Precautionary Saving, Credit Constraints, and Irreversible Investment: Theory and Evidence From Semiarid India

Marcel Fafchamps
Department of Economics, Stanford University, Stanford, CA 94305-6072

John Pender
International Food Policy Research Institute, Washington, DC 20036

This article investigates the extent to which poor households are discouraged from making a nondivisible but profitable investment. Using data on irrigation wells in India, we estimate the parameters of a structural model of irreversible investment. Results show that poor farmers fail to undertake a profitable investment that they could, in principle, self-finance because the nondivisibility of the investment puts it out of their reach. Irreversibility constitutes an additional disincentive to invest. Simulations show that the availability of credit can dramatically increase investment in irrigation and that interest-rate subsidization has little impact.

KEY WORDS: Agricultural development; Economic development; Nondivisible investment; Poverty trap; Structural estimation.

This article investigates the extent to which poor households are discouraged from making a highly profitable but nondivisible investment. Poor farm households have two motives for saving, to insure against income shortfalls and to self-finance profitable investments when credit is not available. If returns to savings are low, they may find it difficult to accumulate enough wealth to finance a large nondivisible investment, even if it is highly profitable. They remain trapped in poverty (e.g., Lewis 1954; Nurkse 1953). We also examine whether investment irreversibility serves as an additional deterrent. A reversible investment can be turned into liquidities should the household face an external shock beyond what can be handled with other accumulated wealth. An irreversible investment, on the other hand, detracts permanently from the household's liquid wealth and thus impinges on its ability to self-insure. A household with a precautionary motive for holding wealth may thus treat irreversible and reversible investments differently. In particular, the wealth threshold at which it is willing to make a reversible investment may be below that at which it makes an irreversible investment.

We begin by constructing a stochastic dynamic programming model of savings and investment. The model is used to illustrate the role that nondivisibility and irreversibility play in investment decisions. We then estimate the model using household survey data on income and savings from semiarid India. The investment considered in this article is the digging of an irrigation well. The structural parameters of the savings and investment model are estimated using full information maximum likelihood. Estimation results show that lack of credit to finance a nondivisible investment in a well is a major determinant of poor farmers' reluctance to invest. Irreversibility constitutes an additional deterrent to investment.

It has long been recognized that poor farmers in the Third World find it hard to finance large, lumpy investments (e.g., McKinnon 1973). Credit constraints are commonly regarded as the major explanation for this state of affairs, and in the literature much emphasis has been put on the role that credit constraints play in farm size distribution and investment patterns (e.g., Carter 1988; Eswaran and Kotwal 1986; Feder 1985; Iqbal 1986). Credit constraints may result from interest-rate restrictions (e.g., Gonzalez-Vega 1984; McKinnon 1973; Shaw 1973), from asymmetric information (e.g., Stiglitz and Weiss 1981), or from enforcement considerations (e.g., Bell 1988; Pender in press). In addition, in a risky environment farmers may choose to avoid credit if the penalties for default are sufficiently severe. Regardless of the reason, farmers in developing countries must often self-finance a large share of the investments they make. Trying to determine what impact this has on their ability to make a highly profitable but nondivisible and irreversible investment is the object of this article.

A key question is why poor farmers who lack access or willingness to use credit do not choose to save to self-finance highly profitable investments. One possible explanation is that they find it hard to save. Often contributing to the difficulty are government interest-rate restrictions and other policies that keep the returns to savings low (McKinnon 1973). Such policies were in place in India during the 1970s and 1980s, the period of the present study (Pender 1992). Being constantly faced with life-threatening situations for which poor farmers must liquidate their meager assets, the argument goes, they can never accumulate enough to finance a large investment. We investigate this possibility directly by estimating the structural parameters of a precautionary saving model and examining the saving and investment behavior predicted by the model.

Journal of Business & Economic Statistics
April 1997, Vol. 15, No. 2

Other explanations emphasize the role of risk and point out that poor, risk-averse producers unable to insure themselves against income shocks tend to shy away from risky activities (Arrow 1971; Pratt 1964; Sandmo 1971). To examine the possibility that risk serves as a disincentive to invest, we estimate risk aversion, taking into account the effect of constructing a well on the distribution of income. A third possible explanation is that the irreversibility of well construction operates as a disincentive to invest. As Epstein (1978) stressed early on, flexibility—that is, the capacity to revise certain decisions—assumes an important role in a multiperiod setting. Fafchamps (1993), for instance, estimated a three-period structural model of labor-allocation decision in semiarid farming and demonstrated that flexibility differently affects farmers' decisions to plant and weed. Dixit (1989) and Dixit and Pindyck (1994) showed that it may be optimal for an investor faced with a (partly or totally) irreversible investment to wait until more information is available on the investment's profitability. By investing now, the investor indeed loses the option to collect more information and make a better decision later.

The situation that we are interested in is different in that little or no new information is gained over time about the profitability of the investment. Investment irreversibility may nevertheless affect the investor's decision if the investor has a precautionary motive for saving. By waiting, the agent is better able to use liquid wealth to cope with income shortfalls. Tying all his/her money into an illiquid asset may generate an unbearable risk. The trade-off between a higher return on wealth and better consumption smoothing may thus generate a liquidity premium—that is, a level of precautionary savings deemed comfortable enough for the investment to take place. The liquidity premium might, however, be 0 if the investment itself reduces risk, as is typically the case for irrigation.

Hints that irreversibility matters were given by Rosenzweig and Wolpin (1993, hereafter R&W). Using household survey data from semiarid India, they showed that poor farmers are less likely to invest in irrigation equipment than in bullocks despite the fact that the return on the former is higher than that on the latter. The reason is, they argued, that bullocks can be sold when the need arises but pumps cannot. This article revisits this issue and attempts to quantify the effect that irreversibility and credit constraints have on farmers' willingness to undertake a large, nondivisible investment. Instead of using data from the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) on pumps, we rely on original data on the digging of wells collected by one of the authors in the ICRISAT villages. Well construction represents an average cash outlay 6.5 times larger than the purchase of a pump. In addition, used pumps are more easily sold than wetland, which has a limited market due to problems of asymmetric information, high transaction costs, and lack of institutional credit to finance land purchases in rural India. The effect of irreversibility and credit constraints should thus be more perceptible for wells than for pumps. Finally, ownership of a well is required for a pump to be useful. Not all ICRISAT households own wells, a feature that may have affected R&W's results.

We begin by developing a model of self-financed, nondivisible investment. The model combines a continuous decision—how much to save—with a discrete choice—whether to invest in a well or not. The possible effect of irreversibility is explicitly taken into account. We then estimate the parameters of the model using a computer-intensive simulation-based technique. Our approach is similar in spirit to that of R&W, but it differs in many important respects. We combine discrete and continuous decisions; their state space was discrete. We estimate households' rate of time preference; they did not. We focus on investment in wells and the accumulation of liquid assets in general; they studied the life-cycle accumulation of bullocks and pumps. Unlike R&W, we also allow for constrained borrowing in one version of the model.

We are able to derive fairly precise estimates of the rate at which surveyed households discount future consumption and of their coefficient of relative risk aversion. These estimates are sensitive to assumptions regarding the credit market and probability of well failure, but they are by and large consistent with other evidence on risk aversion (e.g., Binswanger 1980) and rate of time preference (e.g., Pender in press) in the area. Results suggest that credit constraints (whether externally imposed or self-imposed) are a major deterrent to investment in irrigation wells in the study village. Irreversibility constitutes an additional but minor deterrent. With low incomes, high risk aversion, and little ability to save, households are seldom able to accumulate the necessary wealth to make the investment on their own. As a result, the probability that a farmer invests in any given year is small, unless credit is made available to finance part of the well. This may explain why the number of wells constructed in the survey village increased steadily between 1975 and 1991 but at a relatively slow pace in spite of high expected returns (Pender 1992). Simulation results indicate that credit, whether subsidized or not, and higher returns to savings can increase the probability of investing.

1. A SIMPLE MODEL OF WELL INVESTMENT

We begin by formalizing the arguments presented in the introduction. We consider an agent who faces two possible iid income streams with probability distributions $F(y;\tau_0)$ and $F(y;\tau_1)$. By building a well at cost k, the agent can exchange an income stream $F(y;\tau_0)$ against the income stream $F(y;\tau_1)$. Parameter vectors τ_0 and τ_1 thus characterize the shape of the income distribution without a well and with a well, respectively. Income is restricted to the positive orthant; that is, $y \in [0,\infty)$. We consider two cases, one in which the agent cannot recoup investment cost k and revert to $F(y;\tau_0)$—the irreversible case—and one in which he/she can—the reversible case. We begin with the irreversible case.

1.1 A Model of Irreversible Nondivisible Investment

Let X_t stand for the agent's cash on hand at time t; that is, $X_t = W_t + y_t(W_t)$, where W_t is the agent's accumulated wealth at the beginning of year t and y_t is his/her realized net income from all sources at the end of year t, which is a function of liquid wealth at the beginning of the period. After the investment, the optimization problem facing the agent is summarized by the following Belman equation:

$$V_1(X_t) = \max_{W_{t+1}} U(X_t - W_{t+1}) + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_1). \tag{1}$$

Instantaneous utility $U(.)$ is continuous and concave and exhibits decreasing absolute risk aversion: The agent thus has a precautionary motive for saving (Kimball 1990).

We further assume that $U(c) > -\infty$ for all $c \geq 0$, but it is $-\infty$ or not defined for $c < 0$: The agent cannot have negative consumption. This implies that, as Zeldes (1989) and Carroll (1992) showed, the agent optimally decides never to borrow beyond the annuity value of his/her minimum possible income. We further assume that, under both income streams, the minimum possible income is 0. Then, along the optimal path, the agent never is a net borrower: If creditors insist on being paid under any circumstance, then an agent with a minimum income of 0 will not be able to become a net debtor, and net borrowing cannot be used to smooth consumption. An alternative interpretation is to postulate that there is a penalty for breach of contract and that the penalty is so severe that the agent chooses not to incur debt. [The same argument applies to strictly enforceable contingent contracts (Zame 1993).] Whether the agent is refused credit because he/she cannot repay in all possible states of the world or fears the possible consequences of default, the result is the same. Of course, if default is allowed, credit can be used to provide insurance (Eaton and Gersovitz 1981; Grossman and Van Huyck 1988; Kletzer 1984).

Let δ be the agent's rate of time preference and let $1/(1+\delta) \equiv \beta$. If we further assume that δ is greater than the return on liquid wealth, the agent is a natural dissaver: He/she saves for the sole purpose of smoothing consumption (Deaton 1991; Kimball 1990). As argued by Deaton (1990, 1992a,b), countless poor consumers, particularly in Third World countries, find themselves in exactly this predicament. Now consider the agent's decision before the investment has taken place. Formally, the agent computes his/her expected utility under two alternative scenarios: Invest now, or wait until later. In case he/she invests now, his/her expected utility is

$$V_0^1(X_t) = \max_{W_{t+1}} U(X_t - k - W_{t+1}) + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_1). \tag{2}$$

In case he/she chooses to wait, his/her expected utility is

$$V_0^0(X_t) = \max_{W_{t+1}} U(X_t - W_{t+1}) + \beta \int_0^\infty V_0(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_0). \tag{3}$$

The agent chooses to invest if $V_0^1(X_t) > V_0^0(X_t)$. The value function $V_0(X)$ corresponding to the no-investment situation can thus be found by solving the following Belman equation:

$$V_0(X_t) = \max\{V_0^0(X_t), V_0^1(X_t)\}. \tag{4}$$

We now show that the option to invest in the future is valuable even though, unlike in the work of Dixit and Pindyck (1994), no new information is gained about the investment's profitability.

Proposition 1.

1. If the return to the investment is such that there exists a level of wealth at which the agent would want to invest, then the option to invest raises the agent's ex ante utility.
2. An agent given the option to wait may choose to defer investment compared to an agent who must invest now or never.

Proof. See Appendix A.

In Proposition 1, we assume that a sufficiently wealthy individual would want to invest. But, depending on the parameters of the model, it may be optimal never to invest. If, for instance, $F(y; \tau_0)$ stochastically dominates $F(y; \tau_1)$, then investing is not optimal because it would reduce the agent's expected utility for any initial level of cash on hand. The converse is not true, however: Even if $F(y; \tau_1)$ stochastically dominates $F(y; \tau_0)$, investment will not take place if the agent has insufficient wealth—that is, if $X_t < k$.

In the remainder of this article, we focus our attention on the simple case in which there is a level of wealth at which investing is optimal. Let X^* be the minimum level of cash on hand at which the investment takes place—that is, such that $V_0^0(X^*) = V_1(X^* - k)$. We then define the *liquidity premium* P as the amount of liquid wealth that the agent wishes to hold immediately after the investment:

$$P \equiv \arg\max_{W_{t+1}} U(X^* - k - W_{t+1}) + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_1).$$

The liquidity premium acts as a deterrent to investment because the agent must accumulate not only the cost of the investment itself but also the amount of liquid wealth he/she wishes to hold as precautionary saving.

1.2 A Model of Reversible Nondivisible Investment

The cost of irreversibility can be found by considering the reversible case. Formally, the latter can be seen as an extension of the irreversible case. In each period, the agent can be in one of two states—with or without the investment.

Each of these states has its own value function. The value functions, in turn, reflect the fact that, before deciding on consumption, the agent may invest and pay k or liquidate the investment and receive k. Intermediate cases in which divestment is possible but at a cost can be analyzed in a similar manner. We thus get a system of two Belman equations:

$$\bar{V}_0(X_t) = \max\{\bar{V}_0^0(X_t), \bar{V}_0^1(X_t)\} \tag{5}$$

and

$$\bar{V}_1(X_t) = \max\{\bar{V}_1^1(X_t), \bar{V}_1^0(X_t)\}, \tag{6}$$

where

$$\bar{V}_0^0(X_t) = \max_{W_{t+1}} U(X_t - W_{t+1}) + \beta \int_0^\infty \bar{V}_0(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_0), \tag{7}$$

$$\bar{V}_0^1(X_t) = \max_{W_{t+1}} U(X_t - k - W_{t+1}) + \beta \int_0^\infty \bar{V}_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_1), \tag{8}$$

$$\bar{V}_1^1(X_t) = \max_{W_{t+1}} U(X_t - W_{t+1}) + \beta \int_0^\infty \bar{V}_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_1), \tag{9}$$

and

$$\bar{V}_1^0(X_t) = \max_{W_{t+1}} U(X_t + k - W_{t+1}) + \beta \int_0^\infty \bar{V}_0(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_0). \tag{10}$$

As before, $\bar{V}_0^1(X_t) = \bar{V}_1(X_t - k)$ and $\bar{V}_1^0(X_t) = \bar{V}_0(X_t + k)$. This system can be solved simultaneously by backward induction. The liquidity premium for a reversible investment can similarly be defined as

$$\bar{P} \equiv \arg\max_{W_{t+1}} U(X^* - k - W_{t+1}) + \beta \int_0^\infty \bar{V}_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_1). \tag{11}$$

$P - \bar{P}$ represents the cost of irreversibility. It is clear that, if the return on the nondivisible investment is certain and investors face credit constraints, the cost of irreversibility $P - \bar{P} \geq 0$. When the return to investment is variable, however, $\bar{P}$ need not be 0. To see why, note that, when the investment is reversible, $\bar{P} + k$ is the level of precautionary saving. As Dreze and Modigliani (1972) and Kimball (1990) showed, this level is an increasing function of the variance of income when absolute risk aversion is decreasing. Thus, the higher the variance of income after investment, the higher $\bar{P}$. For a sufficiently high variance of the post-investment income process, therefore, $\bar{P} > 0$. On the contrary, if undertaking the investment reduces the variance of income and the investor is credit constrained, then $\bar{P}$ may be 0. In that case, P alone constitutes a good indicator of the cost of irreversibility. Finally, $\bar{P}$ cannot exceed P: Irreversibility can only raise the liquidity premium in the presence of credit constraints and a precautionary motive for saving. If $P = 0$, then $\bar{P} = 0$ as well.

Reversibility does not imply that the savings behavior of the agent is unaffected by the presence of a nondivisible, high-return investment. As Pender (1992) showed in the certainty case, in the presence of credit constraint the agent's willingness to save increases in the vicinity of the threshold level of wealth k—even if it means momentarily accumulating wealth at a rate of return inferior to δ. The reason is that the agent anticipates the benefits from higher returns and strives to reap them. Pender (1992) showed that a low return on saving may have a perverse disincentive effect on investment because it makes it difficult for a credit-constrained agent to accumulate enough to undertake the investment (McKinnon 1973). The presence of a liquidity premium reinforces this argument: Not only do agents have to accumulate enough to invest, they must also build up a sufficient buffer stock of liquid wealth. A low return on liquid wealth thus has a disincentive effect on an agent's willingness to accumulate and invest that is compounded by the presence of a liquidity premium.

2. ESTIMATION OF THE MODEL

We now econometrically estimate the model of irreversible investment presented in Section 1, using simulation-based maximum likelihood. The data come from two sources, household-level data from India that were collected by ICRISAT over a period of 10 years and original survey data on wells collected in the same villages by one of the authors.

The ICRISAT data have been widely used to study issues relative to consumption smoothing and wealth accumulation patterns (e.g., Morduch 1990, 1991; Pender 1994; Rosenzweig 1988; R&W; Townsend 1994). They are particularly well suited for our purpose because most of the assumptions made by our model are satisfied: Villagers are known to be risk averse (Binswanger 1980) and impatient (Pender 1994); they are poor and face a lot of risk (Walker and Ryan 1990); they are unable to fully insure through mutual insurance and credit arrangements (Morduch 1991; Townsend 1994); they are unable to fully finance the cost of well construction through credit (Pender 1992); and they buy and sell assets to smooth consumption (Lim and Townsend 1994; R&W).

Investments in individual wells for irrigation offer a perfect opportunity to study the effect of nondivisibility and irreversibility on investment behavior. Well construction represents an average case outlay 6.5 times larger than the purchase of a pump, a form of irreversible investment examined by R&W. The effects of nondivisibility and irreversibility should thus be more perceptible for wells than pumps. Wells are also quite irreversible: Although a pump can be sold, money spent digging a hole cannot be recouped by filling it up! (One could argue that the land on which the well is constructed can be sold. The truth is that wetland sales are extremely rare in semiarid India: No wetland sales were recorded over the 10 years of the ICRISAT surveys in the study village. In contrast, there were 31 dryland sales.) Finally, the 1975–1984 period covered by the ICRISAT survey was a period of high well construction in Kanzara, one of the surveyed villages (Pender 1992, 1994).

The model estimation philosophy is in the line of Wolpin (1987), Rust (1987), Fafchamps (1993), and R&W. A simulation model representing the agent's savings and investment choices is estimated by using a sophisticated numerical algorithm to iteratively calibrate the model on the data. By relying on the likelihood function as calibration criterion, full information maximum likelihood estimates are obtained for key model parameters. To keep things manageable, we first estimate the distribution of income as a function of household attributes. We then find the values of household-preferences parameters at which the savings and well-investment decisions predicted by the model are closest to the data.

Although our approach is inspired by that of R&W and uses some of the same data, it differs from theirs in several important respects. First, they studied small, mostly liquid investments; we focus on wells because they represent large, nondivisible investments for which irreversibility is more likely to be a problem. Second, they postulated the household's rate of time preference δ; we estimate it. Third, they did not consider the effect that investment may have on the variance of income. To reflect the dramatic effect that irrigation has on farming and possible risk-aversion motives for well construction, we allow both the mean and the variance of income to differ with and without a well. Fourth, on average bullocks constitute only 22% of liquid wealth. Unlike R&W, we include in our analysis other forms of liquid wealth such as grain stocks (21% of liquid wealth), financial assets (43%), and consumer durables (14%). Neither the R&W assumption that there are no other liquid assets besides bullocks nor our assumption that all assets other than wells, land, and farm implements are liquid and have the same return is an exactly accurate description of asset markets. What is needed is a portfolio model of saving. This is left for future research. Fifth, they iterated on a finite-horizon, life-cycle model with bequest. We iterate on an infinite-horizon model because we believe that parents take into account the welfare of their children when deciding to invest in something as costly as a well.

2.1 The Data

The estimation is based on data collected in the village of Kanzara in the Akola district of Maharashtra, India. Compared to most other ICRISAT villages, the black soils in Kanzara are of good quality and the returns to irrigation high. The decade over which the data were collected was the golden age of well construction in Kanzara. In 1975, there were only 15 wells in the village; by the end of the ICRISAT surveys in 1985, there were 44. Most of the farmers, however, did not construct a well. Subsequently, the Uma Canal project made irrigation water available from other sources, and well construction slowed considerably.

Contributing to the boom in well construction over the 1975–1985 period were the availability of electricity for pumping water and government lines of credit to finance well construction. Banks limited the amount lent for well construction to 10,000 Rs. (rupees)—significantly less than the average cost of construction, which is 15,280 Rs. (Pender 1992). Among those households that dug wells, 57% of the construction costs were financed through credit; the rest was financed through farmers' own savings. None of the wells was financed by sales of land. Unlike in other Indian villages (Pender 1992; Walker and Ryan 1990), all wells in Kanzara are individually owned. This and the fact that well construction was a recent phenomenon in the village are the main reasons why we chose to focus on Kanzara.

The data are from two sources, (1) panel data on household income, wealth, and demographic characteristics collected between 1975 and 1984 as part of ICRISAT's village-level studies program and (2) a survey of farmers' investments in irrigation wells, conducted by one of the authors in 1991 (see Pender 1992 for details). For the estimation, we consider only households that owned land during the 1975–1984 period and that were included in the irrigation well survey in 1991. Twenty-six households are included in the estimation. Income regressions are run on all 10 years of available data—or 260 observations. The estimation of household-preference parameters is performed using the same households, but the last year of data is lost because information on assets was only collected once a year, and we need both W_t and W_{t+1} to estimate the model. This leaves 226 observations. (Because a well cannot be dug on rented land, eight observations were dropped because the household did not own land in that particular year.)

Structural estimation of the model requires data on households' cash on hand X_t and liquid wealth W_{t+1} at the end of the year, the average cost of wells k, the return on liquid wealth, the probability of well failure p, and whether and when the household has constructed a well. Cash on hand is equal to liquid wealth at the beginning of the year W_t plus income during the year y_t, both of which are available from the ICRISAT panel data. In the ICRISAT data, income is defined as net returns to family-owned resources, including family labor, owned bullocks, capital, and land (Walker and Ryan 1990, p. 66). Both monetary and imputed values of all traded and nontraded goods, such as crop by-products and manure, are incorporated in the computation of household income. Income is thus the sum of net returns to crop and livestock production and income from trade, crafts, wages, remittances, and pensions. Liquid wealth comprises the value of livestock, consumer durables, commodity stocks, and financial assets but excludes land, buildings, and farm equipment, which are considered less liquid. The return to liquid wealth is included in y_t. All values are corrected for inflation and converted to 1983 rupees.

Table 1. Maximum Likelihood Estimates of the Income Equation

Variable	w/iid errors	w/heteroscedasticity correction
Land area (ha.)	.0823**	.0800**
	(.0369)	(.0296)
Farm implements ('000 Rs)	.0516	.0531
	(.0392)	(.0319)
Liquid wealth ('000 Rs.)	.0035	.0040
	(.0033)	(.0033)
Well dummy	.8419**	.8216**
	(.4230)	(.3584)
Well × land	−.0537	−.0527
	(.0389)	(.0327)
Well × implements	−.0298	−.0304
	(.0404)	(.0341)
Average intercept	8.3223	8.3301
σ_ε	.2946	.2687
	(.0243)	(.0141)
θ		.3569**
		(.1907)
Number of observations	260	260
Log of likelihood fn.	−43.072	−41.295

NOTE: Standard errors are in parentheses. **indicates significant at the 5% level (two-sided test).

The average cost of a well, the probability of well failure, and whether and when households constructed a well are taken from the well survey. The average cost of a well is 15,280 Rs., including 2,354 Rs. for a pump. Well digging, which represents most of the well cost, is done by contract labor and must be paid for in cash. Between 1970 and 1991, 10 wells were constructed by households in the well survey, many of which are not included in the ICRISAT panel data. Three of these wells failed to reach water. The probability of well failure is thus likely to be at least 30%. (It may be more if farmers only dig wells in areas where they suspect underground water can easily be reached. Farmers claim that wells have failed only on one side of the village. This issue deserves more research.) Three ICRISAT sample households constructed wells between 1975 and 1984, all of which were successful. In the estimation, we experiment with various probabilities of well failure.

2.2 Estimation of Income Distributions

We first estimate the parameters that shape the distribution of income with and without a well—that is, τ_1 and τ_0. The log of income y_t is assumed to be a linear function of cultivated land, farm implements, liquid wealth, and well ownership. Other household characteristics like age, household composition, inherited wealth, education, experience, and so forth are controlled for via fixed household effects. The estimated equation is

$$\ln(Y_{it}) = \alpha_i + \alpha_l L_{it} + \alpha_f F_{it} + \alpha_w W_{it} + \alpha_d D_{it} + \alpha_{dl} L_{it} D_{it} + \alpha_{df} F_{it} D_{it} + \varepsilon_{it}, \quad (12)$$

where Y_{it} is the income of household i in year t. Variable L_{it} stands for cultivated land, F_{it} for the value of farm implements, and W_{it} for liquid wealth. The dummy variable D_{it} takes the value 1 if household i possesses a well in year t, 0 otherwise. Cross-terms between well ownership, land, and farm implements are included to control for possible interaction between them. The variance of ε_{it} is interpreted as an estimate of the true variance of the income process around its household-specific mean. Using the log of income as dependent variable ensures that predicted income never falls below 0, a feature that is important for the success of value-function iterations.

We explicitly consider the possible effect of well ownership on the distribution of income by allowing for heteroscedasticity in the error term. We thus estimate Equation (12) letting

$$\text{var}[\varepsilon_{it}] = \sigma_\varepsilon^2 e^{\theta D_{it}}. \quad (13)$$

Maximum likelihood estimates of Equation (12) with iid errors and heteroscedasticity correction are presented in Table 1. Fixed-effect coefficients are not shown in the table but are used in the estimation of preference parameters. The signs of the estimated coefficients are as one would expect, and the most important ones are significant. Both the Breusch–Pagan and the likelihood ratio tests for heteroscedasticity are significant at the 6% level. The implied standard deviation of the log of income is .269 without well and .321 with well.

For a household with average characteristics and the average fixed-effect coefficient, expected income with and without well are 12,273 and 7,292 rupees of 1983, respectively. The standard error of income is 1,995 rupees without a well and 4,045 with a well. The implied coefficients of variation of income are .27 and .33, respectively. The implied real return to liquid wealth varies between 3% and 5% a year, slightly above the real rate of return on silver and gold, which is known to revert around 3% a year during the survey period (Pender 1992).

The difference between expected incomes with and without a well is 4,981 rupees; it is fairly constant across farm sizes, probably because a well can only serve to irrigate a set area. This compares to an average well cost of 15,280 rupees. Assuming a 20-year lifespan, the (real) internal rate of return on a successful well is 32%. With a 10-year lifespan, it is 30%. (It is unclear whether all well maintenance costs were adequately mea-

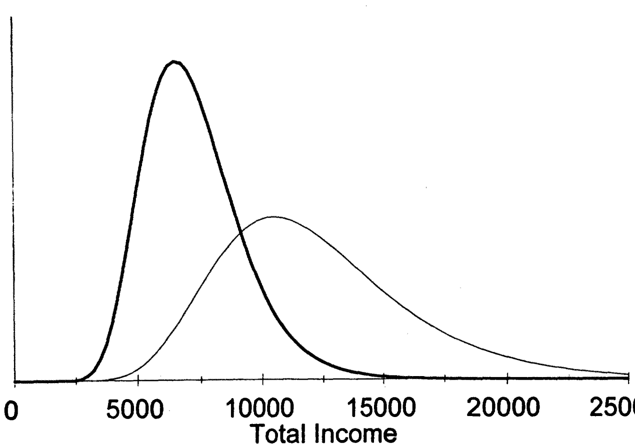

Figure 1. Distribution of Income With and Without Well; Heavy Line, Without Well; Lighter Line, With Well.

sured in the ICRISAT survey and deducted from agricultural income. If they were not, we may have overestimated the returns to well construction.) Even after taking into account the 30% probability of well failure, the expected return from well construction, 19–22%, still compares very favorably to the rate of return on liquid wealth. Well ownership increases the variance of income, but it reduces the risk of low income. The distributions of income with and without a well are presented in Figure 1 for a representative household. Post-investment income is shown to stochastically dominate pre-investment income: Not only does irrigation raise yields, it also gives the farmer a better control over crops and reduces downside risk. The steady but relatively slow adoption of wells in Kanzara can therefore not be blamed on low return or increased risk from successful wells.

2.3 Estimation of Household Preference Parameters

Armed with estimates of the distribution of income that each of the 26 households can expect with and without a well, we are ready to go ahead with the estimation of household-preference parameters. We assume that instantaneous utility exhibits constant relative aversion; that is, $U(c) = c^{1-\gamma}/(1-\gamma)$. Household preference parameters thus boil down to two, δ, the rate of time preference, and γ, the coefficient of relative risk aversion. We estimate δ and γ by "calibrating" the irreversible investment model presented in Equations (1)–(4) on observed decisions about savings and well investment made by Kanzara villagers between 1975 and 1983. The year 1984 had to be dropped because we do not have information about savings at the end of the year. The estimation criterion is full information maximum likelihood. The estimation technique is a set of nested algorithms that iterate on the likelihood function and on the Belman equation.

We first derive the likelihood function before going into the details of the algorithm. Three types of observations must be distinguished—observations for which the investment in a well has already taken place, observations for which the investment has not yet been made, and observations for which the investment is being made.

2.3.1 Cases in Which Investment Has Already Been Made. These are the simplest cases. We postulate that cash on hand X_t is observed accurately but not savings W_{t+1} because of errors of measurement in assets. Let u_t be the gap between observed savings, W_{t+1}, and the level predicted by the model, W^*_{t+1}; that is,

$$u_t = W_{t+1} - W^*_{t+1}. \tag{14}$$

Assuming that the u's are iid and normally distributed with mean 0 and variance σ_u^2, the contribution of one observation to the log-likelihood of observing the entire sample is

$$-\frac{u_t^2}{2\sigma_u^2} - \frac{1}{2}\log 2\pi - \log \sigma_u. \tag{15}$$

For any reasonable guess regarding δ, γ, the residual corresponding to a particular observation, is computed as follows. First, we derive the value function $V_1(X)$ by iterating on the Belman equation (1) until convergence. Future income is computed as

$$\begin{aligned} Y_{it+1} &= e^{\hat{\alpha}_i + \hat{\alpha}_l L_{it} + \hat{\alpha}_f F_{it} + \hat{\alpha}_w W_{it+1} + \hat{\alpha}_d D_{it+1} + \hat{\alpha}_{dl} L_{it} D_{it+1} + \hat{\alpha}_{df} F_{it} D_{it+1}} \\ &\quad \times e^{\varepsilon_{it+1}}, \end{aligned} \tag{16}$$

where ε_{it+1} follows a normal distribution with mean 0 and variance $\hat{\sigma}_\varepsilon^2 e^{\theta D_{it+1}}$.

Given this value function, W^*_{t+1} is found by solving

$$\begin{aligned} W^*_{t+1} &= \arg\max_{W_{t+1}} U(X_t - W_{t+1}) \\ &\quad + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \hat{\tau}_1). \end{aligned} \tag{17}$$

The residual u_t is simply $W_{t+1} - W^*_{t+1}$.

2.3.2 Cases in Which Investment Has Not Yet Been Made. Two types of information are conveyed by an observation in this category, the level of savings W_{t+1} and the fact that the household chose not to invest. The level of savings W_{t+1} can be treated in exactly the same fashion as in the previous case. The only difference is that W^*_{t+1} is now derived by solving

$$\begin{aligned} W^*_{t+1} &= \arg\max_{W_{t+1}} U(X_t - W_{t+1}) \\ &\quad + \beta \int_0^\infty V_0(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \hat{\tau}_0). \end{aligned} \tag{18}$$

This requires that an approximation to $V_0(X)$ be obtained. To do so, we follow the same method as the one outlined for case 1.

To handle the second piece of information, we derive the likelihood that the household did not invest. To do so, we assume that the true cost of building a well varies across households. Households know their cost of building a well, but we do not accurately observe it. All we know is the average cost of well construction $\bar{k}$. The true cost k_i for a particular household i diverges from the average cost $\bar{k}$ by a measurement error e_i:

$$e_i = k_i - \bar{k}. \tag{19}$$

For simplicity, we assume that the e_i's are iid, normally distributed with mean 0 and variance σ_e^2, and independent of u_t.

We then proceed with the estimation as follows. For each observation, we first compute the cost of the well k_t^* at which the household would have been indifferent between investing and not investing. Each of these k_t^* is treated as an independent observation. Small differences in k_t^* for the same household result from shifts in cultivated land and farm implements. We interpret these shifts as unanticipated changes in the household's future income distribution. (We could have added more structure to the estimation process by explicitly recognizing that k_i should be the same for all observations regarding a single household. Doing so would have complicated the algorithm without adding significantly to the estimation: Given that the k_t^*'s do not vary much for the same household, the difference between such an estimator and the one we have used is minimal.) Let $e_t^* = k_t^* - \bar{k}$. Then the probability that the household did not invest is equivalent to the probability that the true cost of the well, and therefore e_i, was large enough to deter investment; that is,

$$\Pr(k_i \geq k_t^*) = \Pr(e_i \geq e_t^*) = 1 - \mathbf{\Phi}\left(\frac{e_t^*}{\sigma_e}\right), \quad (20)$$

where $\mathbf{\Phi}(.)$ stands for the cumulative standard normal distribution. k_t^* is derived iteratively as the value of k_t that satisfies the following equation:

$$\begin{aligned}
&\max_{W_{t+1}} U(X_t - k_t^* - W_{t+1}) \\
&\qquad + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_1) \\
&= \max_{W_{t+1}} U(X_t - W_{t+1}) \\
&\qquad + \beta \int_0^\infty V_0(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_0). \quad (21)
\end{aligned}$$

The likelihood of observing a no-investment observation is thus the product of the likelihood of observing u_t and of the likelihood of not investing. Taking logs, the contribution of a no-investment observation to the likelihood function is

$$-\frac{u_t^2}{2\sigma_u^2} - \frac{1}{2}\log 2\pi - \log\sigma_u + \log\left(1 - \Phi\left(\frac{e_t^*}{\sigma_2}\right)\right). \quad (22)$$

2.3.3 Cases in Which Investment Is Being Made. Two types of information are also conveyed by an observation in this category—the actual cost of the investment k_i to the household was low enough to trigger investment, and the household decided to save W_{t+1}. The first type of information is dealt with in exactly the same fashion as in the previous case, and the threshold investment cost k_t^* is derived numerically. The probability of observing investment is thus

$$\Pr(e_i \leq e_t^*) = \mathbf{\Phi}\left(\frac{e_t^*}{\sigma_e}\right). \quad (23)$$

W_{t+1}, however, must be dealt with in a slightly different manner. Optimal savings are given by

$$W_{t+1}^* = X_t - k_i - C_t^*(X_t - k_i), \quad (24)$$

where C_t^* denotes optimal consumption at t. By our own assumptions, when the household invests we do not accurately observe the true cost of the investment k_i. This means that it is impossible to derive W_{t+1}^* and thus u_t precisely. Define u_t^* as

$$u_t^* = W_{t+1} - X_t + k_t^* + C_t^*(X_t - k_t^*). \quad (25)$$

u_t^* can easily be computed using the level of savings that comes out of the computation of k_t^*. We know that $k_i \leq k_t^*$. Then we also know that $u_t \leq u_t^*$. The likelihood of observing a case in which investment is being made is thus

$$\Pr(e_i \leq e_t^*)\Pr(u_t \leq u_t^*) = \mathbf{\Phi}\left(\frac{e_t^*}{\sigma_e}\right)\Phi\left(\frac{u_t^*}{\sigma_u}\right). \quad (26)$$

2.4 Algorithm

For any (reasonable) guess about δ, γ, σ_u, and σ_e, Equations (15), (22), and (26) provide a method for computing the likelihood of observing each of the three possible cases that arise in the data. The likelihood of observing the entire sample is the sum of individual log-likelihoods. Finding the maximum likelihood estimates of δ, γ, σ_u, and σ_e is but a matter of trying out various parameter vectors until finding the one that gives the highest likelihood value. This can be achieved by a variety of numerical optimization algorithms.

In this article, we use a combination of the Nelder–Mead simplex algorithm (for its robustness) and the quasi-Newton (for its rapidity) as follows. For each guess about δ and γ, Chebyshev approximations to the value functions $V_1(X)$ and $V_0(X)$ are first derived by iterating on the Belman equations (1)–(4). Technical details about the algorithm are presented in Appendix B. Gauss–Hermite quadrature is used to compute $EV_i(X)$. Estimates of u_t, e_t^*, and/or u_t^* are then computed, depending on whether the household has already invested (case 1), has not invested yet (case 2), or is investing (case 3). Using these estimates, a quasi-Newton inner optimization algorithm iterates on σ_u and σ_e until it finds those that maximize the likelihood value. An outer Nelder–Mead simplex algorithm (see Gill, Murray, and Wright 1981) iterates on δ and γ. The outer algorithm thus de facto maximizes the concentrated likelihood function. This approach is preferred because it reduces the number of evaluations required for the value functions $V_0(X)$ and $V_1(X)$. The programming cost of the exercise is high.

2.5 Model Specifications

To reflect the fact that we have incomplete information about the precise environment farmers face, we estimate the parameters δ and γ under a series of model specifications. In the base run (model 1a), we allow for the possibility that digging a well may fail to reach water. We set the value of p, the probability that a well fails, equal to its sample mean of 30%. With failed wells, Equation (2) becomes

$$\begin{aligned}
&V_0^1(X_t) \\
&\quad = \max_{W_{t+1}} U(X_t - k - W_{t+1}) \\
&\qquad + (1-p)\beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_1) \\
&\qquad + p\beta \int_0^\infty V_{00}(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF(\tilde{y}_{t+1}; \tau_0). \quad (2')
\end{aligned}$$

Equation (26) must also be amended; that is,

$$\begin{aligned}
&(1-p)\Pr(e_t \leq e_t^*)\Pr(u_t \leq u_t^*) \\
&\qquad = (1-p)\mathbf{\Phi}\left(\frac{e_t^*}{\sigma_e}\right)\mathbf{\Phi}\left(\frac{u_t^*}{\sigma_u}\right). \quad (26')
\end{aligned}$$

To compensate for the small number of observations on which the p value of 30% is based, we experiment with other values of p and reestimate the model with p set to 0% (model 1b) and 80% (model 1c), respectively.

Next, we examine whether parameter estimates are sensitive to assumptions regarding financial transactions and credit markets. In the first version of the model, we assume away credit (models 1a, 1b, and 1c). Financial claims and liabilities are excluded from liquid wealth, and the entire cost of the well is assumed to be financed from own funds. These assumptions offer the advantage of being internally consistent: Households whose income can fall to 0 should be unable or unwilling to obtain undefaultable credit.

In practice, however, credit contracts can be defaulted or rescheduled, and some Kanzara households receive credit. Households participating in the well survey report that they were able to borrow to finance the construction of the well. On average, 57% of the investment cost was allegedly financed through subsidized credit from local banks. The ICRISAT survey data also contain information on households' financial liabilities. Incorporating credit into the model is not an easy task. On the one hand, unless debts can be defaulted, the theory predicts that households never are net borrowers. On the other, modeling defaultable credit contracts is beyond the scope of this article.

To keep things manageable, we adopt the following approach. Let L_t denote net financial liabilities at the beginning of year t. First, we deduct net financial liabilities L_t from households' wealth W_t at the beginning of the year. Next, in the absence of data on interest payments, debt-repayment horizon, and rescheduling practices, we simply deduct the perpetuity value of end-of-period liabilities rL_{t+1} from future income y_{t+1}, where r is assumed to take the value of 3%. (Assuming a finite debt-repayment horizon would require time-indexed value functions, a complication that is beyond the scope of this article.) If $W_{t+1} + y_{t+1} - rL_{t+1} < 0$, we assume that payment of the debt is forgiven and that $c_{t+1} = \varepsilon$, where ε is a small positive number. Estimates of this variant of the model, assuming no borrowing for well construction, are presented as model 2.

Model 3 is like model 2 except that we now assume that households can borrow 57% of the cost of the well and repay the debt in the form of a 3% perpetuity. In all probability, this is an overestimate because many households that have not invested in a well may be credit constrained. To verify this assumption, we compare model 3 to model 2 using a likelihood ratio test.

We also experimented with another way of reconstructing wealth. As is common in household surveys, the ICRISAT data on liquid wealth and incomes is hard to reconcile with that on consumption expenditures. Lim and Townsend (1994) hypothesized that the difference may be accounted for by the hoarding of cash. To explore this possibility, we reconstructed changes in liquid wealth as the difference between measured incomes and consumption and added the reconstructed liquid-wealth series to measured assets at the beginning of the survey. This procedure results in much smoother consumption data over time and in larger variations in assets to compensate for income shocks. Presumably, these variations capture changes in cash holdings. Probably because of underreporting of consumption, the reconstructed liquid-wealth series also exhibits a strong upward trend, even after years for which data are known to be poor have been eliminated (see Lim and Townsend 1994). Reestimating the income regressions with the reconstructed data led to negative coefficients for liquid wealth, a highly unlikely possibility. Consequently, we decided not to use the reconstructed data for estimation.

2.6 Estimation Results

Results are presented in Table 2. To check for possible identification problems, we computed for model 1b the value of the log-likelihood for a wide range of possible δ's and γ's. Results are summarized in Figure 2 in the form of a contour map. They clearly indicate that the likelihood function has a single maximum and that δ and γ are separately identified. Asymptotic confidence intervals are derived using the outer product of the gradient vector as an estimate of the information matrix. Indeed, if l_n is the contribution of observation n to the log-likelihood function and λ is the parameter vector, then (Judge, Hill, Griffiths, Lutkepohl, and Lee 1985, p. 178)

$$\sqrt{N}(\hat{\lambda} - \lambda) \rightarrow^d N[0, \lim(I(\lambda)/N)^{-1}],$$

where $I(\lambda)$ is the information matrix and $I(\lambda)/N$ can be replaced by the consistent estimator $[(1/N)\sum_{n=1}^{N}(\partial l_n/\partial\lambda)(\partial l_n/\partial\lambda')]$ (Berndt, Hall, Hall, and Hausman 1974). All asymptotic standard errors are tight, suggesting that we are able to identify δ and γ with precision. The reader should keep in mind, however, that they are not corrected for the fact that the income process on which they are based is itself estimated. It is thus possible that our ability to sta-

Table 2. Maximum Likelihood Estimates of Utility Parameters

Parameters	Model 1a	Model 1b	Model 1c	Model 2	Model 3
δ	.181	.292	.170	.259	.740
	(.013)	(.026)	(.008)	(.023)	(.070)
γ	2.089	3.062	1.771	3.101	3.100
	(.235)	(.080)	(.229)	(.058)	(.069)
σ_u	.642	.654	.651	.676	.717
σ_e	.332	.383	.537	.416	.184
Log-likelihood	−235.644	−239.931	−242.175	−246.376	−278.422
R^2	.877	.872	.873	.863	.846

NOTE: Asymptotic standard errors of the coefficients are in parentheses. Log-likelihood values for models 1a, 1b, and 1c on the one hand and models 2 and 3 on the other are not directly comparable as the values of cash on hand, and savings are not identical. All values are in 1983 rupees divided by 10,000. The reported R^2 is for savings only (see text for details).

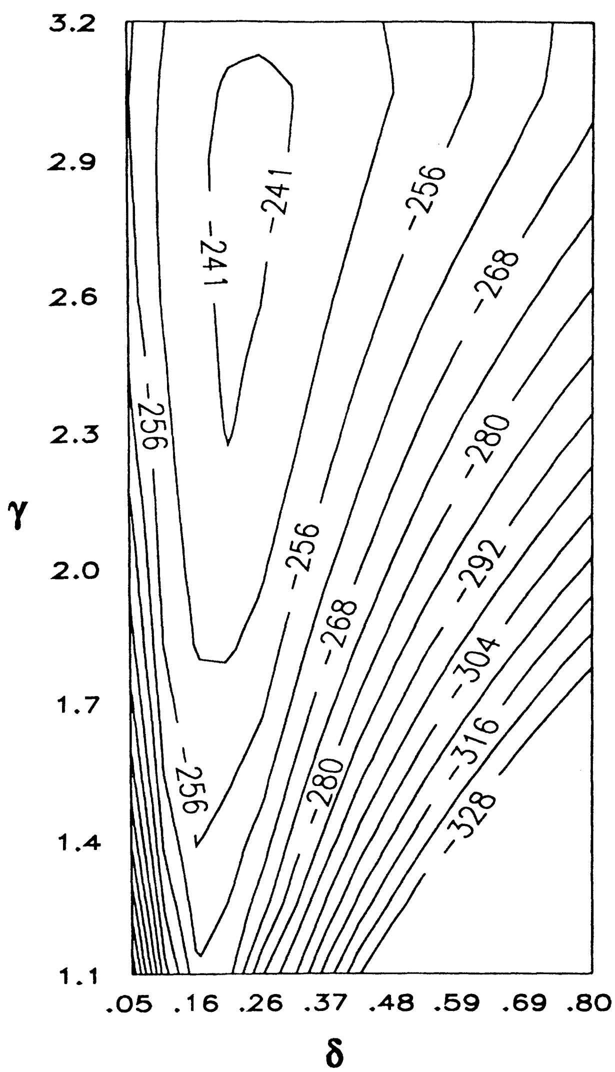

Figure 2. Contour Map of the Log-Likelihood Function.

tistically disentangle the discount rate and risk-aversion parameter results from assuming incorrectly that the estimates of the income-generating function are known without error. The only way to tell would be to undertake a joint estimation of the income-generating function and the household intertemporal choice, as shown by R&W. This is left for future research.

Our best estimates, those for model 1a, are $\delta = 18\%$ and $\gamma = 2.09$. Our estimates of relative risk aversion revert around 1.8–3.1, somewhat high but not altogether implausible given the low income levels in the area (Walker and Ryan 1990). In contrast, R&W estimated γ to be much smaller—.96. This low result may be because they did not estimate the rate of time preference δ but posited that it is 5%. In addition, the utility function R&W used includes a minimum consumption parameter that is likely to have captured consumption smoothing independently from γ. Using an Euler-equation approach and assuming a constant relative risk-aversion coefficient as we do here, Morduch (1990) estimated the coefficient of relative risk aversion in Kanzara to be 1.39.

Our estimates of δ vary from one model to another, but they are all well above 5%. In models 1 and 2, δ varies between 17% to 29%. These values are lower but of the same order of magnitude as the median discount rates measured by Pender (in press) using experimental games in two of the ICRISAT villages. Discount rates are not a direct measure of the pure rate of time preference δ because they are affected by consumption smoothing motives as well. But if we account for seasonal effects and income shocks, the existence of high discount rates in semiarid India (median values between 50% and 60% in most experiments) is consistent with a rate of time preference as high as estimated here.

Model 3, in which households are assumed able to borrow for well construction, stands in sharp contrast with the other models. There, δ is estimated to be as high as 75%—an unlikely value. The reason for this is easy to guess. With half of the investment cost covered by borrowing at 3%, the profitability of the investment is much higher than in models 1 and 2: The internal rate of return on the investment rises to 31%. Given that building the well also reduces income risk, the only way the algorithm can reconcile the model with the observed low level of well investment is by postulating that households are more impatient.

Although we do not know what probability of well failure p the surveyed households anticipate, it is easy to see from Table 2 that assuming that they expect wells to fail 30% of the time fits the data better than assuming that households expect either all wells to succeed or most wells to fail. Formally, let H_0 be $p = a$ and let H_1 be $p = b$ and let L_0 and L_1 be the log-likelihood values obtained assuming that H_0 and H_1 are true, respectively. Let α be the desired significance level. Then, if $2(L_0 - L_1) < \chi^2(1, \alpha)$, we conclude that H_0 and H_1 are equally consistent with the data and cannot be distinguished. Otherwise we accept the p value with the highest log-likelihood. The value of the test is 8.573 between models 1a and 1b and 13.061 between models 1a and 1c. Assuming that about a third of the wells fail—$p = .3$—thus fits the data significantly better than assuming either that they all succeed—$p = 0$—or that most of them fail—$p = .8$.

A similar test can be used to check whether assuming that all households can borrow for well construction fits the data better than assuming that none of them can. The value of the likelihood ratio test between models 2 and 3, which is 64.091, constitutes overwhelming evidence that not all households can borrow to construct a well. It thus appears that many of those who did not invest in a well lack the access to institutional credit used by many of those who did invest.

The model fits observed behavior fairly well, given the panel nature of the data. To assess how accurately the model predicts savings, we compute an equivalent to the usual R^2 statistic as $1 - \sigma_u^2 T / \sum_{t=1}^{T} W_t^2$. Results, shown in Table 2, illustrate that the model performs quite satisfactorily, at least according to the standard R^2 criterion. Although our estimation results are based on maximum likelihood, not the method of simulated moments suggested by McFadden (1989) and Pakes and Pollard (1989), they reproduce fairly accurately the first two moments of the sample distribution

Table 3. Predictive Power of the Model

Year	Number observations	Investment predicted: realized:	yes yes	no yes	yes no	no no	Investment already made
1975	25		0	0	1	17	7
1976	25		0	0	1	17	7
1977	26		0	0	1	18	7
1978	26		0	0	1	18	7
1979	26		0	0	0	19	7
1980	25		0	1	1	16	7
1981	25		1	0	0	16	8
1982	24		0	1	0	14	9
1983	24		0	0	0	14	10
Total	226		1	2	5	149	69

of savings. Average liquid wealth over all sample households is 9,335 Rs. compared to an average predicted savings of 9,063 Rs. for model 1a. The standard error of actual and predicted savings are 15,707 Rs. and 15,013 Rs., respectively. Similar results are obtained with the other models.

Next, we turn to the ability of the model to predict the timing of well investment. There are 157 observations for which a well had not yet been dug at the beginning of the survey period. For each of these observations we used the average well cost and the parameter estimates from model 1a to compute the threshold cash on hand at which investment should in principle take place. Comparing these results with actual cash on hand enables us to ascertain how well the model predicts investment behavior. Results, computed separately for each survey year, are summarized in Table 3. In 150 of the 157 relevant observations, the model makes the correct inference. Of the three cases of well construction occurring in the sample, one is accurately predicted, one is not predicted, and the third is predicted to happen earlier than it actually did. Close inspection of the result reveals that all five cases of false prediction of well construction are for the same household that constructed a well in a subsequent period; the model only got the timing wrong. A possible explanation is that well construction and planning take more than one year. Unfortunately, we do not have data on the time required to dig a well.

2.7 Credit Constraints and Poverty Trap

Having estimated γ and δ we are now in a position to ascertain whether the precautionary motive for saving plays a significant role in surveyed households' reluctance or inability to invest in well construction. Using the estimated parameters from model 1a and the average well cost, we simulated for each of the 157 observations without well at the beginning of the period the threshold cash on hand and liquidity premium at which investment takes place (Table 4). The threshold cash on hand is found iteratively as the X^* at which the following equation is satisfied:

$$\begin{aligned}
&\max_{W_{t+1}} U(X^* - k - W_{t+1}) \\
&\quad + \beta \int_0^\infty V_1(W_{t+1} + \tilde{y}_{t+1}(W_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_1) \\
&= \max_{W'_{t+1}} U(X^* - W'_{t+1}) \\
&\quad + \beta \int_0^\infty V_0(W'_{t+1} + \tilde{y}_{t+1}(W'_{t+1}))\, dF\,(\tilde{y}_{t+1}; \tau_0). \quad (27)
\end{aligned}$$

The liquidity premium is simply W_{t+1} at the solution of Equation (28).

Results show that the liquidity premium is positive but small: Once they reach the required threshold cash on hand, households are predicted to invest almost all of their wealth

Table 4. Wealth, Income, and Investment

Samples	Average	St. dev.	Min.	Max.
Sample with well (69 observations)				
Liquid wealth	17,840	20,650	920	81,510
Annual income	16,630	13,830	1,700	48,960
Cash on hand	34,470	33,000	3,560	124,230
Sample without well (157 observations)				
Liquid wealth	4,430	6,540	250	41,150
Annual income	7,740	6,330	1,680	41,900
Cash on hand	12,170	12,290	2,340	69,370
Simulated values (157 observations)				
Threshold cash on hand	25,440	18,840	19,586	202,141
Liquidity premium	3,108	13,809	0	140,754
Experiment results* (141 observations)				
Threshold cash on hand	35,541	26,702	21,686	193,940
Liquidity premium	11,441	21,147	0	132,312

NOTE: All numbers in 1983 rupees.

* Simulation of investment behavior by sample households without well assuming that the return to the well is cut by half (see text for details). Of 157 observations, 16 never invest. Threshold cash on hand and liquidity premium are reported for the remaining 141 observations.

Table 5. Summary of Wealth Accumulation Simulations

	No borrowing	Borrowing[a]			No borrowing[b]	
		at 3%	at 20%	at 35%	$r(W) \times 2$	$r(W) \times 4$
Internal rate of return[c]	22%	49%	26%	7%	22%	22%
Threshold wealth[d]	22,520	10,956	12,247	28,136	22,854	31,615
Liquidity premium	0	0	0	11,139	0	7,188
Percent investment[e]	0%	91%	53%	0%	0%	17%
Time to invest[f]	n.a.	19	23	n.a.	n.a.	26

NOTE: Table is based on 100 replications of 50 year-long simulations for a household with average characteristics.
[a] Assuming that the household can borrow the equivalent of 57% of the cost of well investment.
[b] No borrowing but higher returns $r(W)$ to liquid wealth.
[c] Assuming a 30% probability of well failure, and accounting for default.
[d] Cash in hand required for investment to occur.
[e] Percentage of 50 year-long runs in which investment takes place.
[f] Average number of years until the investment if the household invests.

in digging the well. For most households, irreversibility constitutes a relatively minor impediment to investment. This need not always be the case, however. In an experiment, we reduce the value of the well dummy coefficient in the income equation so that, for the average sample household, the expected return from digging a well drops by half. Keeping all other parameters unchanged, we recompute the threshold cash-on-hand and liquidity premium for all 157 observations without well. In this case, 16 of them never invest in the well. For the others, the liquidity premium amounts, on average, to 75% of the cost of the well, and the threshold cash in hand goes up by 40%. In this case, irreversibility clearly deters investment.

In simulations based on estimated parameters, we see that the threshold cash on hand at which households without well would consider investing is equivalent to more than three times their average preinvestment income and is over twice their average cash on hand after harvest. These results suggest that many households fail to undertake the investment in irrigation because they are unable to accumulate enough wealth to cover the investment cost. To verify this possibility, we simulate the income and saving pattern of a household with average characteristics. As Table 4 indicates, inability to invest is associated with large differences in welfare: The average income of households with a well is over twice that of households without well, and their liquid wealth is nearly four times as much. We conduct 100 simulations, each of them 50 years long. In none of these 100 simulations does the household accumulate enough to invest in the well (Table 5). Households thus appear trapped—in a probabilistic sense—in poverty: Because their income is low, they are too concerned about their immediate survival to accumulate much, they never manage to have enough to undertake indivisible but highly profitable investments, and they remain poor.

Simulation results nevertheless indicate that poor households attempt to save for the well. We simulate liquid savings for households facing the option to invest in the well and compare the results to those of hypothetical households without that option. On average, households with the option to construct a well save 40% more than identical households without this option. These results are consistent with theoretical propositions derived by Pender (1992).

To test whether credit can help households out of poverty, we redo the simulations assuming that the household can borrow at a 3% interest rate the average credit received by households who dug a well, which is equivalent to 57% of the value of the well. Debt repayment is assumed forgiven in bad years. This assumption is essential; otherwise agents optimally decide not to incur debt. Results show that in almost all of the simulations investment takes place. The waiting time to investment is long, however—19 years on average for investing households. The reason is that, with borrowing, the threshold cash on hand is less than half of what it is without borrowing. This puts the investment within the range of what households can afford with moderate savings after a good cropping season.

To check whether subsidizing credit plays an important role, we redo the simulations assuming that borrowed funds carry a 20% and a 35% (real) interest rate. The expected rate of return on well construction drops accordingly (Table 5). Results indicate a reduction in investment, but the rate charged on borrowed funds must be raised from 3% to 35% before all investment disappears. What matters is not so much the cost of credit but rather its availability. To successfully promote well construction, credit must bring investment within the reach of poor households.

Finally, we investigate the effect of higher returns to liquid wealth, as could be achieved, for instance, by a deregulation of interest rates on savings accounts. As predicted by McKinnon (1973) and Pender (1992), higher returns on liquid wealth can make investment possible by encouraging households to save. We redo the simulations assuming no outside borrowing but higher coefficient on liquid wealth W_{t+1} in Equation (12). Simulation results confirm McKinnon's and Pender's theoretical intuitions, but they also indicate that, in this particular case, a sizable increase in returns to liquid wealth is required for a noticeable rise in investment to materialize.

3. CONCLUSIONS

In this article we investigated whether poor farmers in India are discouraged from making a highly profitable investment because it is nondivisible and irreversible. To do so, we constructed a model of irreversible investment by an agent with a precautionary motive for saving. We then proceeded to apply the model to well construction in semiarid India. We computed maximum likelihood estimates of the rate of time preference and of the coefficient of relative risk aversion of Indian farmers. The estimation algorithm relies on orthogonal polynomials for approximating the value function and on nested iterative algorithms to search for the best vector of parameter estimates.

Resulting estimates of impatience and risk aversion are somewhat high but not implausible given the extent of risk and poverty in the surveyed village. The model explains over half of the variation in savings and predicts the actual lack of investment fairly well. Simulations conducted with estimated parameters suggest that many poor farmers may find themselves trapped in poverty due to their inability to accumulate enough wealth to self-finance the construction of an irrigation well. Risk aversion per se does not explain the reluctance to invest: Farm incomes with a well stochastically dominate incomes without. Irreversibility constitutes a small additional deterrent to investment.

Our results demonstrate empirically the magnitude of the inefficiency and inequity caused by poor households' inability to finance profitable but nondivisible investments. An investment yielding a real rate of return of 19–22% was never considered by most households who were, in effect, forced to accept a lower return on divisible liquid wealth. In the context of financial repression common in India during the study period—but which has since been reformed—such outcome is consistent with concerns raised by McKinnon (1973), Shaw (1973), and others in the 1970s. It also suggests the importance for poor farmers of having access to remunerative savings opportunities (e.g., McKinnon 1973; Pender 1992).

The link between poverty and low investment apparent in our results is reminiscent of "vicious circle" and "big push" theories of development propounded decades ago by Nurkse (1953), Lewis (1954), Nelson (1956), and others. Modern versions of these theories can be found in the work of Gaylor and Ryder (1989) and Barro and Sala-I-Martin (1995). Our contribution is to demonstrate their empirical plausibility in a specific context. These issues deserve more empirical research at the village and household level.

The work reported here presents the advantage of integrating the theory of precautionary saving with that of credit constraints and irreversible investment under risk. It can be extended in several directions. Other investments in which nondivisibility may serve to deter investment by poor households—for example, human capital accumulation or firm creation and expansion—can be studied similarly. Irreversibility is a feature common to many economic decisions. Investment in schooling, human fertility, and the construction of a production unit, for instance, are all situations in which decisions cannot be reversed. Partial irreversibility is even more widespread because many decisions can only be reversed at a cost—for example, migration, purchase of durables, purchase of equipment. We have shown that agents with a precautionary motive may refrain from incurring an irreversible investment. More work needs to be done to derive all the implications of irreversibility on decision making and to ascertain under which circumstances irreversibility serves as an additional deterrent to investment.

ACKNOWLEDGMENT

We thank Ken Wolpin, Lars Hansen, Rob Townsend, Chris Udry, Kiminori Matsuyama, two anonymous referees, and seminar participants at Stanford, Northwestern University, and the University of Chicago for their useful comments. We are grateful to ICRISAT for making the data available and for assisting the second author in collecting data on well investment.

APPENDIX A: PROOF OF PROPOSITION 1

Part 1. Let $V_{00}(X)$ denote the agent's value function if the investment were not allowed. Ex ante, having the option to invest cannot make the agent worse off than $V_{00}(X)$. The agent's expected utility if he/she were to invest today is $V_0^1(X)$, which, by construction, $= V_1(X-k)$. We have shown that the agent cannot or does not want to borrow. Consequently, for $X < k$, $V_1(X-k)$ is not defined or is $-\infty$. If the investment is profitable enough, $V_1(X-k)$ must eventually cross $V_{00}(X)$.

Suppose that the agent was made a once-and-for-all offer to invest today. $V_1(X-k)$ is the value of using the option; $V_{00}(X)$ is the value of not investing. If $V_1(X-k)$ and $V_{00}(X)$ cross, say at X^*, then the agent invests if $X > X^*$ and does not invest if $X < X^*$. Now suppose that the agent can invest either today or tomorrow. If he/she invests today, he/she gets the same utility from investment $V_1(X-k)$ as before. Suppose he/she decides to wait and chooses an optimal level of W_{t+1}, given that he/she will have the option to invest tomorrow. Let the value of that choice be denoted $\bar{V}_0^0(X)$. Because he/she still has the option to invest tomorrow, the utility he/she will get from a given level of cash on hand X tomorrow is the sup of $V_{00}(X)$ and $V_1(X-k)$. Denote that utility $\bar{V}_0$. Clearly $E\bar{V}_0$ is larger than EV_{00}. By Equation (3), it therefore must be that $\bar{V}_0^0(X) \geq V_{00}(X)$ for all X: Tomorrow's option to invest raises the agent's utility.

Prolonging the time during which the agent may decide to invest can only further increase his/her ex ante utility. To see why, suppose that the agent is given three periods during which investment is possible. Consider the first period. His/her payoff if he/she invests immediately is unchanged; it is $V_t(X-k)$. If he/she waits, his/her utility tomorrow is

$$\bar{\bar{V}}_0(X) = \max\{\bar{V}_0^0(X), V_1(X-k)\}.$$

It is clear that $\bar{\bar{V}}_0(X) \geq \bar{V}_0(X)$, which was itself $\geq V_{00}(X)$. We can thus apply the same argument as before: By Equation (3), the utility of waiting has increased further. Applying the same logic recursively, it is clear that the option to invest raises the agent's utility above $V_{00}(X)$ even when the investment is not undertaken. It cannot, however, raise the agent's utility above what it would get by investing immediately.

Part 2. Consider an agent who can invest either today or tomorrow. In the proof of Proposition 1, we saw that

$\bar{V}_0^0(X) \geq V_{00}(X)$. This means that $\bar{V}_0^0(X)$ cuts $V_1(X-k)$ above X^*—say at X^{**}. There is therefore a range of values of cash on hand for which an agent without the option to wait would invest, whereas an agent who can wait would prefer to do so. By the proof of Proposition 1, $V_0^0(X)$ can only be raised further when more options are added. Adding options can therefore only increase the range of cash-on-hand values over which it is preferable to wait.

APPENDIX B: TECHNICAL DETAILS ABOUT THE ALGORITHM

We begin by iterating on Belman Equation (1) to find $V_1(.)$. Value-function iterations are slow but ensured to converge. Past iterates of $V_1(X)$ are recycled for subsequent δ and γ iterates so as to speed up value-function iterations on the Belman equation. The number of required iterations thus goes down rapidly as the search for δ and γ converges.

Next, we compute $V_{00}(.)$, the value function when the investment is not allowed. Taking $V_{00}(.)$ as first iterate, we then iterate on Equation (4) to find $V_0(.)$. $V_0(X)$ is not computed for households that have already dug a well. Iterating on the Belman equation is performed in much the same way as when the value function is discrete; that is, the right side of the Belman equation is maximized for a chosen invariant set of cash-in-hand values X_t. The difference is that the chosen values of X_t are the optimal nodes of a Chebyshev polynomial. Interpolation to between nodes values of X_t is done using the Chebyshev iterative formula (see Judd 1991). Chebyshev is known to dramatically outperform other approximation methods, including discrete approximations (e.g., Atkinson 1989). Five nodes are used for the Chebyshev polynomials.

Gauss–Hermite quadrature is used to compute $EV_i(X)$. Like discrete approximation and other interpolation methods, Gaussian quadrature boils down to evaluating $V_i(X)$ at a finite number of values of X and summing the results using an appropriate set of weights. The difference is in the careful way nodes and weights are chosen. Gaussian quadrature is known to dramatically outperform interpolation methods for simple integrals (Atkinson 1989; Judd 1991). Gauss–Hermite is best suited to our problem because income shocks are normally distributed. Seven nodes are used for quadrature. The value of k_t^* that equates both sides of Equation (21) is found using a combination of secant (for robustness) and Newton (for speed) methods (see Atkinson 1989).

Debugging is extremely time consuming because delicate numerical problems crop up that call for additional coding. Most of our programming effort was devoted to maximizing numerical precision at high values of γ when the utility function becomes nearly flat and close to 0 for consumption above some level. Problems were also frequent when, during the search, the algorithm failed to find the root of Equation (21). These failures mean that the parameter vector cannot be reconciled with the data. To prevent the search for the best parameter vector from being aborted by these incidents, penalty functions had to be devised that would prevent the algorithm from exploring bad parameter vectors but keep the search going. These penalty functions are not binding at the optimum. The algorithm, coded in FORTRAN, requires about 1,500 lines of code and used a variety of NAG subroutines (see Numerical Algorithms Group 1986). Estimation is computer intensive: One run takes several hours of central processing unit time on a Sun 10 with four coprocessors.

[Received January 1995. Revised May 1996.]

REFERENCES

Arrow, K. J. (1971), *Essays in the Theory of Risk Bearing*, Chicago: Markham.

Atkinson, K. (1989), *An Introduction to Numerical Analysis*, New York: Wiley.

Barro, R., and Sala-I-Martin, X. (1995), *Economic Growth*, New York: McGraw-Hill.

Bell, C. (1988), "Credit Markets and Interlinked Transactions," in *Handbook of Development Economics*, eds. H. Chenery and T. N. Srinivasan, Amsterdam: North-Holland, pp. 801–850.

Berndt, E. K., Hall, B. H., Hall, R. E., and Hausman, J. (1974), "Estimation and Inference in Nonlinear Structural Models," *Annals of Economic and Social Measurement*, 3/4, 653–665.

Binswanger, H. P. (1980), "Attitudes Towards Risk: Experimental Measurement Evidence in Rural India," *American Journal of Agricultural Economics*, 62, 395–407.

Carroll, C. D. (1992), "The Buffer-Stock Theory of Saving: Some Macroeconomic Evidence," *Brookings Papers on Economic Activity*, 2, 61–156.

Carter, M. R. (1988), "Equilibrium Credit Rationing of Small Farm Agriculture," *Journal of Development Economics*, 28, 83–103.

Deaton, A. (1990), "Saving in Developing Countries: Theory and Review," in *Proceedings of the World Bank Annual Conference on Development Economics 1989*, eds. S. Fisher and D. de Tray, Washington, DC: The World Bank, pp. 61–96.

——— (1991), "Saving and Liquidity Constraints," *Econometrica*, 59, 1221–1248.

——— (1992a), "Household Saving in LDCs: Credit Markets, Insurance and Welfare," *Scandinavian Journal of Economics*, 94, 253–273.

——— (1992b), "Saving and Income Smoothing in Cote d'Ivoire," *Journal of African Economies*, 1, 1–24.

Dixit, A. (1989), "Entry and Exit Decisions Under Uncertainty," *Journal of Political Economy*, 97, 620–638.

Dixit, A. K., and Pindyck, R. S. (1994), *Investment Under Uncertainty*, Princeton, NJ: Princeton University Press.

Dreze, J. H., and Modigliani, F. (1972), "Consumption Decisions Under Uncertainty," *Journal of Economic Theory*, 5, 308–335.

Eaton, J., and Gersovitz, M. (1981), "Debt With Potential Repudiation: Theoretical and Empirical Analysis," *Review of Economic Studies*, XLVIII, 289–309.

Epstein, L. G. (1978), "Production Flexibility and the Behavior of the Competitive Firm Under Price Uncertainty," *Review of Economic Studies*, 140, 251–262.

Eswaran, M., and Kotwal, A. (1986), "Access to Capital and Agrarian Production Organization," *Economic Journal*, 96, 482–498.

Fafchamps, M. (1993), "Sequential Labor Decisions Under Uncertainty: An Estimable Household Model of West-African Farmers," *Econometrica*, 61, 1173–1197.

Feder, G. (1985), "The Relation Between Farm Size and Farm Productivity," *Journal of Development Economics*, 18, 297–314.

Gaylor, O., and Ryder, H. E. (1989), "Existence, Uniqueness, and Stability of Equilibrium in an Overlapping-Generations Model With Productive Capital," *Journal of Economic Theory*, 49, 360–375.

Gill, P. E., Murray, W., and Wright, M. H. (1981), *Practical Optimization*, London: Academic Press.

Gonzalez-Vega, C. (1984), "Credit Rationing Behavior of Agricultural Lenders: The Iron Law of Interest Rate Restrictions," in *Undermining Rural Development With Cheap Credit*, eds. D. W. Adams, D. H. Graham, and J. D. Von Pischke, Boulder, CO: Westview Press, pp. 78–95.

Grossman, H. I., and Van Huyck, J. B. (1988), "Sovereign Debt as a Contingent Claim: Excusable Default, Repudiation, and Reputation," *American Economic Review*, 78, 1088–1097.

Iqbal, F. (1986), "The Demand and Supply of Funds Among Agricultural Households in India," in *Agricultural Household Models*, eds. I. Singh, L. Squire, and J. Strauss, Washington, DC: The World Bank, pp. 183–205.

Judd, L. (1991), "Numerical Methods in Economics," draft, Stanford University, Hoover Institution.

Judge, G., Hill, R. C., Griffiths, W. E., Lutkepohl, H., and Lee, T. (1985), *The Theory and Practice of Econometrics*, New York: Wiley.

Kimball, M. S. (1990), "Precautionary Savings in the Small and in the Large," *Econometrica*, 58, 53–73.

Kletzer, M. (1984), "Asymmetries of Information and LDC Borrowing With Sovereign Risk," *Economic Journal*, 94, 287–307.

Lewis, W. A. (1954), "Economic Development With Unlimited Supplies of Labour," *The Manchester School*, XXII, 139–191.

Lim, Y., and Townsend, R. (1994), "Currency, Transaction Patterns, and Consumption Smoothing: Theory and Measurement in ICRISAT Villages," mimeo, University of Chicago, Dept. of Economics.

McFadden, D. (1989), "A Method of Simulated Moments for Estimation of Discrete Response Models Without Numerical Integration," *Econometrica*, 57, 992–1026.

McKinnon, R. (1973), *Money and Capital in Economic Development*, Washington DC: The Brookings Institution.

Morduch, J. (1990), "Risk, Production and Savings: Theory and Evidence From Indian Households," mimeo, Harvard University, Dept. of Economics.

——— (1991), "Consumption Smoothing Across Space: Tests for Village-Level Responses to Risk," mimeo, Harvard University, Dept. of Economics.

Nelson, R. (1956), "A Theory of the Low-Level Equilibrium Trap in Underdeveloped Economies," *American Economic Review*, 46, 894–908.

Numerical Algorithms Group (1986), *The NAG Fortran Workstation Library Handbook*, Oxford, U.K.: Author.

Nurkse, R. (1953), *Problems of Capital Formation in Underdeveloped Countries*, New York: Oxford University Press.

Pakes, A., and Pollard, D. (1989), "Simulation and the Asymptotics of Optimization Estimators," *Econometrica*, 57, 1027–1057.

Pender, J. L. (1992), "Credit Rationing and Farmers' Irrigation Investments in South India: Theory and Evidence," unpublished Ph.D. thesis, Stanford University, Food Research Institute.

——— (1994), "Farmers' Investments in Irrigation Wells in the Presence of Credit Constraints: Theory and Evidence From Rural India," mimeo, Brigham Young University, Dept. of Economics.

——— (in press), "Discount Rates and Credit Markets: Theory and Evidence From Rural India," *Journal of Development Economics*, 37.

Pratt, J. (1964), "Risk Aversion in the Small and in the Large," *Econometrica*, 32, 122–136.

Rosenzweig, M. R. (1988), "Risk, Implicit Contracts and the Family in Rural Areas of Low-Income Countries," *Economic Journal*, 98, 1148–1170.

Rosenzweig, M. R., and Wolpin, K. I. (1993), "Credit Market Constraints, Consumption Smoothing, and the Accumulation of Durable Production Assets in Low-Income Countries: Investments in Bullocks in India," *Journal of Political Economy*, 101, 223–244.

Rust, J. (1987), "Optimal Replacement of GMC Bus Engines: An Empirical Model of Harold Zurcher," *Econometrica*, 55, 999–1033.

Sandmo, A. (1971), "On the Theory of the Competitive Firm Under Price Uncertainty," *American Economic Review*, 61, 65–73.

Shaw, E. S. (1973), *Financial Deepening in Economic Development*, New York: Oxford University Press.

Stiglitz, J. E., and Weiss, A. (1981), "Credit Rationing in Markets With Imperfect Information," *American Economic Review*, 71, 393–410.

Townsend, R. (1994), "Risk and Insurance in Village India," *Econometrica*, 62, 539–591.

Walker, T. S., and Ryan, J. (1990), *Village and Household Economics in India's Semi-Arid Tropics*, Baltimore, MD: Johns Hopkins University Press.

Wolpin, K. I. (1987), "Estimating a Structural Search Model: The Transition From School to Work," *Econometrica*, 55, 801–817.

Zame, W. R. (1993), "Efficiency and the Role of Default When Security Markets Are Incomplete," *American Economic Review*, 83, 1142–1164.

Zeldes, S. P. (1989), "Optimal Consumption With Stochastic Income: Deviations From Certainty Equivalence," *Quarterly Journal of Economics*, 104, 275–298.