Technology Adoption with Uncertain Profits: The Case of Fibre Boats in South India

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Abstract: We study adoption of a new technology when the profitability of the new technique differs across individuals and there is uncertainty about these individual-specific differences. We model the learning process about individual profitability with the new technology and show how such individual-specific uncertainty may result in a financing constraint when debt contracts are characterized by limited liability and limited commitment on the side of the borrower. In data from Tamil Nadu, in which fishing boats made from fibre reinforced plastic became available in 2001, we find significant evidence for individual-specific uncertainty about the profitability of the new technology. The empirical results suggest that inferring individual profitability takes more than two years - despite of the high frequency of fishing activities. Additional results imply that this uncertainty reduces the amount of external finance available for the technology switch by 30%. The resulting need for complementary self-finance creates a wealth threshold, below which adoption, even if profitable, is not feasible.

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Introduction

It is generally recognized that the adoption of new technology plays a fundamental role in the economic growth process. In the context of technology adoption by farmers, numerous recent papers have recognized the importance of complementarities and network effects that arise from the necessity of learning to use a new technology efficiently (Bandiera and Rasul, 2004; Conley and Udry, 2002, 2004; Foster and Rosenzweig, 1995). Such social learning about a new technology can give rise to an adoption S-curve and potentially calls for policies that incentivate individual agents to simultaneously adopt a new technology and thus move to a high productivity equilibrium. Another branch of empirically oriented literature on the subject models learning about the profitability of a new technology (Besley and Case, 1993, 1994).

The contribution of this paper is twofold. First we characterize a so far neglected kind of uncertainty which is important in the context of technology adoption. We provide evidence that the profitability of a new technology may significantly differ over individuals of the same village and that there is substantial uncertainty about these individual-specific differences. Second, when adoption of the new technology is costly, we show how such uncertainty leads to a credit constraint, which arises in the simultaneous presence of limited liability and limited commitment in the borrower-lender relationship.

These insights have important consequences for economic policy. In particular, poor, risk-averse entrepreneurs may not adopt for two reasons. First, uncertain profitability prospects may deter a risk-averse entrepreneur from adoption. Moreover, such individual-specific uncertainty cannot be alleviated by informational externalities of rich entrepreneurs, who adopt first, as hypothesized in Besley and Case (1994) where the new technology has a profitability common to all villagers. Second, the inherent limits to technology financing demonstrated here may make adoption unaffordable for entrepreneurs with low levels of wealth. Both of these effects can give rise to a poverty trap, in which adoption does not occur with wealth below a certain threshold - even if switching to the new technology has a positive net present value.

The novel identifying feature of our analysis is an individual-specific measure of expec-

tations about how profitable a new technology will be. By comparing these expectations with realized profits earned with the new technology, we are able to show that expectations predict actual individual profits with a substantial, non-systematic error. In contrast, all existing work on technology adoption in rural subsistence economies lacks an appropriate measure of villager's expectations about how profitable a new technology will be, at the individual as well as the aggregate level.

Methodologically, our analysis brings together a literature in labor economics on Bayesian learning about a worker's ability (e.g. Jovanovic, 1979), limited liability in interlinked contracts (see Bell and Srinivasan, 1989), and under-investment as a consequence of limited commitment. This latter issue is also known as the "holdup problem", where the impossibility of commitment by the contracting parties not to renegotiate ex-post results in under-investment ex ante (see Che and Hausch, 1999, for a general treatment and Jacoby et al., 2002, for an application to tenure insecurity and farm-plot investments). A peculiar feature of our analysis is that the holdup is a consequence not of hidden action on the side of the agent, but of hidden information on ability types of agents.

Our analysis is motivated by a capital-intensive technological innovation in the small-scale fishing sector of South India, the shift from traditional wooden to modern fibre reinforced plastic (FRP) boats, which, on average, are about fifty percent more profitable than the traditional technology. The scenario we consider is as follows. An entrepreneur, a fisherman, lacks sufficient funds to finance the new technology on his own and is thus forced to rely on external finance. There is limited liability as interest payments and the repayment of the principal have to be generated from operating the new technology. The output, the amount of fish catches on any given day, is a function of two factors. First, a stochastic element, which we take to be the boat owner's luck to find a school of fish or weather conditions. Second, the entrepreneur's inherent ability to operate the new technology, which positively affects expected output. Initially, each fisherman's ability is unknown and can only be estimated by some prior distribution, G say. As the fisherman operates the new technology, both the lender and the fisherman himself learn about his true ability through the amount of output he produces.

Lenders are risk neutral and behave competitively. This implies, first, that lending to

an entrepreneur earns an expected profit of zero at any point in time. Second, and more importantly, an entrepreneur always has the option to increase his debt by switching lenders after adoption has occurred and having the new lender settle his outstanding balance. Lenders, in turn, are eager to attract entrepreneurs who already have a record of successful catches.

Under these assumptions, we show, first, that the absence of individual-specific uncertainty about how profitably the new technology will be operated implies that the level of debt advanced to an entrepreneur before adoption is proportional to the net present value of output to be produced with the new technology. After adoption, the level of debt will not be affected by the amount of output actually produced. When individual-specific uncertainty is present, however, the expected net present value of the enterprise and thus debt will be adjusted up or downward as information on the entrepreneur's ability is revealed through the amount of output he produces. Second, when there is a limit to the extent to which debt can be adjusted downward in response to bad news about the entrepreneur's ability, the loan amount advanced to an entrepreneur whose ability is estimated by G is smaller (sometimes substantially) than the amount a lender would advance to the same fisherman with known ability equal to the mean of G.

Since an entrepreneur willing to adopt the new technology has to self-finance the difference between the cost of the boat and the amount advanced by the lender, an entrepreneur will not be able to adopt when self-finance is limited - even though the technology switch is economically viable in expectation and no risk aversion is present on either side. Among a population of entrepreneurs whose abilities are distributed according to the known distribution G, but the actual ability of each one is unknown, no single entrepreneur may obtain sufficient finance to adopt, although if abilities were known, most entrepreneurs would adopt, thus giving rise to a non-adoption trap. When wealth is distributed across entrepreneurs, sufficiently wealthy entrepreneurs may adopt while poor ones may not. This threshold effect results in an increase in inequality within a group of entrepreneurs and can, in addition, lead to economically inefficient outcomes when a wealthy but, in expectation, less able entrepreneur adopts but a poor, more able one, does not.

The rest of this paper is organized as follows. In the next section, we develop a theoretical model of dynamic lending with limited liability, limited commitment and learning about the borrower's ability. Section 2 introduces the empirical context and data. In Section 3, we present econometric results. Section 4 contains concluding remarks.

1 Background

The village we study is located in the southern part of the coast of the gulf of Bengal, close to the pilgrim center of Tiruchendur in Tamil Nadu, India. With a population of 1,500, there are 75 boats operated by about 250 men. Like many other villages along the southern coast of India, it has neither a harbor nor a jetty, a fact that restricts operations to beach-landing boats only. All year-round operating vessels have a crew of three to four men and are operated by local households. All of these households belong to the catholic fishing community of the village, which collectively converted about 400 years ago from the fisherman's Hindu cast.

On a typical day, boats leave the shore around 1am and land at the village's market place on the beach between 7 and 11 in the morning. There, local fish auctioneers market the catches to different buyers, including local traders and agents of larger fish-processing companies.

During the monsoon months, mechanized vollam-boats with a crew of five land on the village's beach to market their shrimp catches. Although the local fishing techniques, catamaran and FRP fishing, continue during this period, some boat-owners abandon their boats to enlist as wollam laborers because they find it more profitable.

The catamaran is the traditional fishing technology in southern India. Currently there are... It is a raft-like vessel made of two Alphesia logs tied together with two crossbeams at the two ends.

The beach-landing, fibre-reinforced plastic (FRP) boat is, in contrast, a recent technology. The fibre-reinforced plastic used in these crafts is a composite material made of a polymer matrix reinforced with glass fibres commonly used in aerospace and marine industries of developed countries since the 1950s. FRP boats can cope with rough surf and

are, at the same time, more comfortable, faster and more economical than catamarans. In addition, the FRP can be powered by the same 8 or 9 horsepower outboard engine, which was already commonly used with catamarans in 2000, when the FRP became available. In most cases, catamaran owners that switched to FRPs continued to use the outboard engine of the catamaran.

With the same number of laborers, FRP landings are about 50 percent bigger than those of a catamaran. Given the yields of fibre-boat fishing, every owner of a catamaran in the village we interviewed assured that he wanted to switch to a fibre boat as soon as possible. Fishing with an FRP may require a different set of skills than those needed for a catamaran since FRPs fish further into the sea.

In our study village, boat-owners typically finance about 35 percent of the cost of the FRP using own resources. The rest mainly comes from fish auctioneers who advance them loans in exchange for the right to market their catches. FRPs are generally not accepted as collateral by commercial banks.[1]

The marketing of daily fish catches involves a fairly common credit cum marketing contract that depends type of vessel used. For catumaran owners, the auctioneer gives a loan for the purchase of the gear, which at the time of our 2004 interview was between Rs. 15,000 and 25,000. In return, the boat owner agrees to sell all his daily catches through that auctioneer, who keeps 5 percent of the value of the sales. In addition, another 2 percent is kept and put into a savings account whose balance is refunded to the fisherman in December for the celebration of Christmas and New Year, the major holiday season among fishermen. The principal is never repaid. As a consequence, the commission comprises a compensation for the marketing services as well as an implicit interest payment on the amount owed.

For owners of an FRP boat, in addition to a commission of 7 percent, the auctioneer keeps another 10 percent of daily sales, which he deducts from the principal owed by

[1] Despite this evidence of credit constraints, a fibre boat rental market does not exist, possibly due to moral hazard. According to qualitative interviews conducted in the village, great diligence and attention is required in order not to damage an FRP and associated gear, such as nets, during operations. In contrast, a hired crew only seeks to maximize catches and cannot be held liable for any damage to the gear or boat.

the boat owner. Another 3 percent are kept for the savings account and are refunded in December. The feature of debt reduction allows the auctioneer to adjust the debt level downward when the fisherman's ability to use the new technology turns out to be lower than expected. As modeled in the theory section, however, the contractual terms limit the extent to which such downward adjustment can occur, which in turn will affect how the amount of credit auctioneers are willing to lend. Unlike a catamaran owner whose level of debt remains constant, an FRP owner asks his auctioneer for additional funds from time to time. If such an additional loan is granted, it is added to the fisherman's outstanding balance and does not bare any extra interest. In our data sample of FRP owners, the loan balance is increased every five months on average. The data shows that the boat owner never makes lumpy repayments of the principal, possibly because on any given day, the liability of the boat owner is limited by the catches obtained.

Regardless of the type of boat used, the contract can be terminated by the boat owner at any time if he can pay off his outstanding loan balance. When a boat owner switches auctioneers, the new auctioneer settles the debt with the previous one. Switching of auctioneers does occur occasionally. According to villagers, the superiority of this interlinked share arrangement over separate debt and marketing contracts is a result of, first, limited liability of the fisherman and, second, costless monitoring of the fisherman's day-to-day success by the auctioneer.[2]

It is interesting to note that all nine auctioneers in the village use the same contract terms. There is no menu of contracts, as would be expected if auctioneers adjusted the debt reduction share to reflect the priors about the ability of their clients to operate the FRP. In addition, if the capital required to finance the new FRP boat varies across prospective boat owners, auctioneers could adjust the commission share since as shown in the theory section, the higher the commission, the higher the amount of credit that auctioneers are willing to advance. In any event, this uniformity of contractual parameters within a village is a well-documented fact (see e.g. Shaban, 1987, for share contracts

[2]Limited liability is also Basu's (1992) key argument for the predominance of share contracts in agricultural areas of low income countries. Platteau and Nugent (1992) provide a useful general discussion of contract choice in fisheries of low-income economies.

in agriculture) and has been attributed to either collective bargaining (Datt, 1996) or bounded rationality (Singh, 1989). In interviews, fishermen responded that a higher rate of commission would be usurious and unacceptable.

Because all fish is auctioned at the same marketplace and observed by all auctioneers, information about the performance of individual boat owners is costlessly observed by everyone. Moreover, auctioneers keep detailed hand-written records of daily sales and loan transactions for each of their clients with are given to them at the end of the year. Thus, each boat owner can document precisely his record of catches.

2 The Model

In this section, we adapt the firm-worker model of Harris and Hölmstrom (1982) to our auctioneer-boat owner context described in the previous section. We consider a population of auctioneers (principals) providing funds to boat owners (agents) in order to finance a new technology, the FRP boat. As discussed above, auctioneers operate in a competitive environment and earn zero expected profits. The only input provided by auctioneers is credit and boat owners can switch auctioneers at no cost.[3]

2.1 Stochastic Output and Learning about Ability

A boat owner i of profitability type θ_i who uses an FRP boat produces in a given day t

$$y_{it} = f(\theta_i, \epsilon_t) = \theta_i + \epsilon_{it}$$

where ϵ_t is a realization of a random shock that is normally distributed with mean 0 and variance 1. Thus, like in the analysis of Harris and Hölmstrom (1982), we eliminate any moral hazard consideration by assuming that workers do not dislike effort and supply labor inelastically.

[3] The assumption of perfect competition among moneylender/traders has also been made by Bell and Srinivasan (1989) in a model of interlinked credit and marketing in agriculture. It is also studied by Petersen and Rajan (1995) in the context of bank competition.

When a boat owner begins to operate the new technology, his profitability is not known with certainty. To allow for aggregate as well as individual specific uncertainty about profitability, we decompose

$$\theta_i = \psi + \nu_i.$$

Initial beliefs about ψ (that is before the first fisherman adopts) are distributed normally with mean $\widehat{\psi}_0$ and variance σ^2_ψ. The additional term ν_i, on the other hand, may be viewed as an individual-specific random effect, which is normally distributed with mean zero and variance σ^2_ν. We will assume that, like in a random effects model, ν_i is distributed independently across individuals.

We consider a population of m fishermen who simultaneously adopt the new technology. As output is observed, beliefs are updated. In accordance with the previous section, because the history of catches of a given boat owner is verifiable at no cost by all auctioneers, we assume that all information, in particular all fishermen's sales, is common knowledge and thus all auctioneers and boat owners share common beliefs about θ at every period[4].

Employing the familiar Bayesian updating formula, it follows that beliefs about θ_{it} in any period t are normally distributed, which we will denote as

$$\widetilde{\theta}_{it} \sim N(\widehat{\theta}_{it}, \sigma^2_{\theta t}),$$

where $\widetilde{\theta}_{it}$ denotes the random variable specifying beliefs about θ_{it}. At date zero, $\widehat{\theta}_{i0} = \widehat{\psi}_0$ and $\sigma^2_{\theta 0} = \sigma^2_\psi + \sigma^2_\nu$.The updated parameters mean profitability is given as

$$\widehat{\theta}_{it} = \frac{t\sigma^2_v}{1 + t\sigma^2_v}\overline{y}_{it} + \frac{tm\sigma^2_\psi}{(1 + t\sigma^2_\psi)\left[1 + t(m\sigma^2_\psi + \sigma^2_\nu)\right]}\overline{\overline{y}}_t + \frac{1}{tm\sigma^2_\psi + t\sigma^2_\nu + 1}\widehat{\psi}_0, \tag{1}$$

where $\overline{y}_{it}$ is the average performance of i over the first t time periods,

$$\overline{y}_{it} = \frac{1}{t}\sum_{\tau=1}^{t} y_{i\tau},$$

and $\overline{\overline{y}}_t$ is the average performance in the population,

$$\overline{\overline{y}}_t = \frac{1}{m}\sum_{i=1}^{m} \overline{y}_{it}.$$

[4]We test this assumption in the next section.

The updated variance is

$$\sigma_{\theta t}^2 = \frac{\sigma_\psi^2 + \sigma_\nu^2 + tm\sigma_\psi^2\sigma_\nu^2 + t\sigma_\psi^2}{(1 + t\sigma_\nu^2)(1 + tm\sigma_\psi^2 + t\sigma_\nu^2)}. \tag{2}$$

Both boat owners and auctioneers are risk neutral and discount the future at rate β. Because boat owners have linear preferences, they do not resent consumption fluctuations and will save whatever income they obtain from the old technology (catamaran) until the accumulated savings in addition to the initial loan from the auctioneer covers the cost of the FRP boat. The rest of this section is devoted to characterizing the initial and future loans advanced by the auctioneer.

2.2 The Debt Contract

Suppose that on a given day t, the boat owner owes D_t to the auctioneer. According to the terms of the contract, the auctioneer, say A, keeps the fraction $\gamma + \mu$ of the sales revenue, where γ is the commission that covers the auctioneer's cost of capital and the fraction μ is used to reduce the principal D_t.

Thus far, the boat owner's debt would be reduced by μy_t every day and would eventually be completely repaid. As noted in the previous section, however, additional loans are granted, thereby increasing the debt level after varying time periods. Because boat owners and auctioneers discount the future at the same rate, it can be shown that boat owners prefer receiving additional credit to repaying their current debt. In addition, competition among auctioneers implies that at the end of any given day the boat owner can switch auctioneers, from A to A', say, provided that auctioneer A' is willing to settle the boat owner's debt with auctioneer A and grant him additional funds. We denote by V_t the amount that auctioneer A' has to pay auctioneer A to settle the boat owner's debt. In essence, V_t reflects the equilibrium value of the right to market the boat owner's catches. Thus, after each day, auctioneer A will be indifferent between keeping the boat owner as a client or losing him to auctioneer A' in exchange for V_t. If the equilibrium V_t is lower than current debt D_t, the boat owner is over-indebted and auctioneer A makes a loss equal to $D_t - V_t$ when settling the boat owner's debt. In addition to settling the boat owner's debt

with auctioneer A, auctioneer A' may grant a new loan of d_t to the boat owner. The new debt level that the boat owner owes to auctioneer A' will be $V_t + d$. This completes the transactions on day t.

Next, we characterize the equilibrium debt values under two informational regimes. First, the hypothetical regime of full information, where θ_i is known to both auctioneers and boat owners. Second, the true regime where θ_i is unknown but inferred over time.

2.3 Lending with no Profitability Uncertainty

The case where individual profitability is known and public knowledge serves as a useful benchmark. We are interested in the amount of debt, denoted $\overline{D}(\theta_i)$, that an auctioneer making zero profits is willing to extend to a boat owner of profitability type θ_i. Because the auctioneer earns the fraction γ of the boat owner's daily catches, perfect competition among auctioneers implies the maximum loan any auctioneer is willing to extent should equal to the present value of the infinite stream of revenues from commissions. More formally, it must be the case that,

$$\overline{D}(\theta_i) = E\left[\sum_{t=1}^{\infty} \beta^t \gamma y_{it}\right] = \sum_{t=1}^{\infty} \beta^t \gamma \int y\, \phi(y;\theta_i)\, dy = \frac{\beta\gamma\theta_i}{1-\beta}, \tag{3}$$

where $\phi(y;\theta_i)$ is the normal density of daily output because by assumption $Y_{it} \sim N(\theta_i, 1)$. From Equation 3 it is clear that the equilibrium debt increases with the revenues from commissions, either because of a higher commission share γ or a higher profitability θ_i. However, it does not depend on the reduction parameter μ. In practice, the *observed* debt level always coincides with the *equilibrium* debt level and thus, the degree to which the boat owner is liable to repay the loan is irrelevant because any reduction of the debt is given back to the boat owner in the form a new loan so that the debt level is always the equilibrium one.

The value $V \equiv V^F(D, \theta_i)$ (F for full information) is the expected stream of income derived by auctioneer A from marketing the catches of a boat owner of profitability θ_i that owes him D. If the boat owner becomes auctioneer A''s new client, auctioneer A' agrees to give a new loan d to the boat owner. After production, the new debt is reduced

by μy_{it} and the auctioneer collects γy_t as commission. In equilibrium, no auctioneer will want to lend more than $\overline{D}(\theta_i)$. Thus, if the boat owner has debt D satisfying $D \leq \overline{D}(\theta_i)$, then $d = D^*(\theta_i) - D$, otherwise, if $D > \overline{D}(\theta_i)$, then $d = 0$. More formally,

$$\begin{aligned} V^F(D, \theta_i) &= -d + \beta \int \left[(\gamma + \mu)y + V^F(D + d - \mu y, \theta_i)\right] \phi(y; \theta_i) dy \\ &\quad \text{where} \quad d = \max\{\overline{D}(\theta_i) - D, 0\}. \end{aligned} \tag{4}$$

The loss that an auctioneer would experience if he sold the rights to market the catches of a boat owner with profitability θ who owes him D is simply

$$L^F(D, \theta_i) = D - V^F(D, \theta_i), \tag{5}$$

because D is the amount owed to the auctioneer and $V^F(D, \theta_i)$ is amount that in equilibrium the auctioneer would receive from another auctioneer. This functional equation does not have a closed form solution when the debt reduction parameter satisfies $0 < \mu < 1$. In the Appendix, we solve for the loss function in the case where the boat owner has unlimited liability, that is, when the boat owner can access funds other than current catches in order to reduce the debt to the equilibrium level after every period, $\mu \in [0, \infty)$, and the case where the boat owner has limited liability so that there is no debt reduction at all, $\mu = 0$.

2.4 Lending with Profitability Uncertainty

When individual profitability is inferred over time, the amount V_t depends not only on the debt level and expected profitability but also on the precision of the prior on profitability. To keep the analysis tractable, we focus on individual-specific uncertainty in this subsection, i.e. we assume that $\sigma_\psi^2 = 0$. The equivalent of Equation 4 is given by

$$\begin{aligned} V(D, \widehat{\theta}_{it}, \sigma_{\theta t}^2) &= -d + \beta \int \left[(\gamma + \mu)y + V(D - \mu y + d, \widehat{\theta}_{i,t+1}(y), \sigma_{\theta t+1}^2)\right] \phi(y; \widehat{\theta}_{it})\, dy \\ &\quad \text{where} \quad d = \max\{D^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2) - D, 0\} \end{aligned} \tag{6}$$

and $\widehat{\theta}_{i,t+1}(y)$ and $\sigma_{\theta t+1}^2$ are updated given sales y according to the equations in (1) and (2). The equilibrium debt level $D^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2)$ is defined as the largest loan that an auctioneer is

willing to lend to a boat owner with uncertain profitability given by mean prior $\widehat{\theta}_{it}$ and variance $\sigma^2_{\theta t}$.

As before, the Appendix contains the solutions to the loss functions for the unlimited and limited liability cases. We now characterize in more detail the equilibrium debt level under these two liability cases.

2.4.1 Unlimited Liability: Full Debt Adjustment

When a fisherman's liability for reduction of the principal is unlimited, even if his profitability is uncertain, the equilibrium debt level $D^*_\infty(\widehat{\theta}_{it}, \sigma^2_{\theta t})$, where subscript ∞ denotes unlimited liability, is equal to the one when individual profitability is known. Intuitively, mistakes about the boat owner's true profitability can be corrected at no cost by requiring that the boat owner fully adjusts the debt to its desirable level. Thus, only the mean prior $\widehat{\theta}_{it}$ (and not the precision) plays a role in determining the equilibrium debt. The following proposition states this result more formally which is proved in the Appendix.

Proposition 1 *When individual profitability is uncertain and liability for adjustment of the principal is unlimited, the equilibrium debt level is* $D^*_\infty(\widehat{\theta}_{it}, \sigma^2_{\theta t}) = \overline{D}(\widehat{\theta}_{it})$.

In the following subsection, we show that, in contrast, mistakes about boat owners' true profitability are costly when they have limited liability.

2.4.2 Limited Liability: No Debt Adjustment

In this case, the auctioneer cannot adjust the boat owner's debt. Thus, if the boat owner turns out to be of a lower than expected profitability, the auctioneer incurs a cost. The higher the uncertainty about the boat owner's true profitability, or equivalently, the lower the precision, the higher the probability of making mistakes.

The following proposition shows that auctioneers optimally respond to this situation by reducing the equilibrium debt $D^*_0(m, h)$ (0 for limited liability) below that of known profitability.

Proposition 2 *When individual profitability is uncertain and there is no debt reduction, the equilibrium debt level is given by*

$$D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2) = \overline{D}(\widehat{\theta}_{it}) - \frac{\beta}{1-\beta} \int L_0(D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2), \widehat{\theta}_{i,t+1}(y), \sigma_{\theta t+1}^2)\phi(y; m)\, dy.$$

The equilibrium debt level $D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2)$ is strictly increasing in $\widehat{\theta}_{it}$ and decreasing in $\sigma_{\theta t}^2$, and

$$\lim_{\sigma_\theta^2 \to 0} D_0^*(\widehat{\theta}_{it}, \sigma_\theta^2) = \overline{D}(\widehat{\theta}_{it}).$$

The expression for the equilibrium debt $D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2)$ is analogous to the optimal wage equation in Harris and Holmstrom (1982). Indeed, one can write

$$\begin{aligned} D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2) &= \overline{D}(\widehat{\theta}_{it}) - z(\widehat{\theta}_{it}, \sigma_{\theta t}^2), \\ \text{where} \quad z(\widehat{\theta}_{it}, \sigma_{\theta t}^2) &= \frac{\beta}{1-\beta} \int L_0(D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2), \widehat{\theta}_{i,t+1}(y), \sigma_{\theta t+1}^2)\phi(y; \widehat{\theta}_{it})\, dy \end{aligned}$$

In the Appendix, we show that $z(\widehat{\theta}_{it}, \sigma_{\theta t}^2) > 0$, $z(\widehat{\theta}_{it}, \sigma_{\theta t}^2)$ is increasing in its second argument, and that it converges to zero as precision increases. Thus, $D_0^*(\widehat{\theta}_{it}, \sigma_{\theta t}^2) < \overline{D}(\widehat{\theta}_{it})$ but converges to the limit point $\overline{D}(\widehat{\theta}_{it})$ as learning proceeds.

An important feature of our setup is that of limited commitment due to competition among auctioneers. The fact that boat owners are free to end their relationship with an auctioneer if another one is willing to advance them more money is key to this under investment result. If exclusive contracts could be written between auctioneers and boat owners, then auctioneers would cover ex-post losses from worse than expected boat owners with ex-post profits from better than expected boat owners. But due to limited commitment, auctioneers can never make a profit from better than expected boat owners since there will always be another auctioneer that is willing to bid him away by offering him the updated (and larger) equilibrium debt level. Thus, when the boat owner has limited liability and individual profitability is unknown, competition among auctioneers creates an asymmetry between zero profits from better than expected boat owners and sure losses from worse than expected boat owners. The auctioneer's optimal response to

this situation is to reduce the equilibrium debt level. We will refer to such behavior as "cautious lending" in the sequel.[5]

3 Data

We surveyed the study village in 2002 and 2004, and 2006 collecting detailed lending and sales data from auctioneers. We use data from eight auctioneers catering to 39 fishermen. The sample underlying the empirical analysis thus comprises a panel of financial data of 39 owners of FRPs and 62 months, the time of the first adoption of a fibre boat in the village, January of 2001, to February 2006. Descriptive statistics are set out in Table 1.

4 Empirical Analysis

The objective of this section is twofold. First, we seek to test for uncertainty about profitability and, if it exists, characterize the nature of it. Our second goal is to test whether initial lending is cautious in the sense of Section 2.4.2 and, if so, to which extent. We start out, however, by examining some fundamentals underlying the previous theoretical analysis.

4.1 Dynamics of Individual Sales

A particular assumption of the learning model in section 2 is that individual profitability does not exhibit a trend, apart from a common trend. Recall that $\theta_{it} = \psi + \nu_i$. While our subsequent analysis will accomodate for potential trends in ψ, our interest is in whether individual profitability is stationary controlling for a common trend. Toward this, we estimate

$$y_{it} = a_i + \sum_{k=1}^{5} b_k yearsex(k)_{it} + \sum_{k=2001}^{2006} c_k year(k)_t + \varepsilon_{it},$$

where i indexes fishermen and t months since adoption. $yearsex(k)_{it}$ is a dummy variable capturing the year (k) since fibre boat adoption (range from one to five) and $year(k)_t$

[5] This is also found in the context of bank competition by Petersen and Rajan (1995).

is a dummy for the year (ranges from 2001 to 2006). In principle, there are at least two reasons to expect a positive relationship between time since adoption and sales. First, learning by doing, that is the fisherman operates the new technology more efficiently as he gathers experience. Second, the price of output, fish, may increase over time because of the general inflationary process.

The results are set out in Table 2. For this estimation we use all individuals who started fibre boat fishing with a commercial auctioneer. We thus also include sales observations from such individuals from the time when they switched to an NGO auctioneer subsequently, which happened to 11 of the 39 individuals in this sample. The specification in column 1 has only the $yearsex(k)$ dummies, which are not individually significant. An F test of the joint hypothesis that all b coefficients equal zero, which attains a $p-$value of 0.07. Column two reproduces estimates of the the full specification. With the inclusion of year dummies, sales do not exhibit a trend pattern in a significant way. In particular, the associated F test has a $p-$value larger than 10 per cent.

4.2 Reduced Form Analysis of Debt

The objective of this section is twofold. First, we seek to determine whether there is evidence for individual-specific profitability uncertainty, which will be reflected by the adjustment of debt to observed individual output. Second, we will address the issue of cautious lending and attempt to measure its extent.

4.2.1 Testing for Learning

Recall that, in the unlimited liability model

$$D(\widehat{\theta}_{it}) = \frac{\gamma}{r}\widehat{\theta}_{it},$$

where we denote $(1-\beta)/\beta$ by r for convenience. In order to not attribute different individual scales of production to observed performance, we will consider a slightly more general model in which individual sales $Z_{it} = x_i Y_{it} \sim N(x_i\widehat{\theta}_{it}, x_i^2)$. The individual scale of

production is known by villagers but unobserved by the researcher. Using (1), this gives

$$D_{it} = \frac{\gamma}{r} x_i \widehat{\theta}_{it} = \frac{\gamma}{r} x_i (w_1(t)\overline{y}_{it} + w_2(t)\overline{\overline{y}}_t + w_3(t)\widehat{\psi}_0).$$

Accordingly, we will consider

$$\frac{D_{it}}{D_{i0}} = \frac{\widehat{\theta}_{it}}{\widehat{\theta}_{i,0}} = \frac{w_1(t)\overline{y}_{it} + w_2(t)\overline{\overline{y}}_t + w_3(t)\widehat{\psi}_0}{\widehat{\psi}_0}.$$

Under the null hypothesis of no individual-specific uncertainty, σ_ν^2 in (1) is equal to zero which implies that $w_1 = 0$ for all t. Whenever σ_ν^2 is larger than zero, on the other hand, w_1 approaches one as t grows large. and wAs $\overline{\overline{y}}_t$ is only partially observed by us (there are non-negligible gaps in our sales data), we proxy for $\overline{\overline{y}}_t$ with a piece-wise constant function. Our regression specification is thus

$$\frac{D_{it}}{D_{i0}} = \sum_{k=1}^{5} a_k year(k)_t + b(\overline{z}_{it}/D_{i0}) + \varepsilon_{it},$$

where a_t captures the unobserved process $(w_2\overline{\overline{y}}_t + w_3\widehat{\psi}_0)/\widehat{\psi}_0$ and the null hypothesis of no individual-specific uncertainty amounts to $b = 0$. Notice that the estimate of b captures on $w_1 r/\gamma$, where we expect r/γ to be on the order of one half as $\gamma = 0.07$ and 3 to 4 per cent per month are a realistic estimate of the opportunity costs of capital in the study village.

The results are set out in table 3, column 1. The coefficient on individual sales normalized performance is positive and highly significant. The point estimate of 1.1 moreover implies a value of w_1 of around one half, which is of course well in between its starting value of zero at the time adoption and one, the limiting value for large t. The year fixed effects indicate that, controlling for individual learning, debt levels increased in the aggregate. In particular, the dummies exhibit a steady upward trend and for 2001, 2002, 2003 and 2004, the coefficients are all significantly smaller than the remaining two later ones.

Provided that $\sigma_\nu^2 > 0$, the updating equation as formalized by (1) also implies that $w_1(t)' > 0$. Toward testing for this, we estimate

$$\frac{D_{it}}{D_{i0}} = \sum_{k=1}^{2006} a_k year(k)_t + \sum_{k=1}^{5} c_k yearsex(k)_{it} + \sum_{k=1}^{5} b_k yearsex(k)_{it}(\overline{z}_{it}/D_{i0}) + \varepsilon_{it}.$$

The results are set out in column two of table 3. As predicted by our learning model, the b coefficients are steadily increasing from the first to the fourth year. The coefficient for the fifth year, which is smaller than zero, is puzzling and may suffer, first, from a relatively small number of observations (31) and, second, from the events following the tsunami in December 2004. In particular, all debt renegotiations in this category occurred after that date. In the same vein, the dummy for the fifth year is markedly larger than for the year before, which may be a product of extra emergency credit being disbursed to a fishermen whose material was damaged and who thus had lower sales than usually corresponding to his profitability.

4.2.2 Testing for Cautious Lending

Finally, holding w_1 constant, we attempt to test for the incidence of cautious lending. Toward this, we estimate

$$\frac{D_{it}}{D_{i0}} = \sum_{k=1}^{5} a_k year(k)_t + \sum_{k=1}^{5} c_k yearsex(k)_{it} + b(\overline{z}_{it}/D_{i0}) + \varepsilon_{it}.$$

An upward trend in the c coefficients provides evidence for cautious lending as, in the absence of it, debt does not exhibit a trend when learning about individual and aggregate profitability is controlled for. According to the results in column 3 of table 3, such a trend in fact occurs. The extent is, moreover, economically significant. Taking into account the mean of the variable $\overline{z}_{it}/D_{i0}$, which is roughly 0.49, the point estimates imply that normalized debt increases from around 1.0 in the first to 2.1 in the fifth year, which implies that debt effectively doubles over that period of time. Notice that this result is net of aggregate time effects.

4.3 Structural Analysis of Debt

In this section, we take the structure of learning implied by Bayesian updating and the nature of cautious lending fairly literal and conduct a structural estimation. This has the additional benefit of allowing us to control for additional changes in the environment, such as changes in the opportunity cost of funds on the side of auctioneers. To derive the

structural econometric model, first notice that w_3 in (1) is of order $(tm)^{-1}$, while w_2, as well as $1 - w_2$, is of order t^{-1}. As adoption occurred fairly quickly within the village, i.e. m increased rapidly from its initial value of 5, we normalize w_3 to zero. We consequently write

$$D_{it} = \frac{\gamma}{r(t)} x_i \zeta(t - t_{i0}) \left[w_1 \overline{y}_{it} + (1 - w_1) \widehat{\psi}_t \right] = \frac{\gamma}{r(t)} x_i \zeta(t - t_{i0}) \left[w_1 \frac{\overline{z}_{it}}{x_i} + (1 - w_1) \widehat{\psi}_t \right],$$

where $r(t)$ captures the time dependence of r and $\zeta(\ )$ captures the possibility of cautious lending (which corresponds to $\zeta' > 0$ and $lim_t \zeta(t) = 1$). Further,

$$D_{i0} = \frac{\gamma}{r(t_{i0})} x_i \zeta(0) \widehat{\psi}_{ti0}.$$

The ratio then is

$$\begin{aligned} \frac{D_{it}}{D_{i0}} &= \frac{r(t_{i0})}{r(t)} \frac{\zeta(t - t_{i0})}{\zeta(0)} \left[\frac{w_1 \overline{y}_{it}}{\widehat{\psi}_{ti0}} + (1 - w_1) \frac{\widehat{\psi}_t}{\widehat{\psi}_{ti0}} \right] \\ &= \frac{r(t_{i0})}{r(t)} \frac{\zeta(t - t_{i0})}{\zeta(0)} \left[w_1 \gamma \frac{\overline{z}_{it}}{D_{i0}} \frac{\zeta(0)}{r(t_{i0})} + (1 - w_1) \frac{\widehat{\psi}_t}{\widehat{\psi}_{ti0}} \right]. \end{aligned} \tag{7}$$

We parametrize

$$r(t) = \exp\left(\sum_{k=1}^{2006} r_k year(k)_t \right),\ \zeta(t) = \exp\left(\sum_{k=1}^{5} \zeta_k year(k)_t \right),\ \widehat{\psi}_t = \exp\left(\sum_{k=1}^{5} \widehat{\psi}_k year(k)_t \right). \tag{8}$$

Since the model only identifies $\widehat{\psi}_t - \widehat{\psi}_{t_{0i}}$, we restrict $\widehat{\psi}_0$ to zero. Similarly, as only $r_{t_{0i}} - \zeta_1$ is identified, we restrict ζ_1 to zero. The regression model is obtained from taking the difference between the logarithm of the left and right hand sides of equation (7) and minimizing the resulting sum of squared residuals.

The results of this exercise are set out in table 4. The first column gives results in which w_1 is forced to stay constant over time since adoption. The parameter w_1 is estimated positive, at 0.26, and significant. Opportunity costs of lenders exhibit a fair amount of fluctuation, especially during the first three years. We also find some evidence for aggregate uncertainty, which is manifested by the negative and significant $\widehat{\psi}$ coefficients. Taking these results together with those of the reduced form analysis, it appears that

the secular factors opportunity cost of funds and ability estimates roughly cancelled each other out to yield no significant variation over time in the reduced form analysis. The more interesting results are those of the ζ parameters. From the first to the second year, there is a dramatic increase, from zero to 0.45, in this number, and an additional increase to 0.88 another 3 years later. This suggests that lenders act cautiously to a significant extent. According to these point estimates, cautious lending may amount to more than one third.

Column 2 gives the results for a more flexible parametrization of w_1, which is analogous to (8). Since the numerical minimization does not converge when different values of w_1 are allowed for each year, the values for the last two years are restricted to be equal. In accordance with the theoretical model, we find strong evidence for uncertainty about individual profitability, which is manifested by a steady upward trend in the w_1 parameters over time since adoption. Cautious lending, on the other hand, is less pronounced in this set of results. A Wald test of the hypothesis that all ζ parameters are zero, is nevertheless rejected ($p-$value: 0.001). In contrast to the first set of results, the fluctuation in the path of ψ is much weaker. In fact a Wald test of the hypothesis that all ψ coefficients are zero fails to reject at conventional levels ($p-$value: 0.133).

5 Concluding Remarks

We have identified an important feature for the adoption of a new technology whose revenue is highly dependent on the context in which it is operated. For fishermen in a South-Indian village, we have established that individual-specific uncertainty about how successfully an entrepreneur will operate a new technology is substantial and that it takes well over a year until this uncertainty is resolved. Such uncertainty may deter poor entrepreneurs from switching to the new technology for at least two reasons. First, if poor individuals are more reluctant to bear risk than wealthy ones, a poor entrepreneur may not make the technology switch while a wealthy one may. Moreover, since this uncertainty is individual-specific, it cannot be resolved by others who move first, as is the case in models of learning by doing (Foster and Rosenzweig, 1995) or when the new

technology has an identical value for all entrepreneurs (Besley and Case, 1994). Instead such uncertainty calls for an insurance scheme for poor entrepreneurs, which mitigates the risk implied by the lack of knowledge about one's own ability. In this connection, it has to be applauded that the observed arrangement through which the new technology, the FRP, is financed, takes the form of a share contract, which shifts part of the risk from the small-scale entrepreneur to a lender/trader, who is in a position to insure individual risks.

On the downside, however, we find that contracts are such that the borrower cannot fully commit to the lender, which results in lenders not being able to fully bundle the risk of individual-specific uncertainty about ability. As a consequence, ex post successful entrepreneurs cross-subsidize unsuccessful ones in only a limited fashion, which in turn results in reduced initial finance compared to the case of full cross-subsidization. This financial constraint constitutes a second reason for why a poor entrepreneur is excluded from enjoying the fruits of the new technology: lack of self-finance. This market imperfection calls for either an insurance scheme for lenders, which mitigates the risk of being locked-in with an ex post unsuccessful entrepreneur, or additional subsidized, uncollateralized credit for entrepreneurs, which makes up for the financing constraint generated by ability uncertainty and limited commitment.

To summarize, we have identified two channels through which individual-specific uncertainty can create a threshold effect and poverty trap. In the absence of policy interventions like insurance schemes or subsidized credit, the scenario portrayed here can create dynamics of sharpening inequality, where initially wealthy households enjoy the fruits of income growth through technological progress, while the poor are excluded.

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6 Appendix

Here we provide the solution to the loss functions which characterize the optimal behavior of auctioneers for both informational regimes. In addition, we provide the proofs to the propositions that appear in the text.

6.1 Full Information

The loss function in Equation 5 has no closed form solution. In what follows, we provide instead the solution to the loss function for the unlimited liability case of $\mu \in [0, \infty)$ and for the limited liability case of $\mu = 0$. These loss functions provide the lower and upper bound to the general case where μ satisfies $0 < \mu < 1$.

6.1.1 Full Debt Reduction

When the debt adjusts immediately to its equilibrium level, the debt reduction parameter μ satisfies

$$\mu = \max\left\{\frac{D - \overline{D}(\theta)}{y}, 0\right\}. \tag{9}$$

The following proposition gives the closed form solution to the loss function $L_{\infty}^{F}(D,\theta)$, where the subscript ∞ denotes the case of unlimited liability where $\mu = [0,\infty)$.

Proposition 3 *When ability is known and there is full debt reduction, the loss function is given by*

$$L_{\infty}^{F}(D,\theta) = \max\left\{0, (1-\beta)[D - \overline{D}(\theta)]\right\}$$

Proof. Let $D < \overline{D}(\theta)$. From Equation 9 we have that $\mu = 0$. Thus, we rewrite Equation 4 as

$$\begin{aligned} V_{\infty}^{F}(D,\theta) &= D - \overline{D}(\theta) + \beta \int \left[\gamma y + V_{\infty}^{F}(\overline{D}(\theta),\theta)\right] \phi(y;\theta)\, dy \\ &= D - \overline{D}(\theta) + \beta \left[\gamma\theta + V_{\infty}^{F}(\overline{D}(\theta),\theta)\right]. \end{aligned} \tag{10}$$

In addition,

$$\begin{aligned} V_{\infty}^{F}(\overline{D}(\theta),\theta) &= \beta \left[\gamma\theta + V_{\infty}^{F}(\overline{D}(\theta),\theta)\right] \\ &= \frac{\beta\gamma\theta}{1-\beta} = \overline{D}(\theta). \end{aligned} \tag{11}$$

Combining the expressions in 10 and 11 and simplifying we obtain $V_{\infty}^{F}(D,\theta) = D$. Therefore,

$$L_{\infty}^{F}(D,\theta) = 0, \quad \text{for all} \quad D \leq \overline{D}(\theta)$$

Now let $D > \overline{D}(\theta)$ so that $\mu = \frac{D-\overline{D}(\theta)}{y}$. Thus,

$$\begin{aligned} V_{\infty}^{F}(D,\theta) &= \beta \int \left[\gamma y + D - \overline{D}(\theta) + V_{\infty}^{F}(\overline{D}(\theta),\theta)\right] \phi(y;\theta)\, dy \\ &= \beta \left[\gamma\theta + D\right]. \end{aligned}$$

Thus, when $D > \overline{D}(\theta)$ the loss function is

$$L_{\infty}^{F}(D,\theta) = D - V_{\infty}^{F}(D,\theta) = (1-\beta)\left[D - \overline{D}(\theta)\right]$$

Combining the expressions just derived for $L_{\infty}^{F}(D,\theta)$ we obtain the desired result. ■

The expression for the loss function is very intuitive. When $D \leq \overline{D}(\theta)$ the boat owner is under-indebted and thus the right to market his catches can be sold without incurring a

loss. When the debt level is higher than the equilibrium level $\overline{D}(\theta)$ the auctioneer incurs a loss given by the difference between the actual and equilibrium debt levels discounted one period. The one period discount appears in the formula because the debt will be fully adjusted the following period, thus limiting the loss to only the current period.

6.1.2 No Debt Reduction

When the debt reduction parameter $\mu = 0$ the expression for the loss function $L_0^F(D, \theta)$ (subscript 0 for no debt reduction) is given in the following proposition.

Proposition 4 *When ability is known and there is no debt reduction, the loss function is given by*

$$L_0^F(D, \theta) = \max\left\{0, D - \overline{D}(\theta)\right\}$$

Proof. The case when $D \leq \overline{D}(\theta)$ is shown in Proposition 3. So let $D > \overline{D}(\theta)$.

$$\begin{aligned} V_0^F(D, \theta) &= \beta \int \left[\gamma y + V_0^F(D, \theta)\right] \phi(y; \theta)\, dy \\ &= \beta \left[\gamma\theta + V_0^F(D, \theta)\right] \\ &= \frac{\beta\gamma\theta}{1 - \beta} = \overline{D}(\theta). \end{aligned}$$

Thus, when $D > \overline{D}(\theta)$ the loss function is

$$L_0^F(D, \theta) = D - V_0^F(D, \theta) = D - \overline{D}(\theta).$$

and again combining expressions we obtain the desired result. ■

In this case, when the debt is above $\overline{D}(\theta)$, the loss suffered by the auctioneer if he sold the right to market the boat owner's catches is equal to the difference between the actual debt level D and the equilibrium one $\overline{D}(\theta)$ because the debt is never adjusted. Given the solution for no reduction and full reduction, we conclude that the loss function

$$L^F(D, \theta) \in \left(L_\infty^F(D, \theta), L_0^F(D, \theta)\right)$$

when $D > \overline{D}(\theta)$ for the case of $0 < \mu < 1$.

As mentioned in the text, the equilibrium debt level only depends on the commission share γ, but not on the reduction parameter μ. Because in equilibrium the observed debt level of a boat owner with ability θ will never exceed the equilibrium debt level $\overline{D}(\theta)$, the region where the loss function $L^F(D,\theta)$ is positive and depends negatively on μ is never attained. As we will see in the following subsection, this is no longer the case when ability is uncertain.

6.2 Learning

Similar to the Full Information regime, we now provide the solution to the loss function for the unlimited and limited liability case when ability is unknown but inferred over time. Again, as before, these loss functions provide the lower and upper bound to the solution of the general case when $0 < \mu < 1$.

6.2.1 Full Debt Reduction

When μ can be set every period in such a way that the next period's debt level is the equilibrium one, the next period debt level must either be the current equilibrium debt level for relatively high realizations of output y (because)and equal to the updated equilibrium debt level for relatively low realizations of y. More formally, μ must be such that

$$D + d - \mu y = \min\left\{D^*_\infty(m', h'), D^*_\infty(m, h)\right\}.$$

Solving for μ in the expression above we obtain

$$\mu = \frac{\max\left\{D^*_\infty(m,h), D\right\} - \min\left\{D^*_\infty(m',h'), D^*_\infty(m,h)\right\}}{y} \tag{12}$$

The following proposition extends Proposition 1 to also provide the solution to the loss function.

Proposition 5 *When ability is uncertain and there is full debt reduction, the equilibrium debt level is $D^*_\infty(m,h) = \overline{D}(m)$. In addition, the loss function is given by*

$$L_\infty(D,m,h) = \max\left\{0, (1-\beta)[D - \overline{D}(m)]\right\}$$

Proof. Let $D < D^*_\infty(m,h)$. By definition, since $D^*_\infty(m,h)$ is the maximum amount of debt any auctioneer is willing to lend a boat owner whose uncertain ability have mean prior m and precision h, it must by the case that $L_\infty(D,m,h) = 0$ for $D < D^*_\infty(m,h)$, since the auctioneer can sell the right to market the boat owner's catches without incurring a loss. According to Equation 12, if $D^*_\infty(m,h) < D^*_\infty(m',h')$, then $\mu = 0$. Otherwise, if $D^*_\infty(m,h) \geq D^*_\infty(m',h')$, then $\mu = \frac{D^*_\infty(m,h) - D^*_\infty(m',h')}{y}$. Using these expressions for μ and the fact that $V_\infty(D,m,h) = D$ which follows from $L_\infty(D,m,h) = 0$, for all $D \leq D^*_\infty(m,h)$, we can write the analog of the integral in Equation 6 defining $V_\infty(D,m,h)$ as

$$\int \left[(\gamma+\mu)y + V_\infty(D^*_\infty(m,h) - \mu y, m', h')\right] f(y;m)\, dy = \gamma m + D^*_\infty(m,h).$$

Thus Equation 6 can be written as

$$V_\infty(D,m,h) = D - D^*_\infty(m,h) + \beta\left[\gamma m + D^*_\infty(m,h)\right]$$

If we evaluate the expression above at $D = D^*_\infty(m,h)$ we obtain

$$V_\infty(D^*_\infty(m,h),m,h) = \beta\left[\gamma m + D^*_\infty(m,h)\right] = D^*_\infty(m,h)$$

where the last equality again follows from the definition of $D^*_\infty(m,h)$. Therefore,

$$D^*_\infty(m,h) = \frac{\beta\gamma m}{1-\beta} = \overline{D}(m),$$

proving the first part of the proposition. Now let $D > D^*_\infty(m,h)$. If $D^*_\infty(m,h) \leq D^*_\infty(m',h')$, then $\mu = \frac{D - D^*_\infty(m,h)}{y}$. Otherwise, if $D^*_\infty(m,h) > D^*_\infty(m',h')$, then $\mu = \frac{D - D^*_\infty(m',h')}{y}$. Using these expressions for μ and the definition of $V_\infty(D,m,h)$ for all $D \leq D^*_\infty(m,h)$ derived above, we can write the integral in Equation 6 defining $V_\infty(D,m,h)$ as

$$\int \left[(\gamma+\mu)y + V_\infty(D - \mu y, m', h')\right] f(y;m)\, dy = D.$$

Thus,

$$V_\infty(D,m,h) = \beta\left[\gamma m + D\right] \quad \text{and} \quad L_\infty(D,m,h) = (1-\beta)\left[D - \overline{D}(m)\right]$$

Combining the expressions for $L_\infty(D,m,h)$ we obtain the desired result. ■

6.2.2 No Debt Reduction

Despite the fact that the loss function $L_0(D, m, h)$ and the equilibrium debt level $D_0^*(m, h)$ do not have closed form solutions, we characterize their main properties in the following proposition, related to Proposition 2 in the text.

Proposition 6 *When ability is uncertain and there is no debt reduction, the loss function is given by*

$$L_0(D, m, h) = \begin{cases} 0, & \text{if} \quad D \leq D_0^*(m, h) \\ (1-\beta)\left[D - \overline{D}(m)\right] + \beta \int L_0(D, m', h')\phi(y; m)\, dy, & \text{otherwise,} \end{cases}$$

and the equilibrium debt level by

$$\begin{aligned} D_0^*(m, h) &= \overline{D}(m) - \frac{\beta}{1-\beta} \int L_0(D_0^*(m, h), m', h')\phi(y; m)\, dy \\ & \quad \text{where} \quad m' = \frac{hm + y}{h+1} \quad \text{and} \quad h' = h + 1. \end{aligned}$$

Proof. Using the argument in the previous proofs, the definition of equilibrium debt $D_0^*(m, h)$ implies that $L_0(D, m, h) = 0$ for $D \leq D_0^*(m, h)$. Since $V_0(D, m, h)$ evaluated at $D = D_0^*(m, h)$ is

$$V_0(D_0^*(m, h), m, h) = \beta \left[\gamma m + \int V_0(D_0^*(m, h), m', h')\phi(y; m)\, dy\right],$$

the loss function evaluated at the same $D = D_0^*(m, h)$ is

$$\begin{aligned} L(D_0^*(m, h), m, h) &= D_0^*(m, h) - V_0(D_0^*(m, h), m, h) \\ &= (1-\beta)D_0^*(m, h) - \beta\gamma m + \beta \int \left[D_0^*(m, h) - V_0(D_0^*(m, h), m', h')\right] \phi(y; m)\, dy \\ &= (1-\beta)\left[D_0^*(m, h) - \overline{D}(m)\right] + \beta \int L_0(D_0^*(m, h), m', h')\phi(y; m)\, dy = 0 \end{aligned}$$

where m' and h' are updated according to the formulas in (1) and (2), and the last equality follows from the fact that $L_0(D, m, h) = 0$ for $D \leq D_0^*(m, h)$. Solving for $D_0^*(m, h)$ we obtain the expression stated in the second part of the Proposition. Now let $D > D_0^*(m, h)$.

The value $V(D,m,h)$ and loss function $L(D,m,h)$ for a general $D > D_0^*(m,h)$ are given by the expressions above for $D_0^*(m,h)$ replacing $D_0^*(m,h)$ for D. Thus,

$$L_0(D,m,h) = (1-\beta)\left[D - \overline{D}(m)\right] + \beta \int L_0(D,m',h')\phi(y;m)\,dy.$$

As in the previous proofs, combining the expressions for $L_0(D,m,h)$ we obtain the desired result. ■

In order to show the properties of the equilibrium debt level $D_0^*(m,h)$ stated in the second part of Proposition 2, we need to characterize the loss function in greater detail.

Proposition 7 *For $D > D_0^*(m,h)$, the loss function $L_0(D,m,h)$ is a contraction mapping with a unique solution that is increasing in debt D and decreasing in mean prior ability m and precision h. In addition,*

(i) $L_0(D,m,h) > L_0^F(D,m)$, *for all finite h.*

(ii) $\lim_{h\to\infty} L_0(D,m,h) = L_0^F(D,m)$.

(iii) $\lim_{D\to\infty} L_0(D,m,h) = L_0^F(D,m)$.

Proof. We first define the operator $\mathcal{T} : \mathcal{B}(D,m,h) \to \mathcal{B}(D,m,h)$ where $\mathcal{B}(D,m,h)$ is the space of bounded and continuous functions in (D,m,h). Let $L_0^n \in \mathcal{B}(D,m,h)$, then the operator $\mathcal{T}$ is given by

$$(\mathcal{T}L_0^n)(D,m,h) = (1-\beta)\left[D - \overline{D}(m)\right] + \beta \int L_0^n(D, \frac{hm+y}{h+1}, h+1)\phi(y;m)\,dy = L_0^{n+1}(D,m,h).$$

It is easy to show that the operator $\mathcal{T}$ satisfies the Blackwell's sufficient conditions thus proving that it is a contraction mapping. By the Contraction Mapping Theorem (see Stokey, Lucas and Prescott), the operator $\mathcal{T}$ has a unique fixed point $L_0(D,m,h)$ whose properties are established using the Corollary to the Contraction Mapping Theorem (see Stokey, Lucas and Prescott, XX, pp. YY). Let $L_0^n(D,m,h) \in \mathcal{S}(D,m,h)$, where $\mathcal{S}(D,m,h)$ is the space of bounded and continuous functions that are nondecreasing in D

and nonincreasing in m and h. To show that the fixed point $L_0(D,m,h)$ is increasing in D, take $D_1 > D_2$.

$$\begin{aligned}
(\mathcal{T}L_0^n)(D_1,m,h) &= (1-\beta)\left[D_1 - \overline{D}(m)\right] + \beta \int L_0^n(D_1, \frac{hm+y}{h+1}, h+1)\phi(y;m)\,dy \\
&> (1-\beta)\left[D_2 - \overline{D}(m)\right] + \beta \int L_0^n(D_2, \frac{hm+y}{h+1}, h+1)\phi(y;m)\,dy \\
&= (\mathcal{T}L_0^n)(D_2,m,h),
\end{aligned}$$

where the inequality follows from the fact that $L_0^n(D,m,h)$ is nonincreasing in D and that $D_1 > D_2$. Since $L_0^n(D,m,h) \in \mathcal{S}(D,m,h)$ by assumption, $L_0^{n+1}(D,m,h) = (\mathcal{T}L_0^n)(D,m,h) \in \mathcal{S}'(D,m,h)$ where $\mathcal{S}'(D,m,h)$ is the (open) space of bounded and continuous functions that are strictly increasing in D. Hence by the Corollary, the fixed point $L_0(D,m,h) \in \mathcal{S}'(D,m,h)$ and is strictly increasing in debt D. Similar arguments can be used to show that $L_0(D,m,h)$ is decreasing in m and h.

We now show the additional results. First notice that using L'Hôpital Rule,

$$\lim_{h\to\infty} \frac{hm+y}{h+1} = m.$$

Thus,

$$\lim_{h\to\infty} L_0(D,m,h) = L_0(D,m,\infty) = (1-\beta)\left[D - \overline{D}(m)\right] + \beta L_0(D,m,\infty),$$

because $L_0(D,m,\infty)$ integrates out since it does no longer depends on y. Solving for $L_0(D,m,\infty)$ we obtain

$$\lim_{h\to\infty} L_0(D,m,h) = L_0(D,m,\infty) = D - \overline{D}(m) = L_0^F(D,m)$$

which proves item (ii). Item (i) follows trivially from the fact that $L_0(D,m,h)$ is decreasing in h and that the limit point is $L_0^F(D,m)$ (item ii). The proof of item (iii) uses a guess and verify method. Assume that indeed

$$\lim_{D\to\infty} L_0(D,m,h) = D - \overline{D}(m).$$

Then,

$$\begin{aligned}
\lim_{D\to\infty} L_0(D,m,h) &= (1-\beta)\left[D - \overline{D}(m)\right] + \beta \int \left[D - \overline{D}\left(\frac{hm+y}{h+1}\right)\right]\phi(y;m)\,dy \\
&= (1-\beta)\left[D - \overline{D}(m)\right] + \beta\left[D - \overline{D}(m)\right] = D - \overline{D}(m)
\end{aligned}$$

as was to be shown. ■

Proposition 7 item (i) shows that if there is limited liability, mistakes about the true ability of the boat owner are costly. Because the auctioneer cannot adjust the boat owner's debt, if the boat owner turns out to be of a lower than expected ability, the auctioneer incurs a cost. The higher the uncertainty about the boat owner's true ability, or equivalently, the lower the precision h, the higher the probability of making mistakes and thus the higher the loss function (item (ii)). When the boat owner has unlimited liability, the loss function with known ability L_∞^F coincides with the loss function with unknown ability L_∞. When the boat owner has limited liability, the loss function with unknown ability approaches the loss function with known ability as debt becomes arbitrarily large (Proposition 7.iii). In general, the loss function with unknown ability is higher than that of known ability, as shown in Proposition 7.i.

We are now ready to prove the second part of Proposition 2.

Proof. We show that $D_0^*(m,h)$ is strictly increasing in m by partially differentiating the expression for $D_0^*(m,h)$ with respect to m. After arranging terms we obtain

$$\frac{\partial D_0^*(m,h)}{\partial m} = \frac{\frac{\partial \overline{D}(m)}{\partial m} - \frac{\beta}{1-\beta}\int \frac{\partial L_0(D,\frac{hm+y}{h+1},h+1)}{\partial m}\frac{h}{h+1}\phi(y;m)\,dy}{1+\frac{\beta}{1-\beta}\int \frac{\partial L_0(D,\frac{hm+y}{h+1},h+1)}{\partial D}\phi(y;m)\,dy} > 0.$$

Also partially differentiating $D_0^*(m,h)$ with respect to h we get

$$\frac{\partial D_0^*(m,h)}{\partial h} = \frac{-\frac{\beta}{1-\beta}\int \left[\frac{\partial L_0(D,\frac{hm+y}{h+1},h+1)}{\partial h}\frac{m-y}{(h+1)^2} + \frac{\partial L_0(D,\frac{hm+y}{h+1},h+1)}{\partial h}\right]\phi(y;m)\,dy}{1+\frac{\beta}{1-\beta}\int \frac{\partial L_0(D,\frac{hm+y}{h+1},h+1)}{\partial D}\phi(y;m)\,dy} > 0.$$

Finally,

$$\lim_{h\to\infty} D_0^*(m,h) = \overline{D}(m) - \frac{\beta}{1-\beta}L_0(D_0^*(m,\infty),m,\infty) = \overline{D}(m),$$

because the loss function evaluated at the equilibrium level is zero by definition. ■

Table 1. Descriptive Statistics

	Mean	Std Dev	Minimum	Maximum
Initial Debt	58119.27	23224.10	15069	107796
Debt	59558.26	27018.07	2509	157619
Debt at Renegotiation	60771.97	28056.08	3257	157619
Sales (per Month)	23544.38	18305.19	0	116960
Month of Adoption	Jan 2002	10.47	January 2001	September 2005

Table 2. Dynamics of Sales

	(1)		(2)	
Time since adoption (months)				
First Year	1,066.69	(0.85)	3,159.56	(0.82)
Second Year	1,253.32	(1.01)	2,015.81	(0.65)
Third Year	-240.70	(-0.19)	379.22	(0.17)
Fourth Year	-1,276.51	(-0.99)	-1,889.65	(-1.16)
Firth Year	.	.	.	.
Year				
2001			-7,051.88	(-1.57)
2002			-5,210.55	(-1.44)
2003			-6,619.31	(-2.37)
2004			-902.97	(-0.44)
2005			-7,952.07	(-5.59)
2006			.	.
F-Test (p-value)	2.18	(0.07)	1.86	(0.12)
R-Squared	0.62		0.64	
Fixed Effects	Yes		Yes	
Individuals	39		39	
Observations	1,539		1,539	

Notes: T-statistics in parentheses, null hypothesis of F test: all time since adoption dummies equal zero.

Table 3. Reduced Form Analysis of Debt

	(1)		(2)		(3)	
Constant	1.245	(10.44)	2.511	(8.72)	1.566	(10.42)
Sales (normalized)	1.093	(8.96)			0.690	(5.29)
Sales 1st year			0.212	(0.92)		
Sales 2nd year			0.410	(1.57)		
Sales 3rd year			1.593	(6.5)		
Sales 4th year			1.356	(4.68)		
Sales 5th year			-0.706	(-1.79)		
Year 2001	-0.971	(-6.2)	0.061	(0.29)	0.078	(0.36)
Year 2002	-0.653	(-4.99)	0.135	(0.75)	0.218	(1.19)
Year 2003	-0.340	(-2.77)	0.141	(0.85)	0.324	(1.95)
Year 2004	-0.308	(-2.53)	-0.016	(-0.1)	0.066	(0.45)
Year 2005	-0.200	(-0.05)	0.174	(1.32)	0.113	(0.85)
Year 2006	.	.	.	.	.	.
First year			-1.736	(-4.99)	-1.113	(-5.60)
Second year			-1.517	(-4.34)	-0.811	(-4.39)
Third year			-1.628	(-4.8)	-0.319	(-1.93)
Fourth year			-1.459	(-4.35)	-0.185	(-1.23)
Fifth year			.	.	.	.
Observations	449		449		449	
R-squared	0.228		0.375		0.321	

Notes: t-statistics in parentheses.

Table 4. Structural Estimation of Debt

	(1)		(2)	
r 2001	-0.144	(-0.33)	0.166	(0.14)
r 2002	-0.793	(-3.34)	-0.792	(-1.82)
r 2003	-1.067	(-4.47)	-0.571	(-1.08)
r 2004	-1.217	(-3.9)	-0.640	(-1.12)
r 2005	-0.776	(-2.03)	-0.558	(-1.00)
r	-0.645	(-1.32)	-0.035	(-0.05)
ζ 1st year	0.000	.	0.000	.
ζ 2nd year	0.454	(4.69)	0.331	(2.91)
ζ 3rd year	0.739	(5.52)	0.562	(1.37)
ζ 4th year	0.659	(3.69)	0.269	(0.75)
ζ 5th year	0.884	(3.61)	0.287	(0.79)
ψ 2001	0.000	.	0.000	.
ψ 2002	-1.181	(-2.09)	-1.298	(-0.96)
ψ 2003	-1.757	(-2.99)	-1.090	(-0.79)
ψ 2004	-2.602	(-3.54)	-1.347	(-0.92)
ψ 2005	-1.891	(-2.33)	-0.975	(-0.65)
ψ 2006	-1.455	(-1.66)	0.602	(0.35)
w1	0.256	(3.82)		
w1 1st year			0.132	(1.47)
w1 2nd year			0.242	(2.09)
w1 3rd year			0.795	(5.57)
w1 4th year			0.708	(3.63)
w1 5th year			0.708	(3.63)
Observations	445		445	
R-squared	0.294		0.317	

Notes: t-statistics in parentheses