus on new or improved production inputs (e.g. Green Revolution inputs) for conventional agricultural crops (Feder et al. 1985; Feder and Umali 1993). A number of features of agroforestry, however, make analysis of its adoption unique and deserving of its own review. Adoption of agroforestry is considerably more complex than traditional agriculture because it usually requires establishing a new input-output mix of annuals, perennials, green manure, fodder and other components, combined with new conservation techniques such as contour hedgerows, alleycropping, and enriched fallows (Rafiq et al. 2000). Unlike standard agriculture, there are few packaged agroforestry or farm-based, natural resource management (NRM) practices to deliver to farmers (Barrett et al. 2002). As a result, agroforestry and other NRM innovations arc typically more knowledge-intensive than modem

agricultural development packages based on improved seed, chemical, and/or mechanical inputs. Therefore, farmer education, experimentation, and modification are more important for agroforestry and NRM development than for conventional agriculture (Barrett et al. 2002).

This multicomponent, multiproduct nature of agroforestry may limit adoption due to the complex management requirements and the long period of testing and modification that is required compared to annual cropping technologies. An agroforestry system is likely to take three to six years before benefits begin to be fully realized compared to the few months needed to harvest and evaluate a new annual crop or method (Franzel and Scherr 2002). These characteristics can enhance opportunities for adoption by allowing more farmer experimentation and adaptation but can also complicate analysis of who adopts, what they adopt, and how they modify the system adopted (Vosti et al. 1998). The additional uncertainty inherent in these new input-output mixes is also an important reason for slower adoption rates and suggests that agroforestry projects will require longer time periods before becoming self-sustaining and self-diffusing than the earlier Green Revolution innovations (Amacher et al. 1993).

Most research supports the notion that decisions to adopt resource-conserving practices like agroforestry are largely driven by expected contributions to increased productivity, output stability through risk reduction, and enhanced economic viability compared to the alternatives (Arnold and Dewees 1995; Sain and Barreto 1996; Salam et al. 2000; Scherr 2000). Therefore, this review of the agroforestry adoption literature is primarily economics-based. Following on Pattanayak et al.'s (2003) meta-analysis of multiple regression based agroforestry studies, this paper examines the broader adoption literature to assess the current state of knowledge on agroforestry adoption.

Definitions and a brief history of adoption-diffusion research

Innovation, adoption, diffusion

From a sociological viewpoint, an innovation is an idea, practice, or object that an individual perceives as new. Since the focus is on the perception of the idea, the innovation need only be 'new' to the potential adopter. This suggests that adoption is the mental process

from first hearing about an innovation to deciding to make full use of the new idea (Rogers and Shoemaker 1971; Rogers 1983; Evans 1988). Feder et al. (1985) argued, however, that sociological definitions of adoption are usually inadequate for 'rigorous theoretical and empirical analysis' due to their imprecision and failure to distinguish individual or farm-level adoption from aggregate adoption.

From an economic standpoint, an innovation is a technological factor of production with perceived and/or objective uncertainties about its impact on production. Farmers reduce uncertainty over time by acquiring experience, modifying the innovation, and becoming more efficient in its application. Therefore, economists have defined final adoption at the farm-level 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' (Feder et al. 1985).

Diffusion of technological innovations has been defined as the spread of 'successful' innovations as they combine with or displace existing 'inferior' alternatives (Sarkar 1998). Thus, diffusion concerns the extent (spatially and temporally) to which the new innovation is put to productive use. Early adopters are often referred to as innovators and the diffusion process as the spread of the innovation to other members of the population (Feder and Umali 1993).

Adoption typically has been viewed from two perspectives. At the individual farm level, each household chooses whether or not to adopt and the intensity of adoption. Farm-level adoption studies, then, are concerned with the factors influencing the adoption decision either statically or dynamically by incorporating learning and experience. At a macro-level, diffusion studies examine how adoption evolves across a population or region. Since the objective is to identify specific trends in the diffusion cycle over space and time, diffusion models do not explicitly address the innovation process. Diffusion studies typically begin after the innovation is already in use and analyze the spread of the innovation as a dynamic, aggregative process over continuous time (Feder and Umali 1993).

A brief history

Although the adoption and diffusion of agricultural innovations depends on a combination of social, economic, and cultural factors, most theoretical and empirical adoption work has tended to be dominated by separate lines of research by sociologists, econom-

ists, and geographers. Economists historically emphasized profitability and investment risks, while sociologists concentrated on the social rewards and nature of communication channels associated with adoption. Geographers have studied the spatial differences in resource endowment and diffusion, and anthropologists have emphasized compatibility with the norms of society (Boahene et al. 1999).

Adoption-diffusion first emerged as an important research agenda in rural sociology in the 1940s and 1950s (Ruttan 1996). According to Rogers (1983), 'the research tradition that can claim major credit for initially forming the intellectual paradigm for diffusion research, and that has produced the largest number of diffusion studies, is rural sociology.' Sociologists have traditionally conceptualized the adoption-decision process by examining distinguishing characteristics of adopters and nonadopters and opinion leaders, farmers' perceptions of the attributes of the innovations, rates of adoption and diffusion, and the channels of communication during the various stages of the adoption decision process (Marra et al. 2003).

The number of adoption-diffusion studies by rural sociologists began to decline in the 1950s for U.S. and European studies, and in the mid-1960s for developing countries. By the mid 1970s, rural sociology began to lose its dominance.' Several reasons have been advanced for this decline including: i. the lack of attention to theory, ii. over dependence on 'search for variables' approaches to empirical analysis, iii. inadequate attention to how independent and dependent variables are specified, an issue referred to by economists as the identification problem, iv. noncritical use of the epidemic model and the assumed linear relationship between status and adoption, and v. a shift in social theory away from modernization and toward dependency and other class-based perspectives (Ruttan 1996). Ruttan (1996) concludes that the most important reason for the decline in sociological adoption research 'is that sociologists failed to embrace the more formal analytical methods introduced by geographers to understand the process of spatial diffusion or by the economists and technologists to understand the process of technological innovation, substitution, and replacement.'

Although agricultural economists' interest in adoption research began in the 1950s with Griliches' (1957) econometric study of hybrid corn (*Zea mays*) adoption, it was not until the 1970s that economists' work on adoption-diffusion studies began to rapidly expand. Ruttan (1996) provides three primary explanations for the increasing importance and dominance of economics in adoption-diffusion research. First, both domestic and international development agencies demand research that provides policy-relevant knowledge of the sources and diffusion of technical change. Second, economists typically remain skeptical of the sociologists' argument that technology is the problem rather than the solution. Finally, the arguments of agricultural economists that broader economic forces create many of the incentives to innovate have widespread appeal.

At least initially, economists drew heavily on the diffusion work by sociologists, but as the research evolved, economists embarked on an increasingly distinct theoretical and methodological path. The result was that neither sociologists nor economists influenced each other's research during the 1980s and 1990s (Ruttan 1996). Viewed from a multidisciplinary prospective, adoption is a multi-dimensional process dependent on a variety of factors such as perceived profitability, costs of establishment, compatibility with value systems, and the ability to communicate new knowledge and information between and among adopters and potential adopters (Boahene et al. 1999). As Kenneth Arrow stated:

> while (the *economists)* stress the profitability of the investment and risks involved, the sociologists are concerned with the nature of the channel connecting adopters of an innovation with potential followers. . . .*(but)* there is nothing irreconcilable in the two viewpoints: in effect, the economists are studying the demand for information by potential innovators and sociologists the problems in the supply of communication channels' (1969, p.13).

Agroforestry adoption research has followed a similar historical path, with a 20-year lag. Initial efforts in the study of agroforestry adoption during the 1970s and 1980s tended to be descriptive and prescriptive and lacked formal theoretical development or rigorous empirical analysis (Raintree 1983; Fujisaka 1989; Allen 1990). For example, Swinkels and Scherr's (1991) bibliography of 230 studies of agroforestry economics lists only eight publications related to adoption, of which only three were in peer-reviewed journals, one in a conference proceedings, and four unpublished. By the early 1990s, agroforestry research was still primarily concerned with physical and biological interactions with little emphasis on economics or sociology (Swinkels and Scherr 1991; Current et al. 1995; Mercer and Miller 1998). Agroforestry adoption

research blossomed in the 1990s beginning with the Current et al. (1995) case studies in Central America that relied primarily on nonstatistical analyses of project data, cost-benefit analyses, informal and formal surveys of farmers, focus group discussions and interviews with project staff. Since then, adoption studies have expanded considerably.

Adoption-diffusion theory

agricultural applications

The expected utility framework is the most common approach to modeling technology adoption under uncertainty (Feder et al. 1985; Feder and Umali 1993; Marra et al. 2003). Applying the expected utility framework to technology adoption under uncertainty was first proposed by Just and Zilberman (1983) to remedy the lack of a theoretical framework for explaining the stochastic relationship of production under new and old technologies*. The expected utility model assumes that adoption decisions are based on the maximization of expected utility or profit subject to land, credit, labor and other constraints. Since profit is a function of the farmer's choice of crops and technology in each time period, maximizing profit, or utility, depends on the farmer's discrete selection from a menu of alternatives, including traditional practices. Among the important results of the theory is that the correlation of outputs under alternative technologies is crucial to determining adoption rates. For example, if correlation between returns to the old and new technologies is high and if risk aversion decreases sufficiently with increased wealth, adoption of new profitable technologies may be constrained (Marra et al. 2003).

Most of the other adoption models have extended the expected utility framework. Portfolio models view the land allocation decision between new and old technologies as a decision process in which farmers maximize the expected utility of income by choosing a specific combination of crops or systems given their risk aversion levels, the stochastic interactions between variables, and the impacts of socioeconomic variables such as wealth, age and education (Feder and Umali 1993). The 'safety-first' models deviate from the usual assumption of a concave and well-behaved utility function, and instead assume that the utility of income is zero below a certain 'disaster' level and one above it (Feder et al. 1985). As a result, safety-first

criteria for making choices between uncertain alternatives are concerned only with the risk of failing to achieve a certain minimum target or to secure prespecified safety margins such as subsistence (Bigman 1996).

Learning by doing and farmer experimentation models, as developed by Foster and Rosenzweig (1995), show that imperfect knowledge is a barrier to adoption. Although experience appears to initially augment the ability to make appropriate decisions about new technologies, the effect declines rapidly over time as experience increases. The impact of experience and experimentation can also have small but important spillover effects on neighbors. Those with neighbors experienced in the new technology tend to be significantly more profitable than those with inexperienced neighbors. Since the farmer's and neighbors' assets, net of the experience effect, have opposite effects on adoption, incentives exist for farmers to free-ride on the learning of others. For example, a farmer with neighbors experimenting with new technologies like agroforestry may curtail his own experimentation because he can realize higher short-term profits by using traditional methods and shifting to the new technology when there is sufficient experience from his neighbors to make adoption profitable (Foster and Rosenzwieg 1995).

Choosing one specific model as a basis for empirical analysis of adoption, however, can produce estimation errors and biased estimators (Feder and Umali 1993). Perhaps the most comprehensive model of adoption was developed by Abadi Ghadim and Pannell (1999) in response to criticisms that most empirical studies of adoption suffer from omitted variable biases, poor model specification. failure to derive hypotheses from a sound theoretical framework, and/or failure to account for the dynamic learning process in adoption. The Abadi Ghadim and Pannell (2003) model depicts adoption as a multistage decision process that incorporates information acquisition and learning by doing by farmers who vary in their risk preferences and perceptions of the risks associated with the innovation.

As an alternative to the expected utility theory of choice, Gladwin (1976) applied hierarchical decision tree models derived from the work of cognitive anthropologists and psychologists to analyze fertilizer decisions in Mexico. The hierarchical decision tree approach assumes that choices are made in a decomposed, piecemeal basis (i.e. one dimension at a time) in contrast to the assumptions of expected utility

theory in which people are assumed to examine all alternatives simultaneously, formulate separate subjective probabilities and pick the one with the largest expected utility (Gladwin et al. 2002a). During the first stage in the decision tree process, all alternatives with certain negative characteristics are immediately eliminated. The remaining alternatives are then ordered on one or more criteria and subjected to a series of disqualifying constraints. The highest ranked alternative that passes all constraints is chosen. Arrow (1963) referred to decision tree models as 'choice function(s) not built up from orderings.' Although the theory uses a discrete form of the standard neoclassical maximization subject to constraints approach, the ranking process is not connected and not necessarily transitive (Gladwin et al. 2002a).

agroforestry

applications

Theoretical models of agroforestry adoption, which began to appear in the literature in the mid-1990s, have primarily utilized a household production framework to model agroforestry adoption as an investment choice based on maximization of expected utility, or profit, subject to labor, capital, and income constraints (Amacher et al. 1993; Rafiq et al. 2000; Mercer and Pattanayak 2003). Amacher et al. (1993) were perhaps the first to apply household production theory and expected utility models to the problem of agroforestry adoption. Assuming decreasing absolute risk aversion, their model predicts positive impacts of all income sources (farm, off-farm, and forest based), household labor, capital, and land endowments, land tenure and price of tree products for adopting tree planting. In contrast, prices of nonforest consumption goods reduce adoption, while impacts of the variability (i.e. riskiness) of household production of forest products could not be determined by the model. Mercer and Pattanayak (2003) and Pattanayak et al. (2003) use a similar framework for a meta-analysis of multiple regression-based adoption studies to demonstrate that agroforestry adoption is a function of market incentives, biophysical conditions, resource endowments, risk and uncertainty, and household preferences.

Adding a household specific, safety-first constraint to the expected utility model allows the household to evaluate expected returns in terms of a probability distribution for minimum income, which depends on the household's income earning potential (Shively 1997). Shively uses this model to show that when the safety-first constraint is binding, adoption decisions depend on farm size, non-farm income, farm specific attributes such as soil quality and slope, the probability of a consumption shortfall. and, of course, a comparison of net benefits. Including the safety-first constraint shows that when adoption is costly, the probability of falling below the subsistence level for low-income households is crucial to decision-making.

Shively (2001) uses a dynamic expected utility model combined with an equation of motion for soil stocks that includes the probability of a catastrophic erosion event, to show how consumption risks and investment costs influence incentives to adopt contour hedgerows for soil conservation. Although unable to derive an analytical solution to the problem, Shively (2001) uses simulation and stochastic dominance to show that the household's valuation of soil conservation methods depends on investment costs, riskiness of the innovation, and capacity to bear risk. As the decision to invest in soil conservation depends on farm size, adoption is especially costly on small farms due to the increased short-run risk of consumption shortfall. Shively concludes that assuming risk-neutrality may lead to incorrect adoption predictions for low-income households whenever the risk of consumption shortfalls are high.

Besley (1995) examines the impact of property rights on investments in tree planting and other conservation methods in Ghana under three perspectives: security, collateral-based, and gains-from-trade. Besley's model maximizes returns to investment, which depend on the amount of capital invested at time t and property rights at time $t + 1$. The security case assumes the probability of land expropriation in period $t + 1$ is a decreasing function of tenure security. If investment costs are independent of tenure security, the results are analogous to a random tax on land, and investment increases with increasing tenure security. In the collateral-based scenario, when land is easier to collateralize, because individuals have better transfer rights, banks will charge lower interest rates. Since farmers equate the marginal return to 'investing in land to the interest rate, investments increase with increasing land tenure. The gains-from-trade model examines the relationship between land-tenure security, the costs of selling or renting land, and land conservation investment incentives. The implications are similar to those of the other two models: increased land-tenure security increases investment incentives.

Pannell (2003) utilizes a dynamic profit-function analysis, which allows the collection, integration and

evaluation of new information to reduce uncertainty over time. His model demonstrates that uncertainty inhibits adoption, assuming farmers are risk averse, because uncertainty can lead to incorrect predictions of the expected benefits from adoption. As a result, farmers may be better off waiting to adopt in some cases. Pannell (2003) concludes that uncertainty has received inadequate attention as an impediment to adoption of innovative land conservation practices and that on-farm experimentation is indistinguishable from adoption because production systems are continually tested and modified as perceptions and expectations evolve.

Hierarchical decision tree models have been applied to adoption of agroforestry and natural resource management (NRM) by Swinkels and Franzel (1997), Gladwin et al. (2002a,b), and Swinkels et al. (2002). Correctly specified and empirically verified decision-tree models allow identification of constraints to adoption and detailed examination of the decision-making process by breaking the process into a series of sub-decisions which are mapped as branches of a tree (Franzel et al. 2002). Gladwin et al. (2002a,b) increase the rigor of decision tree analysis by subjecting hypotheses derived from the analysis to tests of statistical inference using logit and ordered probit analyses. This is a good example of combining rigorous scientific hypothesis-testing with participatory approaches to adoption analysis and how using cognitive decision models and econometric testing can improve both approaches.

Diffusion theories: General agricultural applications

Induced innovation

Although the basic idea behind the theory of 'induced innovation' can be traced to Hick's (1932) Theory of *Wages,* Boserup's (1965) analysis of agricultural growth was perhaps the major influence on the development of induced innovation theory. Boserup showed that as population densities rise and/or demand for agricultural products increases, the resulting land pressures induce adoption of technological and institutional innovations to intensify land use. Basically, the scarcity of land relative to labor and/or capital induces investment in additional labor/capital inputs to maintain or increase agricultural production. By the 1970s, induced innovation theory was applied to a

wide range of new agricultural technologies to explain the impact of population and markets on the diffusion of innovations in both subsistence and commercial agriculture (Binswanger and Ruttan 1978; Ruttan and Hayami 1984; Pingali et al. 1987). More recently, induced innovation/ intensification analyses have used both micro- and macro-level data and incorporated additional determinants of technology diffusion such as environmental conditions, government policies, and land tenure (Goldman 1993; Humphries 1993; Turner and Ali 1996; Wiegers et al. 1999).

Epidemic or logistic models

The epidemic models of diffusion, first introduced in the 1950s, were based on analogies between the spread of contagious diseases and technological innovations. Since contact with other adopters and information leads to the spread of adoption across a population, diffusion is determined by the epidemic spread of information among potential adopters (Sarkar 1998). Hence, demonstration effects and learning from others' experiences underlie the epidemic model (Feder and Umali 1993). Epidemic models were first used to explain patterns discovered in empirical studies, such as time periods required for adoption within and across farms, varying diffusion rates, and the tendency for adoption to follow a logistic (sigmoid or S-shaped) time path beginning slowly initially, then speeding up, and finally tapering off. Epidemic models assume that adoption rates are a function of the product of the portion of the population already 'infected' with the new technology and the size of the 'uninfected' population (Sarkar 1998). Epidemic models have been criticized for their weak theoretical foundations, restrictive assumptions, and failing to establish theoretical links between decision-theoretic models of individual farmer behavior and the diffusion of innovations (Sarkar 1998).

Decision-theoretic models

In response to criticisms of the epidemic models researchers began to develop models that explain why adoption by different individuals varies over time, why individual households take time to switch between old and new technologies, and how diffusion patterns impact economic growth and employment (Sarkar 1998). Economists have developed decision-theoretic approaches along two lines: neo-classical equilibrium (NE) and evolutionary disequilibrium (ED) approaches.

Following dynamic neoclassical analysis, NE models assume that the diffusion process can be modeled as a sequence of shifting static equilibria among infinitely rational decision makers. NE approaches can be subdivided into the probit models, which assume that the temporal variation in adoption is due to heterogeneity among potential adopters, and the game-theoretic models in which strategic interactions among households rather than differences in household characteristics determine the diffusion path. All NE models, however, assume that adopters are infinitely rational and can evaluate and determine optimal strategies before any diffusion actually takes place (Sarkar 1998). The most important contributions of the NE models include demonstrating the importance of heterogeneity between adopters, interactions in the supply and demand for innovations and adoption rates, strategic interactions among adopters, and the importance of market structure.

Evolutionary disequilibrium (ED) models were developed in response to criticisms of the NE models' assumptions of perfect information, infinite rationality and that diffusion is a continuous equilibrium process. The fundamental features of evolutionary disequilibrium models are that i. adopters' rationality is bounded, ii. profit maximization may not be the only basis for adoption, and iii. diffusion is disequilibriating and endogenously driven and may not necessarily be continuous (Sarkar 1998). The spread of new technologies over time is determined by the competitive advantages of alternatives, behavioral attributes of farmers, and the economic and institutional environment.

In contrast to the NE models, the competitive selection process in ED models assumes that at least some households may not be able to calculate the relative advantages of alternative technologies due to information or cognitive limitations. Initial choices between alternatives are random and the diffusion process endogenously reveals the relative superiority of the alternatives. This view is rooted in path-dependency theory in which final outcomes are dependent on the sequence of prior states that derive from randomness. Hence the process is not necessarily optimal, incremental or cumulative. Decision-making differs between individuals due to differences in motivation, perceptions of possibilities, search behavior, enthusiasm for experimentation, and inferences from observations. Sarkar (1998) provides details on the diverse array of ED models that have evolved recently.

diffusion **models**

The role of infrastructure and supply in the diffusion process are the main contributions of the spatial diffusion models developed by social geographers to describe the aggregate spread of technological innovations (Marra et al. 2003). These models are based on the assumption that farmers are passive participants in the adoption process. Two major strands of research emphasize impacts of neighbors (the neighborhood effect) and the role of technology suppliers and innovators. As such, they have been primarily concerned with the spread of knowledge about the innovation rather than the rate of adoption. Since these models typically ignore the influence of adopters on non-adopters, information. from extension agents, or the impacts of farmer experience and experimentation, some believe they have contributed little to understanding the adoption decision process (Marra et al. 2003). As Man-a et al. (2003) state, spatial and temporal models 'have ignored the central determinant of the rate and pattern of adoption which is the decision process involved in moving from a state of awareness to actual adoption.'

Diffusion theories: agroforestry applications

Scant theoretical work examined the diffusion of agroforestry innovations prior to the 1990s. For example, Scherr (1992) stated that 'No comparable theoretical framework **(to induced** *innovation)* yet guides agroforestry policy' (italics added). Raintree and Warner (1986) were perhaps the first to apply induced innovation theory to agroforestry. They examined the potential pathways for intensification of shifting cultivation, emphasizing the adoption of improved fallows at various stages of intensification. When land is plentiful (the extensive stage) adoption potential for improved fallows is low because: i. investments are not seen as necessary for current or future soil fertility problems; ii. applying additional labor to fallows is not efficient since returns to labor are relatively low; and. iii. planted fallows may not be culturally acceptable. During the intermediate phase of intensification, soil fertility and fallow yields begin to decline and adoption of improved fallows may increase. However, when land pressures become acute during the final stages of intensification, Raintree and Warner (1986) predict that adoption of improved fallows will be rare due to decreasing farm size, abandonment of shifting cultivation for continuous cultivation, and reduction in available land for fallowing. Franzel (1999) shows

how the recent widespread adoption of improved fallows in densely populated areas of Western Kenya requires modifying the Raintree and Warner interpretation of induced innovation theory because of access to off-farm income, bi-modal rainfall, and the use of single season fallows.

Scherr (1992) described some common patterns of agroforestry intensification. She suggested that four types of long-term pressures induce farmers to intensify tree growing: i. declining access to forests and increasing scarcity of wood products; ii. increasing demand for tree products due to population growth, new tree uses or products, and new markets for tree products; iii. increasing population density and declining farm size; and iv. declining land quality. She called for conceptual models of agroforestry intensification under alternative land use conditions, the development of which requires historical and comparative analyses of on-farm tree management under varying agroecological, socioeconomic, and policy conditions.

Applying induced innovation theory to agroforestry, Scherr hypothesized that 'historical increases in tree domestication and management intensity are a response to declining supplies of uncultivated tree resources, increased subsistence and commercial demand for tree products and perceived risks of ecological degradation... [and that] adoption of agroforestry interventions is most likely where consistent with underlying economic incentives for land use change' (1995, p. 788). However, she acknowledged that scarcity alone is insufficient to explain agroforestry diffusion as tree product scarcity may induce substitutions, increased trade, or reduced consumption.

Scherr (2000) applied induced innovation theory to analyze the linkages between poverty, agricultural production, environmental degradation, and adoption of resource conserving technologies such as agroforestry. Her model assumed that pressures from population growth, markets, new technology and other exogenous factors induced changes in local markets, prices and institutions. Community characteristics such as infrastructure, asset distribution, human and natural capital, market linkages and local knowledge and experience determine the local impacts, which induce a variety of household and community agricultural and natural resource management strategies. These strategies may include changes in land use investments and intensity, input and output mix, conservation practices and collective action. The responses may be path-dependent since they are conditioned by community characterist-

ics and land use history. Hence, they may influence the environment, agricultural and tree production, and human welfare, which in turn feed back on local conditions, institutions and natural resource management decisions. The impact of policies and programs that promote agroforestry systems to reduce poverty and promote sustainable land use depends on the dynamics of local change and the relative importance of key factors influencing the poverty-environment relationship. After reviewing a variety of empirical studies, Scherr (2000) concluded that the key factors for increasing farmers' livelihood security while improving or conserving the local resource base were: i. local endowments, ii resource-conserving technologies (conditions for adopting conservation technology), and iii. local institutions supporting the poor.

Glendinning et al. (2001) applied Rogers' (1983) and Rogers and Shoemaker's (1971) sociological theories of innovation-diffusion to examine the relationship between social forestry extension approaches and farmer participation in farm forestry projects in eastern India. Assuming the adoption decision is primarily an 'information-seeking-and-processing activity' to reduce the uncertainty of the returns to adoption, Glendinning et al. (2001) concluded that the most important factor influencing adoption decisions was access to information.

Otsuka et al. (2001) developed a dynamic model of land use to derive the optimal timing of tree planting under different tenure rules. They assumed that households maximized the risk-adjusted, net expected value of land use constrained by the probability that the farmer retains rights to returns from the land. The adoption probability was a function of the time period of production and the land tenure institution. The model predicted two major results. First, shifting cultivation land use and declining land tenure security promoted early tree planting. Second, more secure land tenure would develop in response to increasing land scarcity relative to labor so that the landowner might reap the benefits from investing in land improvement technologies like agroforestry. By increasing the value of cleared land and decreasing the profitability of early tree planting, however, land policies that attempt to increase land rights for cleared forest are likely to be counter-productive for agroforestry adoption.

Empirical adoption studies

General agricultural studies

Feder et al. (1985) and Feder and Umali (1993) reviewed the extensive literature on adoption and diffusion of agricultural innovations. Focusing primarily on the initial stages of Green Revolution technology adoption and diffusion, Feder et al. (1985) concluded that farm size, risk and uncertainty, human capital, labor availability, credit constraints, and tenure were the most important factors determining adoption decisions. However, the impact of farm size depends on the characteristics of the technology and institutional setting and is often a surrogate for a large number of other factors such as access to credit, risk bearing capacity, wealth, and access to information. Since these factors differ spatially and temporally, the relationship between farm size and adoption also varies. In 1985, Feder et al. found that the empirical work on the role of subjective risk was not rigorous enough to draw conclusions concerning its impact on adoption, and this remains the case (Marra et al. 2003; Pannell 2003). Human capital received a good deal of attention in the early adoption literature, most of which suggests that farmers with better education are earlier and more efficient adopters. The direction of the effect of labor availability depends on whether the innovation is relatively labor saving or using. Concerning land tenure, Feder et al. (1985) found that empirical results often differed on the relation between land tenure and adoption and were 'in accordance with the unsettled debate in the theoretical literature over the relation between tenancy and adoption.'

Feder and Umali (1993) updated the Feder et al. (1985) survey emphasizing later stages of adoption-diffusion. As the adoption-diffusion process proceeds, many of the factors that Feder et al. (198.5) cited as important for early adoption including farm size, tenure, education, extension, and credit are no longer significant. For example, in later stages of the diffusion process infrastructure variables such as population density; access to markets, roads, and fertilizers; and irrigation availability are more important determinants of diffusion rates of high yielding varieties of rice. However, the agroclimate appears to be the most significant determinant of locational differences in adoption rates (Feder and Umali 1993).

Feder and Umali (1993) also examined the literature on early adoption of soil conservation technologies, which included many agroforestry practices such as contour hedgerows. They concluded that younger, more educated, wealthier farmers who recognized erosion problems were more likely to adopt soil conservation technologies. As Feder et al. (1985) found for Green Revolution technologies, the impact of tenure on soil conservation investments varied among the empirical studies reviewed and requires more research.

Agroforestry studies

As in the more general adoption-diffusion literature since the 1970s, economists have dominated agroforesry adoption research (Mercei and Miller 1998). This work has two separate and distinct lines. Ex-ante studies of agroforestry adoption based on a 'farming systems' approach have emphasized the adoption potential of various agroforestry systems based on researcher-led and participatory on-farm research methods (Byerlee and Collinson 1980; Chambers et al. 1989; Scherr 1991a, 1991b). The goal is to define the 'boundary conditions' for adopting a particular system or practice based on the biophysical and socioeconomic circumstances that allow the innovation to be 'profitable, feasible and acceptable' to farmers (Franzel and Scherr 2002). Ex-post studies of agroforestry have focused primarily on explaining how characteristics of farmers, farms, projects, and other demographic and socio-economic variables are correlated with past adoption behavior. The empirical work has been based primarily on binary choice regression models estimated from cross-sectional household survey data. Many studies, however, have failed to link the empirical analysis to underlying theory and typically have not examined the full range of potential factors that may influence agroforestry adoption (Pattanayak et al. 2003).

Ex-ante studies

Ex-ante studies rely primarily on social and financial analyses of on-farm trials of agroforestry innovations to assess the adoption potential of and to improve the effectiveness and efficiency of developing, modifying and disseminating new agroforestry practices (Franzel and Scherr 2002). Typically, these studies provide information and data on financial and nonfinancial benefits, what works where and why, differential adoption behavior, intra-household distribution of benefits, and how and why farmers are using and modifying the technologies.

Donor agencies need this type of information and analysis to determine how/if the innovations contribute to household welfare and economic development as a basis for research and development allocation decisions. Researchers developing improved systems need this information to insure that their experimental systems are appropriate for farmers' needs, abilities, and circumstances. Finally, this type of information is invaluable to farmers as they attempt to make informed adoption decisions on agroforestry systems that typically require considerable resources, skills, and time to implement and manage (Franzel and Scherr 2002). Nevertheless, systematic ex-ante assessments of experimental systems during the early phases of adoption are rare, partly because some scientists believe they are too 'soft' or too 'subjective' to qualify as rigorous analyses (Franzel and Scherr 2002). The most important and major works in this area are the Current et al. (1995) collection of eight ex-ante evaluations of 21 agroforestry projects in Central America (Costa Rica, El Salvador, Guatemala, Honduras, Nicaraugua, and Panama) and the Caribbean (Dominican Republic and Haiti) and Franzel and Scherr's (2002) volume of five studies in Zambia and Kenya.

Franzel et al. (2002) develop a framework for assessing adoption potential. The basic approach uses a variety of participatory appraisals and surveys to identify farmers' problems and needs which are then used by researchers and farmers to develop and design systems for on-farm experimentation. The results of the trials and associated analyses are then used to evaluate the potential for widespread adoption of the systems. For further details on methods for *ex-ante* analysis see Current et al. (1995), Barrett et al. (2002), and Franzel and Scherr (2002).

In the first large-scale study of farm level profitability of agroforestry, the majority of the 56 agroforestry technologies in the Current et al. (1995) volume were labeled as potentially profitable, based on positive Net Present Values and assuming a 20% discount rate. In addition to the expected financial returns. the relation between the new technology and the total farm enterprise and the existing capital, labor, and land constraints were crucial to the adoptability of the systems. Local scarcities as reflected in the price of wood products appeared to be the key factor to profitability and adoption in Central America and the Caribbean. Negative NPVs were associated with poor yields on the annual crop component and/or low output prices. Based on these studies, Current et al. (1995) concluded that including trees in agricul-

tural systems reduces sensitivity to annual crop yield and price variability and thereby improves overall profitability.

Likewise, in the five sub-Sahara African case studies in Franzel and Scherr (2002), agroforestry is shown to have potential to increase farm incomes and solve difficult environmental problems. In addition to the products and services provided, African farmers in Kenya and Zambia value the experimental agroforestry systems for their risk reducing impacts. These studies also confirm the impact of wealth on adoption with better-off families more likely to adopt improved fallows. However, Franzel and Scherr note the absence of absolute barriers to adoption by poor households, since about 20% of the poorest farmers in Zambia planted improved fallows during the first four years of on-farm experimentation.

Vosti et al. (1998) examine the adoption potential and related policy issues for adoption of five 'simple' agroforestry systems including cacao and/or coffee combined with bandarra and rubber and *cupuaçu/freijo/black* pepper combinations, in the western Brazilian Amazon. They found that high investment requirements, negative cash flows in early years, and uncertain local or international demand reduce adoption potential by small holders. Vosti et al. (1998) conclude that evaluating agroforestry adoption potential requires a thorough understanding of the physical and financial returns to all factors of production for all phases of the production process including establishment, maintenance, harvest, processing, and marketing/distribution of products. Although profitability of intermediate and final products sold off farm is crucial, other important factors in determining adoption potential are:

i. Scale of production: profitability and returns to factors of production change with scale of production (especially for crop mixes).

ii. Timing/Size of Investment: costs of under-investing or delaying investment can be quite high for agroforestry compared to annual cropping or pasturing.

iii. Maintenance Costs: can be high (especially labor) for agroforestry and may not vary with amount of product extracted.

iv. Costs of Abandonment: can be quite high, even higher than clearing primary forest.

v. Competing Supply Sources: market competition is key to long-range sustainability of agroforestry.

vi. Sources of Risk: markets, land tenure, weather, etc.

Ex-post studies

Pattanayak et al. (2003) reviewed 120 articles on adoption of agricultural and forestry technology by small holders and concluded that the following five categories of factors explain technology adoption: preferences, resource endowments, market incentives, biophysical factors, and risk and uncertainty. They then used this framework to perform a simple meta-analysis of 32 empirical, regression-based analyses of agroforestry and related soil conservation investments. Although household preferences and resource endowments were the most common variables included in the analyses, the most significant influences on agroforestry adoption behavior appeared to be uncertainty and risk, biophysical conditions, market incentives, and resource endowment factors. For example, when included in the analyses, risk and uncertainty variables were significant 71% of the time, market incentives 78%, biophysical factors 64%, and resource endowments 60‰. In contrast, household preference proxies were significant only 41% of the time (Pattanayak et al. 2003). Likewise in a comparison of tree planting between Brazil and Panama, Simmons et al. (2002) found that institutional variables were more important than household preference variables. The Pattanayak et al. (2003) framework and an expanded list of agroforestry adoption studies are used to take a closer look at the results of the ex-post empirical analyses of agroforestry adoption.

Risk and uncertainty Although risk and uncertainty has long been recognized as important in reducing adoption of a variety of agricultural innovations (Feder and Umali 1993; Smale and Heisey 1993), relatively little empirical research has directly addressed the issue (Abadi Ghadim and Pannell 2003; Pannell 2003). As Marra et al. (2003) point out, 'the issue of risk in adoption has rarely been addressed adequately, and strong empirical evidence to test the common view of its importance and impact has been rare and scattered.' For sustainable agricultural and land conservation systems like agroforestry, risk and uncertainty appear to be even more important to adoption decisions (Pannell 2003). Empirical evidence for the influence of risk and uncertainty on adoption is scarce because few studies include risk and uncertainty as explanatory variables, and the few that do have typically used crude proxies for farmers' risk perceptions and attitudes. Abadi Ghadim and Pannell (2003) suggest this omission has led to poor model specification.

In agroforestry adoption studies, risk has been proxied primarily through four types of variables: tenure, experience, extension and training, and membership in cooperatives and community organizations (Pattanayak et al. 2003). Tenure, experience and extension and training are far more likely than membership in organizations to be significant predictors of adoption of agroforestry, with tenure being significant 64%–72%, experience 90%, and extension 100% of the time when included as independent variables. Extension and training were included as risk proxies in 27% of studies analyzed by Pattanayak et al. (2003) and were always significant and positive. Although experience and extension are obviously important criteria for adoption, few studies have focused directly on them.

In 37 empirical studies of agroforestry adoption, (32 in Pattanayak et al 2003), more secure land tenure always had a positive impact on adoption when significant. In a few cases tenure was an insignificant predictor of adoption (Ayuk 1997; Pattanayak and Mercer 1998; Lapar and Pandey 1999; Adesina et al. 2000), but no studies exhibiting a negative relation between tenure and agroforestry adoption were found. Likewise, Simmons et al. (2002) found tree planting in the Brazilian Amazon to be 15.4 times more likely under secure land tenure, and Wiersum's (1994) study of contour hedgerow adoption in east Indonesia found that the landless comprised 3 1% of the population but only 11% of participants in *leucaena* based farming systems. This is in stark contrast with the conflicting empirical results that Feder et al. (1985) found for annual cropping. The longer term nature of agroforestry investments appears to inhibit adoption by farmers lacking secure tenure who might otherwise adopt risky innovations for short-term production goals. Thus, risk and uncertainty may be more important for agroforestry than for annual cropping decisions.

Using logistic regression analysis of household survey data in Sumatra, Otsuka et al. (2001) examined factors involved in the evolution of customary land tenure institutions and their impact on tree planting and agroforestry development. Higher population densities promoted individuation of land ownership through the pressures to convert primary forest and bush fallows to commercial tree plots, often using agroforestry systems. Both clearing forests and planting trees enhanced individual tenure rights, but tenure security acquired by clearing communal forests decreased over time when food crops were grown under shifting cultivation systems. Even though pur-

chased bush fallow lands had the most secure tenure rights, tree planting rates were lower than for lands acquired by clearing primary forests because planting trees on cleared lands enhances tenure security on cleared primary forests but not on purchased bush-fallow lands. Otsuka et al. concluded that under these tenure institutions. policies promoting agroforestry may not only induce tree planting but also increase transformation of primary forests.

Only a few studies have concentrated explicitly on the impacts of various risks and uncertainties on agroforestry adoption. In a series of papers, Shively (1997, 1999a, 1999b, 2001) examined the impacts of yield, prices, and consumption risks on agroforestry adoption in the Philippines. Shively (1997) used a probit model to examine the roles of farm assets and relative consumption risk to explain patterns of contour hedgerows at the farm and plot level in the Philippines. A two-moment analysis elicited subjective yield distributions by asking farmers to guess the most likely, lowest, and highest harvest with and without hedgerows and calculating subjective means and variances of the estimated probability density function. Both mean and variance of farmers' estimates were larger for hedgerows, with the difference between true and subjective mean/variance estimates being higher/lower for adopters than non-adopters. Larger farm size, greater tenure security and higher labor availability were correlated with higher adoption probabilities. Shively posits that farm size may be a proxy for lower consumption risk exposure since larger farms have more productive capacity and greater liquidity. As adoption related consumption risk (the opportunity cost of adoption on a plot) increased, the probability of adoption dropped.

Combining stochastic efficiency analysis with a heteroskedastic regression model, Shively (1999a) found that hedgerow adoption was correlated with increased corn yields. Although hedgerows initially reduced effective and observed yields, over time hedgerows were positively correlated with yields and appeared to dampen or reverse the rate of yield reduction on farmers' fields[3]. Hedgerow intensities between 5%–10% of plot area were required to achieve yield increases. Although not as strong an effect, contour hedgerows were found to reduce corn yield variance by as much as 4% depending on the intensity of adoption. Using stochastic efficiency analysis, Shively found that hedgerows would be preferred by a risk-averse farmer only when the range for the coefficient

of relative risk aversion (based on mean income) was rather high (3–5.5)[4].

Shively (2001) used the same Philippines data to perform a dynamic simulation to demonstrate how the probability of adoption of hedgerows for soil conservation depends on the opportunity costs of adoption and the household's ability to self-insure against low consumption. Break-even discount rates for risk-averse farmers depended on risk preferences, the opportunity costs of investment, and household exposure to consumption risk conditioned by farm size. Soil conservation was found to be a form of consumption insurance against declining yields and low-probability catastrophic soil erosion events. The pattern of under-investment in soil conservation on small farms implied that basing adoption predictions on risk-neutrality may be misleading when risk of food-insecurity is high. Shively found that small farmers' reluctance to adopt soil conservation measures was ameliorated by access to credit. By minimizing the impact of investment costs and consumption requirements, access to credit facilitated investments in risk-reducing and resource-conserving activities with relatively long payback periods, like contour hedgerows.

Household preferences Assuming that farm households are heterogeneous, farmers exhibit differing adoption patterns depending on their attitudes and preferences for a number of factors such as risk tolerance, conservation priorities, and intra-household homogeneity (Mercer and Pattanayak 2003). Since preferences are extremely difficult to measure directly, a variety of proxy variables are usually used to examine the impact of preferences on adoption. Education, age, gender, and socio-cultural status are the most frequently used proxies for household preferences and were included in almost half of the studies examined by Pattanayak et al. (2003). When included they were significant 40% of the time. Although only included in 36% of studies, gender is the most likely proxy for household preferences to be significant (in 63% of included studies). While education and age are more commonly included in the studies (77% and 64% of studies) they are much less likely to be significant (24% of the time for education and 29% of the time for age). Age, when significant was always positive, while education when significant was positive 75% of the time, and males were always more likely to adopt than females (Pattanayak et al. 2003). The lack of significance of education may be due to low variability in education variables among low-income farmers

and correlations between education and other variables such age and wealth. The education of the head of the household may also be irrelevant if the head utilizes the knowledge of other more educated household members. Finally, since educational levels may affect livelihood choices of rural households, samples of only farmers may bias many preference variables like education due to self-selection bias (Barrett et al. 2002).

Several studies have taken a closer look at gender differences in adoption of agroforestry innovations. In a study of tree planting in Kenya, Scherr (1995) found significant gender differences, with male-headed households planting 50% more trees more intensely (more trees per hectare) than women. Men also tended to plant trees on crop land while women planted trees primarily for fuel wood. Using logit and ordered probit analyses, Gladwin et al. (2002a) found that women in female- headed households in Eastern Zambia were significantly more likely to adopt improved fallows than either women or men in male headed households. Adoption rates of improved fallows were almost equal for female headed (47%) and male headed (52%) households in Eastern Zambia (Gladwin et al. 2002a). Place et al. (2002) analyzed the relationship between wealth and gender in adoption of improved fallows in Kenya and Zambia and found that wealthier male headed households were more likely to adopt increased fertilizer and manure applications, while improved fallows, as the Gladwin studies found, were relatively wealth and gender neutral.

Resource endowments The assets and resources available to farmers for investing in new technologies such as labor, land, livestock, savings and credit are critical to adoption decisions. Both the theoretical and empirical literature tell us that early adopters tend to be the better-off households who are better situated to take advantage of new innovations with uncertain prospects. These households are more likely to have the necessary 'risk capital' such as larger incomes and more labor or land to facilitate risky investment in unproven technologies (Hyde et al. 2000; Patel et al., 1995; Scherr 1995). Resource endowments were significant in 60% of the studies in which it was included as an independent variable, with income being significant 50% of the time, assets 100%, labor 33%, and credit (although in only 5% of all studies) 100% of the time (Pattanayak et al. 2003). With the exception of income, depending on the relative importance of farm and off-farm income, and plot size (50% pos-

itive and 28% negatively correlated with adoption), resource endowments were unambiguously and consistently positive influences on adoption. i.e. better-off farmers are more likely to adopt (Pattanayak et al. 2003).

Market incentives Agricultural and tree-product prices are well known influences on land-use decisions (Godoy 1992; Hyde and Amacher 2000; Shively 1999b). Unfortunately. market incentives such as input and output prices, market availability, expected income changes, and transportation costs have rarely been included in agroforestry adoption studies (only 33% of studies) (Pattanayak et al. 2003). Market incentives perform well, however, being significant 55% of the time with overwhelmingly positive influences on adoption (Pattanayak et al. 2003).

Using farm-level data and wholesale agricultural price data, Shively (1999b) investigated how changes in the level and variability of market prices affect farmers' decisions to plant mango trees. A 1% increase in price volatility of rice and corn produced an equal increase in mango tree planting intensity in the Philippines. Tree planting was positively correlated with mango prices and negatively correlated with competing crop prices. However, the price of rice, a subsistence food crop, was more strongly correlated with tree planting than the price of the cash crop, corn. This suggests that the economic tradeoff between food and tree crops was more important than the tradeoff between two cash crops. Although it is not surprising that farmers are price sensitive, the fact that short-run price changes affect low-income farmers' decisions to plant mango trees suggests the need for further research on the impacts of short-run prices on tree planting behavior.

Biophysical factors Biophysical factors such as slope, soil quality, irrigation and others have rarely been included in agroforestry adoption studies. Pattanayak et al.'s (2003) meta-analysis found biophysical factors included in only 27% of agroforestry adoption studies. Nevertheless, they appear to be important predictors of adoption, being significant in 64% of studies when included. The direction of significance of many biophysical factors was inconsistent. Poorer quality soils were usually positively correlated with adoption; however, at some point soil quality can be so poor as to render investments pointless. In contrast, slope variables were positive in all but one previ-

ous study with steeper slopes providing incentives for farmers to adopt (Pattanayak et al. 2003).

Methodological issues The majority of agroforestry adoption studies have relied on logit or probit models to analyze dichotomous adoption decisions in which the dependent variable is binary (1 if adopts, 0 otherwise). The probit model is used when the error term is assumed to follow a normal distribution and the logit when a logistic cumulative distribution is assumed. Only in rare cases, such as when there are very few positive or negative responses, do the two models produce different results, and scant theoretical justification exists for choosing one model over the other (Greene 1997). Alavalapati et al. (1995), Sunderlin (1997), Thacher et al. (1997), Adesina et al. (2000), Salem et al. (2000), Otsuka et al. (2001), Owubah et al. (2001). Adesina and Chianu (2002), Mercer et al. (in press), and provide examples of the logit model, while applications of the probit model can be found in Shively (1997, 1999a, 2001), Pattanayak and Mercer (1998), and Lapar and Pandey (1999).

When analyzing the simultaneous decision of whether or not to adopt and the extent or intensity of use of the new technology, alternative specifications are required. Typically either the tobit (censored regression model) ordered multinomial logit, or two-stage Heckman models have been used in these situations. Unfortunately, these approaches are quite rare in the agroforestry adoption literature, as only a handful of studies have examined both the probability and extent of adoption.

The tobit model is used when the same independent variables influence both the probability and size of the dependent variable. The ordered tobit accounts for the dependent variable being truncated at either the upper or lower limits of its ranges by assuming the error term follows a truncated normal distribution. A major benefit of the tobit model *is* that it allows for elasticities measured at the means to be decomposed into an elasticity of adoption and the elasticity of effort when adoption occurs. Rajasekharan and Veeraputhran (2002) use a tobit model to analyze the extent of adoption, in terms of share of intercropped area in rubber plantations in Kerala, India. The ordered multinomial logit is used when the dependent variable is categorical, hierarchical and censored and when the same variables are assumed to influence both adoption and extent of adoption. Patel et al. (1995) apply the ordered multinomial logit model to analyzing tree planting on small farms in East Africa.

When different explanatory variables are assumed to affect the decision to adopt and the extent or intensity of adoption, a two-stage Heckman model is more appropriate. Generally the first stage consists of either a logit or probit analysis of the probability of adoption followed by an ordinary least squares (OLS) regression of the extent of adoption incorporating the sample selection control function (the inverse Mills ratio) from the first equation (Greene 1997). Caviglia and Kahn (2001) apply the Heckman model to analyze adoption of sustainable agriculture, including agroforestry systems, in Brazil.

Finally, several agroforestry adoption studies have made the common mistake of treating categorical independent variables as continuous. This is equivalent to assuming that the intercept shift is the same for each category of the independent variable in question. The regression would be $y = \beta_1 + \beta_2 x_2 + \delta q + \varepsilon$ where x is a continuous variable and q is a categorical variable with three or more categories and β and δ the respective estimated coefficients. The underlying model, however, is $y = \beta_1 + \beta_2 x_2 + \delta + \varepsilon$ for the first category and $y = \beta_1 + \beta_2 x_2 + 2\delta + \varepsilon$ for the second category, etc. This is a testable restriction on the correct formulation ($y = \beta_1 + \beta_2 x_2 + \delta_1 D_1 + \delta_2 D_2 + \delta_3 D_3 + \varepsilon$ where the D's represent dummy variables derived from the categorical variables) but it is unlikely to be appropriate (Greene 1997).

Conclusions

Although research on the adoption and diffusion of agricultural innovations has a long and rich history dating back to the 1950s, interest in understanding the process with the more complex agroforestry systems is relatively new, beginning in the early 1990s. A substantial literature on agroforestry adoption, however, has been developing over the past 10 years. While the majority of the work has emphasized *ex-post* econometric analysis of factors determining adoption behavior, substantial effort has also been made to understand the potential adoptability of systems *ex-ante.* These complementary efforts are critical to the success of agroforestry as an economically, socially, and environmentally sustainable land use system. *Ex-ante* studies of the profitability, feasibility and acceptability of experimental agroforestry systems are essential for researchers in helping design appropriate systems, for development agencies in determining how and where

to allocate scarce program funds, and for farmers as they experiment and test new systems as part of the adoption process. *Ex-post* studies are equally important for predicting which segments of society will adopt at various times in the adoption cycle, for estimating the welfare and equity impacts of agroforestry projects, and for designing effective policies to encourage adoption by target populations.

As in traditional agricultural adoption, the major influences on adoption concern household preferences, resource endowments, market incentives, biophysical factors, and risk and uncertainty. Also similarly to adoption of agricultural production innovations, agroforestry adoption follows the predictions of economic theory. Farmers will invest in agroforestry when the expected gains from the new system are higher than the alternatives for the use of their land, labor and capital. Early adopters will tend to be those relatively better-off households who have more risk capital available in terms of higher incomes or more resource endowments (land, labor, capital, experience, education) to allow investments in uncertain and unproven technologies.

However, agroforestry adoption also differs from traditional agriculture, especially with regard to the role of risk and uncertainty. For example, although security of tenure has ambiguous impacts on adoption of annual cropping innovations, the review of *ex-post* agroforestry adoption studies found that tenure security has an unambiguous and positive impact on agroforestry adoption. This is likely due to the longer time periods required to begin to reap the benefits from agroforestry investments. It also highlights the relatively larger importance of risk and uncertainty in agroforestry adoption decisions compared to annual cropping innovations. Nevertheless, risk and uncertainty remain one of the most under studied aspects of adoption behavior. In only a few instances has risk been directly evaluated in agroforestry adoption studies. Typically, we just throw in a few risk proxies such as tenure, experience and extension, and conclude that risk is important. To remedy this situation, studies are required that directly measure risk preferences and perceptions and relate them to the adoption decision process. In particular, we need to understand farmers' perceptions of the impacts of the innovation on risk of production or consumption shortfalls; farmers' uncertainty about the innovation; and farmers' attitudes toward risk and uncertainty. This requires incorporating elicitation of risk preferences and subjective probabilities of the riskiness of alternative technolo-

gies into data collection efforts. Norris and Kramer (1990) provide a thorough review of approaches for eliciting subjective probabilities from farmers.

Furthermore, the **ex-ante** adoption literature suggests that in response to high perceived risks associated with new agroforestry systems, households tend to invest only incrementally in new agroforestry technologies and that substantial experimentation, testing, and modification occur before agroforestry innovations begin to diffuse through a community or region. The ability to adapt agroforestry practices over time to emphasize production of different goods and services depending on individual household circumstances and external forces such as markets, policies and weather, appears to be one of the risk-limiting advantages of some agroforestry systems and may be an important factor in differential adoption rates. Understanding this process and incorporating it into the development of dynamic agroforestry adoption models and analyses is essential to understanding the complex patterns of adoption. Other areas that require more research include factors influencing the variability in adoption intensities, the role of adoption of agroforestry practices as complements or substitutes for other farm operations, moving beyond household level analysis to village level and spatial analyses of adoption (e.g. Kristjanson et al. 2002), the impact of diseases like malaria and AIDS on adoption (e.g. Amacher et al. *in* press) and more emphasis in general on the cross disciplinary approaches being championed by the emerging natural resource management adoption literature (Barrett et al. 2002, Franzel and Scherr 2002).

Perhaps the largest deficit in agroforestry adoption research, however, concerns the temporal path of adoption. Adoption is a process that occurs over time. A few households adopt initially, then a few more, and so on, but seldom if ever do all households in a community or region adopt any technology, even over the longest time period. Current **ex-ante** adoption studies based on binary choice regressions have generally been useful only for increasing our understanding of who adopts first and for showing us which communities and which households within those communities to begin with when introducing new agroforestry systems, projects, or programs. if the goal is to assess the potential benefits of agroforestry, however, we need to understand the time path of adoption, the rates and intensity of adoption along that time path, who adopts at different times, and the final level of adoption. Yet, none of these temporal dimensions of agroforestry adoption have been studied empirically. Temporal issues

have also rarely been examined in the more general agriculture, forestry, and natural resource management literature. It is time to begin to collect longitudinal data on agroforestry adoption that will allow analysis of the temporal nature of agroforestry adoption including the rate and time at which a technology will be abandoned. This will take us far in understanding the crucial linkage between micro-adoption and aggregate diffusion necessary for effective policy intervention.

End Notes

1. For example, Rogers (1983) reported that before 1964, 44% of the 950 adoption-diffusion publications were by rural sociologists, whereas between 19761983. only 8% (45 of 578 publications) were in rural sociology.

2. Prior to Just and Zilberman (1983), most rigorous adoption studies were forced to assume that the new technology produced stochastic yields due to the intractability of handling related random variables with prior theories of choice under uncertainty.

3. Although hedgerow plots outperformed conventional plots on both effective (net of hedgerow) and per hectare basis, yield difference may have partly been a result of higher average labor and fertilizer inputs on hedgerow plots (Shively 1999a).

4. The coefficient of relative risk averstion (CRRA)is defined as:
$$CRRA = -wU''(w)/U'(w)$$
where w = wealth, U = utility function, $'$ = first derivative of U with respect to w, and $''$ = second derivative of U with respect tow.

References

Abadi Ghadim A.K. and Pannell D.J. 1999. A conceptual framework of adoption of an agricultural innovation. Agr Econ 21: 145–154.

Abadi Ghadim A.K. and Pannell D.J. 2003. Risk attitudes and risk perceptions of crop producers in Western Australia. pp. 114–133. In: Babcock B.A., Fraser R.W. and Lekakis J.N. (eds) Risk Management and the Environment: Agriculture in Perspective. Kluwer, Dordrecht.

Adesina A.A. and Chianu J. 2002. Determinants of farmers' adoption and adaptation of alley farming technology in Nigeria. Agroforest Syst 55: 99-1 12.

Adesina A.A.. Mbila D., Nkamleu G.B. and Endamana D. 2000. Econometric analysis of the determinants of adoption of alley farming by farmers in the forest zone of southwest Cameroon. Agric Ecosyst Environ 80: 255–265.

Alavalapati J., Luckert M. and Gill D. 1995. Adoption of agroforestry practices: a case study from Andhra Pradesh, India. Agroforest Syst 32: 1–14.

Allen J. 1990. 'Homestead tree planting in two rural Swazi communities.' Agroforest Syst 11: 1 1-22.

Amacher G.S.. Ersado L., Hyde W.F. and Haynes A. Tree planting in Tigray, Ethiopia: the importance of disease and water microdams. Agroforest Syst (In press).

Amacher G., Hyde W. and Rafiq M. 1993. Local adoption of new forestry technologies: an example from Pakistan's NW Frontier Province. World Dev 21: 4455453.

Arnold J.E.M. and Dewees P.A. 1995. Tree Management in Farmer Strategies: Responses to Agricultural Intensification. Oxford University Press, Oxford. 292 pp.

Arrow K. 1963. Social Choice and Individual Values. Wiley, New York. 124 pp.

Arrow K.J. 1969. Classification notes on the production and transmission of technological knowledge. Am Econ Rev 59: 29-35.

Arrow K.J. and Fisher A.C. 1974. Environmental preservation, uncertainty and irreversibility. Q J Econ 88: 312–319.

Ayuk E. 1997. Adoption of agroforestry technology: the case of live hedges in the Central Plateau of Burkina Faso. Agr Syst 54: 189–206.

Bannister M.E. and Nair P.K.R. 2003. Agroforestry adoption in Haiti: the importance of household and farm characteristics. Agroforest Syst 57: 149–157.

Barrett C.B.. Place F., Aboudk A. and Brown D.R. 2002. The challenge of stimulating adoption of improved natural resource management practices in African agriculture. pp. 1-22. In: Barrett C.B., Place F. and Aboud A. (eds) Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. CABI Publishing, Wallingford, UK.

Besley T. 1995. Property rights and investment incentives: theory and evidence from Ghana. J Polit Econ 103: 902-937.

Bigman D. 1996. Safety-first criteria and their measures of risk. Am J Agr Econ 78: 225-236.

Binswanger H. and Ruttan V. 1978. Induced innovation: technology. institutions. and development. Johns Hopkins University Press. Baltimore. 423 pp.

Boahene K., Snijders T.A.B. and Folmer H. 1999. An integrated socioeconomic analysis of innovation adoption: the case of hybrid cocoa in Ghana. J Policy Model 2 1: 167–184.

Boserup E. 1965. The Conditions of Agricultural Growth. Aldine: Chicago. 124 pp.

Buckles D. and B. Triomphe. 1999. Adoption of mucuna in the farming systems of northern Honduras. Agroforest Syst 47: 67–91

Byerlee, D. and Collinson M.P. 1980. Planning technologies appropriate to farmers. CIMMYT, Mexico. 71 pp.

Caveness, F.A. and Kurtz W.B. 1993. Agroforestry adoption and risk perception by farmers in Senegal. Agroforest Sysr 21: 1 1–25.

Caviglia J. and Kahn J. (2001). Diffusion of sustainable agriculture in the Brazilian tropical rain forest: a discrete choice analysis. Econ Dev Cult Change 49: 31 1-334.

Clay D., Reardon T. and Kangasniemi J. 1998. Sustainable intensification in the highland tropics: Rwandan farmers' investments in land conservation and soil fertility. Econ Dev Cult Change 46: 351–378.

Chambers R., Pacey A. and Thrupp L.A. 1989. Farmer First: Farmer Innovation and Agricultural Research. Intermediate Technology Publications. London. 218 pp.

Current D., Lutz E. and Scherr S. 1995. Costs, benefits and farmer adoption of agroforestry. Chapter 1. pp. 1-27. In: Current D., Lutz E. and Scherr S. (eds) Costs. Benefits and Farmer Adoption of Agroforestry: Project Experience in Central America and the Caribbean. World Bank Environment Paper Number 14. The World Bank, Washington, DC.

Daru R.D. and Tips W.E.J. 1985. Farmers participation and socioeconomic effects of a watershed management programme in Central Java (Solo river basin. Wiroko watershed). Agroforest Syst 3: 159–180.

Doss C.R. and Morris M.L. 2001. How does gender affect the adoption of agricultural innovations? The case of improved maize technology in Ghana. Agr Econ 25: 27-39.

Evans P.T. 1988. Designing agroforestry innovations to increase their adoptability: a case study from Paraguay. J Rural Stud 4: 45-55.

Feder G., Just R.E. and Zilberman D. 1985. Adoption of Agricultural Innovations in Developing Countries: A survey. Econ Dev Cult Change 33: 255-295.

Feder G. and Umali D.L. 1993. The adoption of agricultural innovations: A review. Technol Forecast Soc 43: 215-219.

Foster A.D. and Rosenzweig M.R. 1995. Learning by doing and learning from others: Human capital and technical change in agriculture. J Politi Econ 103: 1 176-I 209.

Franzel S. 1999. Socioeconomic factors affecting the adoption potential of improved tree fallows in Africa. Agroforest Syst 47: 305-321.

Franzel S. and Scherr S.J. 2002. Introduction. p.1–1 I. In: Franzel S. and Scherr S.J. feds) Trees on the Farm: Assessing the Adoption Potential of Agroforestry Practices in Africa. CABI, Wallingford.

Franzel S., Scherr S.J., Coe R, Cooper P.J.M. and Place F. 2002. Methods for assessing agroforestry adoption potential. pp. 37-64. In: Franzel S. and Scherr S.J. (eds) Trees on the Farm: Assessing the Adoption Potential of Agriforestry Practices in Africa. CABI, Wallingford.

Foster A.D. and Rosenzweig M.R. 1995. Learning by doing and learning from others: human capital and technical change in agriculture. J Politi Econ 103: 1176-1209.

Fujisaka S. 1989. The need to build upon farmer practice and knowledge: reminders from selected upland conservation projects and policies. Agroforest Syst 9: 141-153.

Gladwin C.H. 1976. A view of the Plan Puebla: an application of hierarchical decision models. Am J Agr Econ 58: 881-887.

Gladwin C.H., Peterson J.S. and Mwale A.C. 2002a. The quality of science in participatory research: a case study from Eastern Zambia. World Dev 30:523-543.

Gladwin C.H.. Peterson J.S., Phiri D. and Uttaro R. 2002b. Agroforestry adoption decisions, structural adjustment and gender in Africa. pp. 115–128. In: Barrett C.B.. Place F. and Aboud A. (eds) Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. CABI Publishing, Wallingford, UK.

Glendinning A., Mahapatra A. and Mitchell C.P. 2001. Modes of communication and effectiveness of agroforestry extension in Eastern India. Hum Ecol 29: 283-305.

Godoy R.A. 1992. Determinants of smallholder commercial tree cultivation. World Dev 20:7 13–725.

Goldman A.C. 1993. Agricultural innovation in three areas of Kenya: Neo-Boserupian theories and regional characterization. Econ Geogr 69: 44-7 I

Greene W.H. 1997. Econometric Analysis: Third Edition. Prentice Hall, Upper Saddle River, New Jersey. 1075 pp.

Griliches Z.1957. Hybrid corn: an exploration in the economics of technological change. Econometrica 25: 501-523.

Hicks J.R. 1932. The Theory of Wages. Macmillan, London. 247 pp.

Humphries S.A. 1993. The intensification of traditional agriculture among Yucatec Mayan farmers: facing up the dilemma of livelihood sustainability. Human Ecol 21: 87–102.

Hyde W.F. and Amacher G.S. 2000. Economics of Forestry and Rural Development: An empirical introduction from Asia. University of Michigan Press, Ann Arbor. 287 pp.

Hyde W.F.. Kohlin G. and Amacher G.S. 2000. Social Forestry Reconsidered. pp. 243-287. In: Hyde W.F. and Amacher G.S. Economics of Forestry and Rural Development: An empirical introduction from Asia. University of Michigan Press, Ann Arbor.

Just R.E. and Zilberman D. 1983. Stochastic structure, farm size, and technology adoption in developing agriculture. Oxford Econ Pap 35: 307–328.

Kristjanson P., Okike I., Tarawali S.A., Kruska R., Manyong V.M. and Singh B.B. 2002. Evaluating adoption of new crop-livestock-soil-management technologies using georeferenced village-level data: the case of cowpea in the dry savannahs of West Africa. pp. 169–180. In: Barrett C.B., Place F. and Aboud A. (eds) Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. CABI Publishing, Wallingford, UK.

Lapar M.L. and Pandey S. 1999. Adoption of soil conservation: the case of the Philippines uplands. Agr Econ 21: 241-256.

Marra M., Pannell D.J. and Ghadim A.A. 2003. The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the teaming curve? Agr Syst 75: 215–234

Mercer E., Haggar J., Snook A and Sosa M. Agroforestry adoption in the Calakmul Biosphere Reserve, Campeche, Mexico. J Crop Production (In press).

Mercer D.E. and Miller R.P. 1998. Socioeconomic research in agroforestry: progress, prospects, priorities. Agroforest Syst 38: 177–193.

Mercer D.E. and Pattanayak S. 2003. Agroforestry adoption by small holders. pp. 283–300. In: Sills E. and Abt K. (eds) Forests in a Market Economy. Kluwer, Dordrecht.

Nair P.K.R. 1996. Agroforestry directions and trends. pp. 74-95. In: McDonald P. and Lassoie J. (eds) The Literature of Forestry and Agroforestry. Cornell University Press, Ithaca, NY.

Norris P.E. and Kramer R.A. 1990. The elicitation of subjective probabilities with applications in agricultural economics. Rev Market Agri Econ 58: 127–147.

Otsuka K., Suyanto S., Sonobe T. and Tomich T. 2001. Evolution of land tenure institutions and development of agroforestry: evidence from customary land areas of Sumatra. Agr Econ 25: 85–101.

Owubah C.E., Le Master D.C., Bowker J.M. and Lee J.G. 2001. Forest tenure systems and sustainable forest management: the case of Ghana. Forest Ecol Manag 149: 253-264.

Patel S.H., Pinckney T.C. and Jaeger W.K. 1995. Smallholder wood production and population pressure in East Africa: evidence of an environmental Kuznets curve? Land Econ 7 1: 500-5 15.

Pattanayak S. and Mercer D.E. 1998. Valuing soil conservation benefits of agroforestry: contour hedgerows in the Eastern Visayas, Philippines. Agr Econ 18: 31-46.

Pattanayak S., Mercer D.E., Sills E. and Yang J. 2003. Taking stock of agroforestry adoption studies. Agroforest Syst 57: 173-186.

Pannell D.J. 2003. Uncertainty and adoption of sustainable farming systems. pp. 67–81. In: Babcock B.A., Fraser R.W. and Lekakis J.N. (eds) Risk Management and the Environment: Agriculture in Perspective. Kluwer, Dordrecht.

Pen S.G. 2003. Social determinants and land use correlates of agricultural technology adoption in a forest frontier: a case study in the Brazilian Amazon. Human Ecol 31: 133-165.

Pingali P., Bigot Y. and Binswanger H.P. 1987. Agricultural mechanization and the evolution of farming systems in sub-Saharan Africa. Johns Hopkins University Press, Baltimore. 216 pp.

Place F., Franzel S., DeWolf J., Rommelse R., Kweisga F., Niang A. and Jama B. 2002. Agroforestry for soil-fertility replenishment: evidence on adoption processes in Kenya and Zambia. pp. 155–168. In: Barrett C.B., Place F. and Aboud A. (eds) Natural Resources Management in African Agriculture: Understanding and Improving Current Practices. CABI Publishing, Wallingford, UK.

Rafiq M.. Amacher G.S. and Hyde W.F. 2000. Innovation and adoption in Pakistan's Northwest Frontier Province. pp. 87-100. In: Hyde W.F. and Amacher G.S. (eds) Economics of Forestry and Rural Development: An Empirical Introduction from Asia. University of Michigan Press. Ann Arbor.

Raintree J.B. 1983. Strategies for enhancing the adoptability of agroforestry innovations. Agroforest Syst 1: 173-187.

Raintree J.B. and Warner K. 1986. Agroforestry pathways for the intensification of shifting cultivation. Agroforest Syst 4: 39–54.

Rajasekharan P. and Veeraputhran S. 2002. Adoption of intercropping in rubber smallholdings in Kerala, India: a tobit analysis. Agroforest Syst 56: I-I 1.

Rogers E.M. 1983. Diffusion of Innovations, 3rd Edition. The Free Press, New York. 367 pp.

Rogers E.M. and Shoemaker F.F. 1971. Communication of Innovations: A Cross Cultural Approach. The Free Press, New York. 476 pp.

Rosenberg N. 1976. On technological expectations. Econ J 86: 523–535.

Ruttan V.W. and Hayami Y. 1984. Induced innovation model of agricultural development. pp. 59-74. In: Clark C.K. and Staatz J.M. (eds) Agricultural Development in the Third World. Johns Hopkins University Press, Baltimore.

Ruttan V.W. 1996. What happened to technology adoption-diffusion research? Sociologia Ruralis 36: 51–73.

Sain G. and Barreto H. 19%. The adoption of soil conservation technology in El Salvador: linking productivity and conservation. J Soil Water Conserv 5 1: 1495– 1506.

Salam M.A., Noguchi T. and Koike M. 2000. Understanding why farmers plant trees in the homestead agroforestry in Bangladesh. Agroforest Syst 50: 77-93.

Sanchez P.A. 1995. Science in agroforestry. Agroforest Syst 30: 5-55.

Sarkar J. 1998. Technological diffusion: alternative theories and historical evidence. J Econ Surv 12: 131–176.

Scherr S.J. 1991 a. On-farm research: the challenges of agroforestry. Agroforest Syst 15: 96–1 10.

Scherr S.J. 1991 b. Methods for Participatory On-Farm Agroforestry Research: Summary Proceedings of an International Workshop. International Centre for Research in Agroforestry (ICRAF), Nairobi. 72 pp.

Scherr S.J. 1992. Not out of the woods yet: challenges for economics research on agroforestry. Am J Agr Econ 74: 802–808.

Scherr S.J. 1995. Economic factors in farmer adoption: patterns observed in Western Kenya. World Dev 23: 787–804.

Scherr S.J. 2000. A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. Food Policy 25: 479198.

Shively G. 1997. Consumption risk. farm characteristics. and soil conservation adoption among low-income farmers in the Philippines. Agr Econ 17: 165–177.

Shively G. 1999a. Risks and returns from soil conservation: evidence from low-income farms in the Philippines. Agr Econ 21: 53–67.

Shively G. 1999b. Prices and tree planting on hillside farms in Palawan. World Dev 27: 937-949.

Shively G. 2001. Poverty, consumption risk, and soil conservation. J Dev Econ 65: 267–290.

Simmons C.S., Walker R.T. and Wood C.H. 2002. Tree planting by small producers in the tropics: a comparative study of Brazil and Panama. Agroforest Syst 56: 89–105.

Sunderlin W.D. 1997. An ex-post methodology for measuring poor people's participation in social forestry: an example from Java. Agroforest Syst 37: 297-3 10.

Swinkels R. and Franzel S. 1997. Adoption potential of hedgerow intercropping systems in the highlands of Western Kenya: 11. Economic and farmers' evaluation. Exp Agr 33: 21 l-223.

Swinkels R. and Scherr S.J. 1991. Economic Analysis of Agroforestry Technologies: An Annotated Bibliography. ICRAF. Nairobi, Kenya. 2 15 pp.

Swinkels R., Shepherd K.D., Franzel S., Ndufa J.K.. Ohlsson E. and Sjogren H. 2002. Assessing the adoption potential of hedgerow intercropping for improving soil fertility, Western Kenya. pp. 89–110. In: Franzel S. and Scherr S.J. (eds) Trees on the Farm: Assessing the Adoption Potential of Agrforestry Practices in Africa. CABI, Wallingford.

Smale M. and Heisey P.W. 1993. Simultaneous estimation of seed-fertilizer adoption decisions. Technol Forecast Soc 43: 353–368.

Thacher T., Lee D. and Schellas J. 1997. Farmer Participation in reforestation incentive programs in Costa Rica. Agroforest Syst 35: 269-289.

Turner B.L., II and Ali A.M.S. 1996. Induced intensification: agricultural change in Bangladesh with implications for Malthus and Boserup. P Natl Acad Sci, USA 93: 14984–14991.

Vosti S.A., Witcover J., Oliveira S. and Faminow M. 1998. Policy issues in agroforestry: technology adoption and regional integration in the western Brazil Amazon. Agroforest Syst 38: 195–222.

Wiegen E.S., Hijmans R.J., Hervé D. and Fresco L.O. 1999. Land use intensification and disintensitication in the upper Cañete Valley, Peru. Human Ecol 27: 3 19-339.

Wiersum K.F. 1994. Farmer adoption of contour hedgerow intercropping, a case study from east Indonesia. Agroforest Syst 27: 163–182.