COOPERATION AGAINST THEFT: A TEST OF INCENTIVES FOR WATER MANAGEMENT IN TUNISIA

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Water theft carried out by manipulating water meters constrains volumetric pricing in semi-arid regions. Cooperative management can reduce theft and improve incentives for efficient water use by inducing peer monitoring. Using a theoretical model, we show that theft is more likely when prices are high, punishments are weak, and cooperatives are large. We also show how cooperative membership and punishment levels are determined endogenously by constraints on monitoring. We test the model on data from Tunisia for the years 2001–2003, relying on instruments that proxy for unobservable monitoring costs. The results confirm that well-designed incentives can reduce theft, and that constraints on monitoring costs affect institutional design.

Key words: cooperatives, cooperative size, irrigation, joint responsibility, peer monitoring, Tunisia, water theft.

JEL codes: D82, Q13, Q15, Q25.

Economic behavior is not only influenced by formal incentives, but also by institutions,which can be understood as informal systems of rules, enforced by a variety of explicit or implicit means. However, institutions themselves evolve in part because of their incentive properties—certain institutions are more suited for some economic environments than others. For instance, many institutions are formed in response to a perceived collective action problem, which the effective design of such institutions can help to alleviate, though rarely without some cost. In this paper we examine the influence of institutions on a serious problem that arises in water management, namely the problem of water theft. The growing scarcity of fresh water in many parts of the world, and especially in the agricultural sector has led to an urgent search for solutions, including the adoption of economic pricing policies to encourage conservation.[1] However, it is becoming apparent that when farmers are in a position to steal water, typically by manipulating water meters,[2] pricing policies may not only fail to encourage conservation, but they may even increase the incidence of theft itself. In the presence of theft, optimal pricing rules need to be adjusted, and prices will typically be lower than in their absence (see section B.1 in the appendix for full details). Thus, it is worth tolerating some allocative inefficiency in water use in return for a lower incidence of theft.

Theft does not take place in an institutional vacuum. Indeed, different types of water institutions may create more or less favorable conditions for theft to flourish. In particular, cooperative institutions may be well-suited to dealing with a number of collective action problems that arise in water management, though their success in doing so depends on some quite precise features of their design. In this article we show that such institutions may also be well-suited to dealing with theft, and we discuss the features of their design that enable them to

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[1] See Johansson (2002) for a review.

[2] The notion of water theft here is distinct from that in the model of Azam and Rinaudo (2000). In their paper, farmers who are located next to a water stream are allocated fixed quotas. The upstream farmer may well exceed her allocated quota, depriving the downstream farmer from part of her quota (meaning that the former steals water *directly* from the latter). In our model farmers do not steal water from each other, but rather directly from the Water Authority.

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do so using both theory and empirical evidence. We also show that the incidence of theft varies considerably in response to these features, and subsequently discuss policy implications. We consider the properties of water users' associations whose members are subject to joint responsibility for aggregate quantities of water used, and show that this feature is likely to induce peer-monitoring by cooperative members, which might be a more efficient means of reducing theft than any other available to more centralized management structures.

Many government authorities are reluctant to acknowledge the severity of the problem of water theft, and it is frequently claimed that the authorities' inability to recover the costs of supplying water to users is due to purely technical difficulties such as leakages from the water supply network (personal communication from several directors of Agricultural Regional Development Commissions [ARDC] of the Governorates where the survey was conducted). Two kinds of evidence from our own research make us think this is an implausible explanation. First, and on an anecdotal level, many farmers can be observed using water in ways that seem inconsistent with their facing full prices (for example, placing rotating sprays at the corners of fields, where only one-quarter of the emitted water falls on the land being irrigated). Secondly, the econometric analysis we perform below, as well as the pricing policy practised in Tunisia indicate that it is unlikely that technical explanations can account for most of the discrepancy, because our results show that the discrepancy is related to economic rather than purely physical variables in a way that theft can account for better than leakage. It is not so much that people respond to prices, whereas pipes do not; better maintenance of the pipes could, after all, both respond to economic incentives and affect rates of leakage. So it is more that theft might respond to prices in a different way from maintenance: higher prices would be expected to increase incentives for theft but diminish leakage via incentives for improved maintenance. Further, the higher rates of leakage may cause rises in price to cover the costs of repairs to the leaks, or to cover the higher costs of pumping the additional water, which ends up leaking. While we cannot rule out this explanation, we are doubtful about its relevance because in practice the Tunisian Ministry of Agriculture sets prices that barely cover the cost of operating and maintaining the water delivery system, let alone the cost of building the infrastructure (The Ministry of Agriculture of Tunisia).

Testing hypotheses about the determinants of theft in cooperatives is a major empirical challenge, since many of the features of the institutional environment that are empirically associated with incentives for theft are not exogenous features of the environment, but rather evolve in response to environmental characteristics that themselves influence theft, and may even evolve in direct response to perceived theft levels.[3] Our procedure is to use theory to focus attention on the underlying determinants of both institutional structure and (together with institutional structure) individual behavior. Theory then guides our search for proxies for unobserved variables, and instruments for observed but endogenous variables that enable us to identify the appropriate causal relationships[4] in our data, which come from an original survey conducted by the authors in Tunisia for the years 2001–2003. We find that a variable that plausibly proxies for monitoring costs can influence theft, in the sense that higher monitoring costs make theft easier. We also find that the incidence of theft is affected by aspects of the institutions, that is, the rules specifying how severely individual members will be punished for theft, and the overall number of members in the cooperative, both of which influence the scope for free-riding. However, measuring this relationship requires us to determine how various constraints affect the way in which these institutions evolve. Once we have accounted for the potential endogeneity of institutional characteristics, we find support, as predicted, for the hypotheses that larger cooperatives entail more theft, and higher punishment levels reduce theft. Other economic, socioeconomic, physical,

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[3] A paper by Asim (2001) argues that the influence of social capital on the performance of infrastructure projects has been overrated because different designs of projects can offset the impact of adverse social capital. Without wishing to take a stance on the relative importance of social capital and project design as explanations for different performance, our results support the idea that improved design of the structure and rules of projects (and related institutions) may compensate for otherwise adverse conditions.

[4] There is a bidirectional causal relationship between institutions and incentives: institutions do affect the behavior of individuals, but institutions themselves evolve endogenously with the environmental characteristics.

personal, and geographical factors seem to be relevant for the design of cooperatives and farmers' decisions, and some of these factors are considered in the empirical analysis.

The article is structured as follows. In section 1, we review the relevant literature. Section 2 sets out our model, where we state a proposition in the cooperative institution describing the dependence of theft on a number of determinants, some of which are themselves determined by more fundamental factors, including costs of monitoring. We use this proposition to make predictions that can be tested empirically. Section 3 describes our data and tests the theoretical predictions, while section 4 concludes. Mathematical details and extensions appear in the appendix.

Literature Review

Our study partially relates with the research on peer-monitoring in group lending programs where peer-monitoring[5] has been recognized as an effective instrument for mitigating the moral hazard behavior of group members who are linked by a joint-liability clause. Though not exactly the the same, the issues tackled in this article also have some similarities to the problem of nonpoint source pollution[6], where unobserved individual emissions can be regulated through instruments that are conditioned on observed aggregate (ambient) pollution. In the peer-monitoring literature, the joint-liability clause creates an incentive mechanism in which each member has an interest in screening and monitoring the other members, and they may also enforce repayment if necessary. In practice the use of peer-monitoring arrangements has been extensive, particularly in developing countries. However, results—as measured by repayment rates—have been mixed, according to a large number of descriptive and empirical articles on the subject that have inspired various theoretical contributions. The seminal publications in this area are Stiglitz (1990) and Varian (1990), where Varian shows that peer-monitoring within groups can prevent members' shirking in their productive efforts, and Stiglitz investigates poor project selection. Group lending programs delegate monitoring activities to group members, thereby improving repayment rates and reducing the costs of lending, which may be translated into lower interest rates for borrowers (Varian) and larger loan contracts (Stiglitz).

More recently several papers (e.g., Armendariz 1999; Ghatak and Guinnane 1999; Che 2002; Conning 2005) elaborate on the Stiglitz-Varian models, relax the assumption of the costless monitoring and deal with various extensions including the optimal group size and monitoring structures and the dynamic aspect of contractual relationship between group members. These papers are also concerned with delegated monitoring, and compare individual liability to joint-liability loans. While emphasizing the benefits of delegated monitoring, most articles (except for Armandariz De Aghion 1999) rule out *ex post* "strategic default" considerations and focus instead on *ex ante* moral hazard. De Aghion (1999) developed a model of strategic default where a borrower's partner(s) can verify her true project return (and impose sanctions if she defaults strategically, where sanctions are given) at some cost, and allows for group members' project returns to be correlated. De Aghion also examined the optimal design of group-lending programs in terms of optimal diversification of risks within peer borrowers, the optimal group size, as well as monitoring structures. Che Koo (2002) developed a model where repeated loan contracts were offered to borrowers, and demonstrates that without introducing an ad hoc penalty technology, the joint-responsibility clause itself makes it credible for members to penalize others through their effort decisions. If the group members can observe the other members' efforts decisions, they can employ a punishment strategy whereby a shirking member is punished by a subsequent shirking by her peers. When such a punishment strategy is self-enforcing, group lending can alleviate the incentive problem facing the members.

Conning (2005) developed a model that analyzed the conditions under which joint-liability loans are more beneficial than outside monitored loans. Such benefits do not rest upon a presumed information or enforcement advantage held by insiders, but instead on an *incentive diversification effect*

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[5] See Wade 1987, an early contribution to what is now a large body of literature.

[6] Pollution is specifically said to be nonpoint if the polluters' individual emissions are fully or partially unobservable by the regulator at a reasonable cost.

that cannot be replicated by outside intermediaries. Subdividing the original project into smaller independent sub-tasks and financing them together reduces the overall minimum collateral requirement relative to the individual liability alternatives of either separate “unlinked” individual contracts for each task, or the original undivided project. Joint-liability clauses are chosen to implement a preferred Nash equilibrium in a multi-agent, multi-task game, where each borrower is given incentives to remain diligent as a financed entrepreneur and as a monitor of others. The Conning model also discusses the effects of collusion among borrowers on group lending efficiency; a lender will guard against this possibility by only agreeing to collusion-proof loans.

Whereas the theoretical literature on peer-monitoring and moral hazard within group lending programs is quite extensive, there are very few empirical studies of these phenomena. One possible explanation is that it is difficult to obtain reliable data on these issues. To our knowledge the only two substantial studies available are carried out by Wydick (1999), and Hermes et al. (2000), who used information from group lending programs in Guatemala and Eritrea, respectively. Wydick analyzes the role of peer-monitoring, internal group pressure to repay loans and social ties within theses groups in mitigating the moral hazard behavior of borrowers. His findings show that while peer-monitoring and (to a lesser extent) peer pressure help to reduce moral hazard and increase the repayment performance of group members, social ties in turn do not have such effects. Hermes found support for the fact that peer-monitoring and social ties of group leaders do help reducing moral hazard between group members. In contrast, peer monitoring by and social ties of other group members are not related to reducing the occurrence of moral hazard within members.

In the literature on nonpoint source pollution, recent policy emphasizes the team nature of the problem by proposing economic instruments based on collective performance, which is the level of observed aggregate (ambient) pollution. This strand of literature follows the pioneering work of Segerson (1988), whose analysis buildt on the earlier theoretical analysis of Holmström (1982), who addressed the problem of free riding in teams in a more general environment. One main finding of Holmström is that in the absence of uncertainty, no budget balancing mechanism exists to solve the problem for avoiding individual free riding in teams. In her pioneering work, Segerson (1988) proposed a tax/subsidy mechanism based on group performance to promote socially optimal behavior. She suggested that the regulator should monitor ambient pollution concentrations and tax (subsidize) the polluters when ambient pollution levels are above (below) an exogenously determined level that is considered as socially optimal by the regulator. In this scheme, each polluter is charged a unit tax based on the aggregate level of pollution, meaning that the liability of each polluter depends on the abatement effort of all polluters, not just her own. When assuming that damage is linear in the ambient pollution level, Segerson (1988) demonstrated that the ambient tax/subsidy rule ensures a first-best outcome without observing individual pollution levels. Furthermore, individual monitoring was demonstrated to be superfluous in the non-linear case as well, as long as the transport mechanism is identical for all polluters. Segerson’s model assumes that polluters are risk-neutral and their number is small enough that they understand that their decisions affect aggregate emissions, that is, polluters assume non-cooperative Nash behavior.

Segerson’s ambient tax has inspired several intriguing extensions. Xepapadeas (1991) suggested a scheme of subsidies and random fines aimed at eliminating the moral hazard problems with budget balancing contracts—in his contribution Xepapadeas studies two different fining regimes: collective and random fining. Under collective fining, all the firms are fined whenever the observed ambient pollution level lies above some predetermined standard. Under the random fining scheme, by contrast, only one firm is randomly chosen to be punished, irrespective of being responsible for the whole group’s deviation from the standard level. Meanwhile, the other producers receive a portion of the fine minus the damages to society. Herriges et al. (1994) illustrate that such an incentive system could be effective at increasing the costs of shirking if polluters are sufficiently risk-averse.

Miceli and Segerson (1991) suggested the introduction of liability rules among parties which actually create incentives that are similar to the ones created by ambient taxes. However, as noted by Litchenberg (1992), liability rules are not likely to be first-best and are probably best-suited for controlling pollution related to the use of hazardous materials, or for non-frequent occurrences of environmental degradation like oil spills.

Karp (2002) proposed a model in which polluters behave strategically with respect to the tax-setting regulator, and found that their tax burden is lower under an ambient tax than taxes based on individual emissions, provided that the tax adjusts quickly, firms are patient, and the number of firms is small. Firms may prefer the case where the regulator is unable to monitor individual emissions, even if the asymmetric information causes the regulator to tax each firm based on aggregate emissions.

Millock and Salanié (2005) extend the theory of ambient taxes to the case when polluters might cooperate, and show that ambient taxes provide strong incentives towards cooperation. However, when the degree of cooperation among polluters is unknown, the optimal regulation requires the regulator to offer a choice between a standard Pigouvian tax and a much lower ambient tax.

There has been substantial experimental[7] research on ambient pollution-based policies for addressing nonpoint source pollution (Alpizar, Requate, and Schram 2004; Cochard, Willinger, and Xepapadeas 2005; Poe et al. 2004; Spraggon 2002; Sutter et al. 2008; Vossler et al. 2006). Such experimental research has evaluated static regulatory mechanisms under the assumption that the regulator has complete information from which to parametrize the optimal policy instrument. Evidence from this research suggests that the ambient tax/subsidy mechanism is likely to be efficient in small group settings of non-cooperating agents, but it will not be efficient if agents are allowed to cooperate (Vossler et al. 2006). The argument is that the ambient tax/subsidy mechanism creates incentives for polluters to cooperate and agree on abatement strategies to reduce their expected tax payment (Hansen 1998; Vossler et al. 2006). The reason is that this strategy benefits the group as a whole because each unit of abatement reduces the return of only one polluter, while all polluters in the group benefit from additional subsidies.

Our model differs from most of the existing theoretical literature on peer-monitoring in two respects. Firstly, in their models the punishment is fixed: in the case of nonrepayment by the group, all members will be denied future access to loans from the program, and defaulters who are caught may face fixed social sanctions. However, in our model the punishment depends continuously on the level of theft undertaken by farmers. Secondly, peer-monitoring in this paper is quite specific in that players are competing in monitoring, which gives rise to two effects rather than one, as is the case in the peer-monitoring theoretical literature. Indeed, in the existing literature peer-monitoring only has an incentive effect in that it aims to mitigate the moral hazard behavior. In turn, in our model peer-monitoring aims not only to reduce the incentives of theft (incentive effect), but it may also allow each cooperative member to shift the cooperative fine on the others (distributional effect).

Moreover, to the best of our knowledge, neither of the empirical studies on peer-monitoring has come close to how individuals choose their institutional rules (thereby ignoring the potential endogeneity of institutional characteristics), and also how these rules affect the individuals' behavior.

As for the ambient tax literature, it differs from our work in several respects. First, in our article the collective responsibility rule creates incentives for peer-monitoring by group members (a substitute instrument of punishment for mitigating the moral hazard behavior), while ambient taxes do not. Second, ambient taxes are charged to all polluters within the area whenever the ambient pollution concentration deviates from a level that is considered socially optimal by the regulator. Further, unlike in our article, there is no predetermined threshold for the amount of water stolen, and punishment is implemented whenever theft occurs. Third, the principle of the ambient tax is that each individual is taxed according to the socially marginal damage when ambient emissions deviate from some exogenously determined level. In our work, however, the distribution of the punishment burden is *endogenously* determined by monitoring. Fourth, in our study whether efficiency is obtained or not depends on the stringency of the punishment

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[7] To the best of our knowledge, ambient-based schemes have rarely been implemented in the field (an exception is presented in Ribaudo, Horan, and Smith 1999). This means that there are very few real data to assess the practical efficiency of the instrument. The experimental economics have overcome the obstacles inherent in the use of real world data by collecting data in a controlled environment, that is, the laboratory.

rate. However, most mechanisms suggested in the ambient tax literature are theoretically suitable for implementing the efficient allocation of abatement efforts in a Nash equilibrium.

The Model

Our model is a deliberately simplified structure designed to capture some features of real-world cooperative water management while consciously abstracting from others. We make no claim that the model should be considered an optimal mechanism. Instead, we take as a given some features of real-life institutions without enquiring into their optimal properties, and use them to determine how the agents operating within them would attempt to optimize, and whether they do so efficiently subject to their constraints. In particular, we shall consider a two-agent model, with a very restricted strategy set for the agents, and we shall look only at symmetric equilibria. Nevertheless, even in this restricted setting, certain features emerge that we believe are both interesting and empirically relevant.

Consider two identical risk-neutral farmers who produce a homogeneous farm good using water as an input. The yield (y) response to water (q) can be described by the relation $y = g(q)$, where $g(.)$ is an increasing and strictly concave function. The cost incurred by each farmer for using water, measured in units of output, is c per unit of water. In addition, the farmer pays a linear price t per unit of water used, which is determined by the Water Authority (WA). The profit-maximizing quantity of water equates the marginal value product of water to the marginal cost of generating such a quantity

$$(1) \qquad g'(q) = c + t$$

In the absence of asymmetric information, and abstracting from any shadow cost of public funds that might imply Ramsey-pricing considerations, the WA can implement the first-best efficient outcome by setting t equal to γ, which represents the full public cost of resource provision, including Operation and Maintenance (O&M) costs, investment costs, extraction externalities associated with pumping from a shared aquifer, and any shadow cost associated with the scarcity of water.

However, when the individual farmer's water use is her private information (unlike the total amount of water used by farmers, which is observable to the WA), the farmer who is equipped with an individual water meter can send a report of the amount used, denoted by q^r, which may differ from the true quantity. We write the amount of water stolen as $a = q - q^r$, and assume that there are no rewards for over-reporting.

The response of the WA will differ according to whether there is centralized or cooperative management.[8] Centralized management is interesting but not crucial for our empirical study; rather than explore it further here, we have included a model of this phenomenon in the appendix.

Cooperative Management

We assume that the total amount of water used by the two cooperative members, $Q = q_1 + q_2$, is publicly and costlessly known, and can thereby serve as a basis for aggregate payments from the cooperative to the WA. In particular, this allows for a joint-liability rule: if theft occurs, the cooperative as a whole receives a punishment proportional to the total amount of water stolen (which is publicly observable). The punishment is measured in terms of the length of time for which water is cut off from the whole cooperative when theft occurs. This length is proportional to the total amount of water stolen in the cooperative. The punishment is assumed to take the form:

$$(2) \qquad F^c = f\left(\sum_{i=1,2} q_i - \sum_{i=1,2} q_i^r\right)$$

where the punishment rate f is positive and given outside the model. The solution to the cooperative management will be indexed with the superscript ^{c}.

Suppose that, relative to the WA, farmers have a comparative advantage in monitoring each other, as a result of geographical proximity and/or long-standing trade links. We assume that peer-monitoring brings

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[8] Since the total amount of water used by farmers is publicly known, this makes it like a moral hazard in teams, where the WA may discipline team members through monetary incentives that break the budget constraint, thereby restoring the full-information outcome (see Holmström 1982). Such a scheme works independent of group size, but may be infeasible when members have endowment constraints.

about only *evidence* of the occurrence of theft, but not of its amount.[9] The WA may then contemplate the possibility of inducing peer-monitoring between the two farmers, typically through the establishment of a cooperative governed by rules that make all members jointly liable.[10] If theft occurs in the cooperative, the fine is shared equally between farmers who are caught stealing; otherwise it is shared by all members.

Peer-monitoring incurs a private cost $\psi(m)$ to a farmer, and is assumed to be increasing, convex, and to satisfy $\psi(0)=0$. Each member commits to a level of monitoring[11] (observable by other members) before actual and reported water uses are decided. The probability that a farmer i is caught stealing is then given by:

$$(3) \qquad P_i(m_j, a_i) = \kappa m_j \max\{a_i, 0\}$$

where $\kappa > 0$ (we assume henceforth that it is sufficiently small to generate an interior solution, which is realistic). This probability is increasing in the farmer's own level of theft and the monitoring effort of the other. Farmers do not collude in either their monitoring or their production decisions.[12] The order of events is therefore that the WA fixes[13] t, then individual members choose m_i, then, having observed each others' choice of monitoring they choose q_i and q_i^r. The outcome will depend on the severity of the punishment rate. If it is sufficiently high, there will be no theft and no monitoring in equilibrium (since this ensures that the collective punishment is sufficient to deter theft). Otherwise, there will be positive theft and positive monitoring in equilibrium (it is this latter case that will be important for our empirical testing). To summarize:

Proposition 1. *If $f \geq 2t$, there exists a unique symmetric subgame perfect equilibrium (m^c, a^c) such that:*

$$(4) \qquad m^c = a^c = 0$$

if[14] *$t < f < 2t$. Then, the unique symmetric subgame perfect equilibrium (m^c, a^c) satisfies*

$$(5) \qquad a^c = \frac{(2t-f)}{2\kappa m^c f}$$

and

$$(6) \qquad m^c : \frac{(2t-f)(2f-t)}{4\kappa (m^c)^2 f} = \psi'(m^c).$$

Proof for this appears in the appendix.

Peer monitoring not only reduces the incentives for theft (incentive effect) but may also allow each cooperative member to shift the cooperative fine on to the other (distributional effect).[15]

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[9] What a member may observe is whether her peers manipulate their meters (besides the farmer herself, only the WA can have access to the former's meter and in case the meter has been indeed manipulated, the evidence about this fact will be established with certainty). However, this does not exclude the possibility that a member might infer her peers' true intakes, particularly for small communities where members know each other. This is less likely for large cooperatives.

[10] It is worth clarifying how peer-monitoring mechanism works in more details: When a cooperative member is declared to be a cheater, the WA checks whether her water meter has been manipulated. A cooperative member may indeed make a monitoring mistake or also deliberately lie and declare her peer as cheater in order to shift the cooperative fine on her (or on others), but when checking the peer's meter and no evidence about her manipulation is established, this latter will not be considered as a cheater. In case all members are declared to have stolen by each other, the WA checks all members' meters and those for whom the evidence about manipulation has been established will be treated as cheaters and punished consequently. In the extreme case, where all members are not mistakenly declared to have stolen, they will split the total fine equally between them, since the evidence about their meters' manipulation will be established with certainty. Finally, in case no member is declared cheating, the WA does not need to check whether the cooperative members meters have been manipulated, the fine will automatically be shared equally between all members (even if cooperative members have colluded to make wrong declaration).

[11] One may think of observable sunk investments being made by cooperative members, and which would commit them to higher monitoring efforts. For instance, it is frequent in developing countries like Tunisia that landlords build little houses in their farms where they keep equipment for daily use and where both landlords and laborers may spend some time.

[12] We sidestep the issue of collusion here because it is not central to the paper's argument, and it is quite complicated analytically. Assuming that collusion in monitoring efforts is not possible may seem a strong assumption, especially if the cooperative represents a small community where all farmers know each other. However, this might be quite plausible for large cooperatives, or in smaller cooperatives where monitoring opportunities are relatively asymmetric (e.g. because people can observe their neighbors more easily than they can observe others).

[13] The price of water t is then exogenous to the cooperative mechanism (carried out at the farmers' level).

[14] The punishment rate f is assumed to be greater than t, because otherwise the farmer will always have an interest in stealing everything. The net return of water theft is equal to $(t - \kappa m^c f a^c) a^c$, with the probability of $\kappa m^c a^c < 1$. If $f < t$, one obtains$\kappa m^c a^c f < f < t$, and therefore theft is strictly beneficial. This essentially implies that the net return is maximized when the farmer steals everything.

[15] The distributional effect is inferred from the proof of proposition 1 (in the appendix), which explains explicitly how peer-monitoring affects the distribution of the punishment burden between cooperative members. The proof is:

The expected share of farmer i from the cooperative fine, denoted by $s_i^{\exp}(a_i, m_i; a_j, m_j)$ is equal to

$$(\text{I}) \qquad s_i^{\exp} = \frac{1}{2}(1 - \kappa m_i a_j + \kappa m_j a_i)$$

Comparative Statics with Quadratic Monitoring Costs

To obtain explicit solutions, where possible we assume that monitoring costs take the quadratic form $\psi(m) = \frac{1}{2}bm^2$, where $b > 0$. We first explore the impact of monitoring costs, water price and the level of punishment on the equilibrium monitoring effort. As one might intuitively expect, monitoring levels are decreasing with the cost parameter b, increasing with water price, and decreasing with the punishment rate[16]

$$(7) \qquad \frac{\partial m^c}{\partial b} = -\frac{m^c}{3b} < 0$$

$$(8) \qquad \frac{\partial m^c}{\partial t} = \frac{1}{12b}\,\frac{(5f-4t)}{\kappa(m^c)^2 f} > 0$$

and

$$(9) \qquad \frac{\partial m^c}{\partial f} = \frac{(t^2-f^2)}{6\kappa b (m^c)^2 f^2} < 0.$$

Secondly, we study the relationship between the monitoring level,[17] the price of water, the punishment rate, and the incidence of theft in equilibrium. As intuition suggests, theft is decreasing with monitoring and punishment levels, and increasing with the price of water:[18]

$$(10) \qquad \frac{\partial a^c}{\partial m} = \frac{(2t-f)}{2\kappa f}\left(-\frac{1}{(m^c)^2}\right) < 0$$

$$(11) \qquad \frac{\partial a^c}{\partial f} = \frac{(2t^2+f^2-6ft)}{3\kappa m^c f^2 (2f-t)} < 0$$

and

$$(12) \qquad \frac{\partial a^c}{\partial t} = \frac{1}{6\kappa m^c f}\,\frac{(7f-2t)}{(2f-t)} > 0.$$

We now explore whether the equilibrium monitoring effort is efficient. We do this by comparing the equilibrium monitoring level to that which would occur in a second-best problem faced by the WA as a social planner who can set monitoring decisions of farmers but not their water-use choices, nor their reports once monitoring decisions have been made. Moreover, we assume that the WA cannot affect the incentives of theft for given monitoring efforts. In particular, the WA cannot ensure that farmers do not steal. The WA picks a monitoring effort that maximizes the social welfare function defined as the sum of the farmers' surpluses, $2[g(q^c) - cq^c - tq^{rc} - fa^c(m)]$, plus the surplus of the WA, which is equal to its revenue from water proceeds $2tq^{rc}$, from which we deduct the cost of supplying water to the cooperative area $2\gamma q^c$ and the cost of

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where, a_i and a_j are the amount of water stolen by farmers i and j given respectively by

$$(\text{II}) \qquad a_i = \left(\frac{2t-f}{\kappa f}\right)\frac{(3m_i - m_j)}{(m_i+m_j)^2}$$

and

$$(\text{III}) \qquad a_j = \left(\frac{2t-f}{\kappa f}\right)\frac{(3m_j - m_i)}{(m_i+m_j)^2}.$$

By differentiating the expected share of farmer i, with respect to the monitoring effort performed by her peer, farmer j, one obtains:

$$(\text{IV}) \qquad \frac{\partial s_i^{\exp}(m_i,m_j)}{\partial m_j} = \frac{1}{2}\left[-\kappa m_i \frac{\partial a_j}{\partial m_j} + \kappa a_i + \kappa m_j \frac{\partial a_i}{\partial m_j}\right]$$

where the partial derivatives of a_j and a_i with respect to m_j, notably $\frac{\partial a_j}{\partial m_j}$ and $\frac{\partial a_i}{\partial m_j}$ are respectively given by

$$(\text{V}) \qquad \frac{\partial a_j}{\partial m_j} = \left(\frac{2t-f}{\kappa f}\right)\frac{(5m_i - 3m_j)}{(m_i+m_j)^3}$$

and

$$(\text{VI}) \qquad \frac{\partial a_i}{\partial m_j} = \left(\frac{2t-f}{\kappa f}\right)\left[\frac{3m_j - 5m_i}{(m_i+m_j)^3}\right].$$

Replacing $\frac{\partial a_j}{\partial m_j}$ and $\frac{\partial a_i}{\partial m_j}$ by their expressions given by equations (V) and (VI) into equation (IV) yields

$$\frac{\partial s_i^{\exp}(m_i,m_j)}{\partial m_j} = \left(\frac{2t-f}{f}\right)\frac{1}{(m_i+m_j)^3}(4m_i^2 + m_j^2) > 0.$$

Thus, the expected share of farmer i from the cooperative fine increases with the monitoring effort performed by her peer, farmer j, meaning that the latter monitors the former to shift the cooperative fine to her.

[16] Equations (7), (8) and (9) come from equation (5) and from the quadratic form of the monitoring cost $\psi(m) = \frac{1}{2}bm^2$ replacing the general monitoring cost function into equation (6). This yields the equilibrium monitoring effort

$$m^c = \left(\frac{(2t-f)(2f-t)}{4\kappa b f}\right)^{\frac{1}{3}}.$$

[17] The monitoring effort is chosen in the first stage of the game, and is therefore a parameter in the second stage when the farmer chooses the amount of water to use and the report to file.

[18] Equations (10), (11), and (12) come from equation (5) and from the quadratic form of monitoring cost function $\psi(m) = \frac{1}{2}bm^2$. Replacing the monitoring effort by

$$m^c = \left(\frac{(2t-f)(2f-t)}{4\kappa b f}\right)^{\frac{1}{3}}$$

into equation (5) allows us to derive the comparative static results $\frac{\partial a^c}{\partial f}$ and $\frac{\partial a^c}{\partial t}$.

performing monitoring, $2\psi(m)$

$$(13)\quad W^{c(sb)}(m) = 2\left[g(q^c) - (c+\gamma)q^c - fa^c(m) - \psi(m)\right].$$

The solution to the cooperative in the second-best option will be indexed with the superscript "$c(sb)$." Thus, $a^c(m) = \frac{(2t-f)}{2\kappa m f}$ is the amount of water stolen by a farmer in the symmetric equilibrium when cooperative members non-cooperatively choose how much water to use and to steal, taking for a given the level of monitoring performed by the WA. The (second-best) efficient monitoring level that equates the marginal reduction of the *total* cooperative fine to the marginal cost of monitoring satisfies

$$(14)\quad \frac{(2t-f)}{2\kappa\left[m^{c(sb)}\right]^2} = \psi'\left(m^{c(sb)}\right).$$

We show that, for the case of quadratic monitoring costs, the equilibrium monitoring effort is lower than the (second-best) efficient level for reducing theft, that is, $m^c < m^{c(sb)}$, where

$$(15)\quad m^{c(sb)} = \left(\frac{2t-f}{2\kappa b}\right)^{\frac{1}{3}} \quad \text{and} \quad m^c = \left(\frac{(2t-f)(2f-t)}{4\kappa b f}\right)^{\frac{1}{3}}.$$

This is because, in addition to reducing the incidence of theft, monitoring increases the risk that the party performing monitoring will have to bear the whole punishment[19], and this second effect (which is purely distributional) acts as a disincentive to undertaking the efficient level of monitoring.

Endogenous Punishment

Here we extend the model to the punishment rate f to be chosen collectively by cooperative members at an initial contracting stage, subject to a cost of inflicting punishment $\varphi(f)$, which is increasing and sufficiently convex[20] to ensure an interior solution. This cost may be pecuniary or may correspond to costs in the deterioration of social relations that occur when punishment is inflicted on members of a close-knit society. Here, members choose the punishment level f^c that maximizes an objective function defined as the sum of cooperative members' surpluses $2\left[g(q^c) - cq^c - tq^{rc} - fa^c - \frac{1}{2}b(m^c)^2\right] - \varphi(f)$, to which we add the WA's surplus equal to its revenue from water proceeds $2tq^{rc}$, from which we deduct the cost of supplying water to the cooperative area $2\gamma q^c$

$$(16)\quad \max_{f\in(t,2t)} W^c(f) = 2\left[g(q^c) - (c+\gamma)q^c - fa^c - \frac{1}{2}b(m^c)^2\right] - \varphi(f).$$

This has a first-order condition:[21]

$$(17)\quad f^c : \frac{1}{3\kappa f^2 m^c(2f-t)}(6f^3 + t^3 - 4f^2 t) = \varphi'(f)$$

which is also sufficient to identify a global maximum.[22]

From this we can show that the punishment level is increasing with monitoring costs. Totally differentiating the first-order condition with respect to f and b and

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[19] The explanation relates to the fact that the probability of catching a cheating member increases in her monitoring by others and in her own level of theft. When a farmer monitors her peer intensively she may reduce significantly her incentives for theft, reducing thereby the likelihood of detecting her stealing, and increasing the expected fine faced by the farmer as a result of her own equilibrium level of theft. This is like a "reverse business stealing" externality that lowers the farmer's monitoring below the (second-best) efficient level.

[20] This is driven by the increased complexity and difficulty of enforcing stringent punishments on individuals from the same community.

[21] Differentiating the cooperative welfare function with respect to f yields

$$\frac{dW^c}{df} = 2\left\{\left[g(q^c) - (c+\gamma)\right]\frac{\partial q^c}{\partial f} - a^c - f\frac{\partial a^c}{\partial f} - 2\frac{1}{2}bm^c\frac{\partial m^c}{\partial f}\right\} - \varphi(f) = 0.$$

Taking into account that $q^c$is independent of f and replacing a^c, $\frac{\partial m^c}{\partial f}$ and $\frac{\partial a^c}{\partial f}$ by their expressions given, respectively, by equations (5), (9), and (11), we obtain the first-order condition corresponding to equation (17) in the text.

[22] This follows from the strong convexity of the cost of inflicting punishment, which ensures the concavity of the objective function $W^c(f)$.

rearranging yields:

$$(18)\quad \frac{\partial f^c}{\partial b} = -\frac{1}{\left(\frac{d^2W^c(f)}{df^2}\right)} \times \frac{\left[6(f^c)^3 + t^3 - 4(f^c)^2 t\right]}{3\kappa (f^c)^2 (2f^c - t)} \times \left(-\frac{1}{(m^c)^2}\frac{\partial m^c}{\partial b}\right) > 0.$$

The above expression is positive because $\frac{\partial m^c}{\partial b} < 0$ and $\left(\frac{d^2W^c(f)}{df^2}\right) < 0$. This result shows that the two instruments, monitoring and punishment can be substituted.

Cooperative Size

The analysis thus far has concentrated on the two-farmer cooperative. In practice, however, most cooperatives that rely on aquifers for irrigation involve up to 40 farmers, and most involve more than 100 farmers when irrigation is based on surface water. Unfortunately, it is quite difficult to find analytical solutions for optimal cooperative size, but in a companion paper we report simulations suggesting (though they do not prove) two relationships that we shall further examine in our empirical section below. First, the incidence of theft appears to increase with the cooperative size[23]. Secondly, the optimal cooperative size appears to be (weakly) decreasing with monitoring costs, as higher monitoring costs reduce the incentives for monitoring, thus increasing the opportunities of theft.

Summary of Empirical Hypotheses

The predictions of the models set out above are as follows:

- Theft increases with the price of water.
- Theft decreases with punishment levels.
- Theft increases with monitoring costs.
- The optimal level of punishment increases with monitoring costs.

The predictions of the simulations in Mattoussi & Seabright (2007) are as follows:

- Theft increases with the cooperative size.
- The optimal cooperative size decreases with monitoring costs.

Testing the Model: Data

This section tests our predictions using survey data from 2001-2003 for 49 irrigation cooperatives, the so-called Collective Interest Groups (CIG) in five governorates in the north of Tunisia. The key question to investigate is what determines the rate of theft of water, a highly scarce resource in this region. Among the difficulties of testing such predictions are that some of the likely determinants of theft (such as monitoring levels) are not observable, at least by the econometrician, while others (such as cooperative size and punishment levels) are very likely to be endogenous.

Moreover, theft as such is not observable. What we do observe is the difference between total water used by each cooperative and the aggregate amount reported by cooperative members' water meters. It is possible that some of this difference may be due to technical problems such as leakage from pipes. This is why the WA deducts from the previous measure an estimate of likely losses due to leakage, which varies with the age of the irrigation system (these losses are measured as a proportion of water distributed to the cooperative minus 10% for systems under 10 years old, and 15% for older systems), as well as an estimate by the WA of leakages due to known breakages in pipes. This measure corresponds to the (estimated) total amount of water theft in the cooperative.

The survey was carried out in five governorates of a northern region of Tunisia (notably Béja, Bizete Jendouba, Manouba, and Sousse), a country that faces growing water scarcity. Government policies for the last three decades have promoted irrigated cropping patterns at the expense of dryland farming. As a consequence, there has been an increase in water use in the agricultural

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[23] It is hard to show this analytically because while cooperative size apparently increases the incentives of members to free-ride on monitoring (The intuition suggests that cooperative size affects monitoring in two ways. On one hand, a larger group discourages monitoring because of free-riding. On the other hand, a larger team may increase the total amount of theft in the cooperative increasing thereby the maximum punishment that would be incurred by a member who was the only one to be caught, increasing therefore the incentives for monitoring.

Due to analytical complexity, we have examined these issues through a numerical example. Simulation results suggest that for punishment levels laying between t and $2t$, the cooperative size reduces the members' incentives to perform monitoring (meaning that the free-riding effect tends to always dominate any other effect) as well as to steal from each other, it also increases the maximum punishment that would be incurred by a member who was the only one to be caught, which acts as an incentive in the opposite direction.

sector. At the same time, the expansion of the other major sectors of the economy (industry and tourism) has increased competing water demands outside the agricultural sector. In addition, a relatively cheap pricing policy, where irrigation water is charged at its average variable cost rather than its long-run marginal cost, has led to a choice of cropping patterns where low value and/or water-intensive crops are grown. Indeed, despite the country's comparative disadvantage in water-intensive crops, the main exported farm goods are dates and citrus fruits, which have water consumption averages of 15,000 m^3 and 10,000 m^3 per hectare, respectively. In this agro-climatic zone, wheat, olives, and gardening products are the main crops in the winter season, with wheat being by far the most important in terms of cultivated area (76.7%). Tomatoes, watermelon, potatoes, grapes, apples, and pears are the main crops in the summer season. The region receives moderate and erratic rainfall averaging 570 mm per year, mainly concentrated during the winter season from December to February. Farmers therefore rely heavily on water sources controlled by water agencies for the remainder of the year. The region is mostly flat, with hills covering only 30% of its total area. One distinguishing feature of the governorates under study is that they vary considerably with respect to geographical and socioeconomic characteristics (see Mattoussi 2006). A centralized mode of regulation dominated water management in the country until 1987, except in the south, where a system of participatory management has been in place in the region of "Djerid" since the 13th century. Under the participatory system, the distribution of water in the oases was held by a "syndic" chosen by the beneficiaries, assisted by the "Kbar" (community elders). Under the centralized scheme, management responsibilities of regional authorities in charge of running public irrigated areas on behalf of the Central Water Authority (CWA), the "Agricultural Regional Development Commissions" (ARDC), include providing public areas with water, dealing with the operation and maintenance of irrigation systems, replacing equipment, monitoring farmers to reduce the occurrence of theft when areas are equipped with measuring devices, and collecting water proceeds. However, since 1987, participatory management was implemented through "Collective Interest Groups" (CIGs), which have become a central component of governmental reforms in the water sector. The participatory approach sped up the transfer of water management from the administration to beneficiaries between 1987 and 2003, when the number of CIGs increased from 100 to over 1,000. The simplest water distribution plan is that related to rural drinking water, followed by small and medium-scale irrigation networks whose areas vary between 20 ha and 700 ha. The CIGs for irrigation cover 56% of irrigated areas equipped by public investment, with a total surface area of 121,000 hectares. The CIGs began by assuming energy costs first and extending afterwards to pump attendants' salaries, thus relieving the state from all energy and personnel costs. The ARDCs still support simple CIGs for major maintenance works and equipment replacement. They also set water tariffs for the CIGs of the region, and decide about the area covered. The main question is how these areas are covered. Such a decision is based on a technical study conducted by the Ministry of Agriculture. The area covered is also influenced by geographical constraints and inferior infrastructure, for instance, areas might be bordered by water streams such as rivers, by mountains and/or by main roads or highways.

Most governorates in the survey have operated under participatory management since 1989, except Zaghouan, for which such management was introduced in 1960 through the project of "Jenan Zaghouan." In 2003 the region contained more than 482 CIGs, of which 182 are for irrigation; the latter manage 58.8% of its public irrigated areas.

Our target population is the 95 CIGs equipped with individual water meters throughout the country. Only 49 of these 95 CIGs are permanently functioning and had data available of the kind needed for our study. We are not aware of any biases that might be introduced into our results by this partial availability of data, but evidently the possibility of selection bias cannot be ruled out.

Our data consist of information about the number of cooperative members[24], the price

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[24] Farmers who have plots of land in the cooperative area decide to become members of the cooperative by signing membership contracts specifying that they will be provided water by the cooperative, pay a fixed fee for their membership and commit to participate in meetings decided by managers to discuss some of the cooperative's affairs when it is necessary.

of water charged to farmers, as well as the socioeconomic characteristics of cooperatives managers such as their age and level of education. We also have information about geographical characteristics such as the percentage of cooperatives' area that are hilly and the sources of water supply available to farmers, including those not controlled by government agencies. In addition, the data include information about characteristics such as the percentage of cooperative areas with red soil, and cooperatives' cultivation processes, namely cropping patterns and the diffusion of drip and sprinkler-irrigation systems.

The data are of an unbalanced panel type, and cover the 3 years from 2001-2003 for 39 cooperatives, and the 2 years from 2002-2003 for the remaining 10 cooperatives. Almost all data were jointly provided by the Agricultural Regional Development Commissions (ARDC) of the five governorates, by the "technical directors" of cooperatives who are in charge of the cooperatives' accounting operations, by the pumping attendants when supply sources are boreholes, and by the CWA when some data were not available for some cooperatives. Only a few data were exclusively collected from cooperative managers. We also obtained information from the cooperatives' managing authorities about the types of natural catastrophes that had stricken cooperatives and the extent of damage they caused, and we also cross-checked our estimates of losses in cooperatives' production with the Cells of Agricultural Development (CAD) of the five governorates. We also asked about the prices of farm goods produced by the region in the previous and current seasons.

Before proceeding with the econometric analysis we clarify how we propose to measure the monitoring costs faced by the cooperative.

Proxy Measure of Peer Monitoring Costs

Given that monitoring levels are not directly observable, we need to find a suitable proxy measure.

- DISTANCE: The length of the main road's portion (measured in kilometers) separating the entrances of the cooperative area and the agglomeration. The entrances are officially determined by municipalities where the agglomeration and the cooperative are located.

This is likely to increase monitoring costs because it reduces the ability of cooperative members to observe the behavior of other members as a by-product of their own day-to-day activities.

Monitoring costs cannot by themselves be used as excluded instruments for the endogenous variables since theory predicts that monitoring costs will determine both the choice of institutions (such as the cooperative size and punishment rate), and also the level of theft conditional on that institutional choice. However, we can investigate whether monitoring costs also directly influence the choice of institutional characteristics, as done in section 4. Table 1 shows the descriptive statistics of each variable. The variables we will use in the subsequent empirical analysis are defined as follows:

- ADVERSE CLIMATE: Scores (+2) when the cooperative faces both peak heat higher than 40 degrees Celsius in the shadow during July, August, and September, and lower than average annual precipitation (lower than 500 mm). The score is (+1) when it faces either peak heat higher than 40 degrees Celsius in the shadow during July, August, and September, *or* lower than average annual precipitation (lower than 500 mm), and is (0) otherwise.
- AGE: The average age of farmers who are in charge of running the cooperative.
- ALTERNATIVE REVENUE: Scores (+1) when more than 10% of cooperative members have income from off-farm sources, and (0) otherwise.
- ALTERNATIVE SOURCE: The percentage of active farmers who have alternative sources of water supply that are not controlled by the Agricultural Regional Development Commissions (ARDC), such as lakes and/or rivers.
- DENSITY: The number of individuals living in the agglomeration (village or little town) where the cooperative is located, divided by the surface of the agglomeration (measured in hectares).
- DISTANCE TO LARGE CITY: The distance (measured in kilometers) between the cooperative area and the nearest large city with public infrastructures

Table 1. Summary of Descriptive Statistics

Variable	Unit of Measure	Obs.	Mean	Std. Dev.	Min.	Max.
AGE	Year	137	48.38	6.49	35	65
ADVERSE CLIMATE	Index	137	1.088	0.59	0	2
ALTERNATIVE SOURCE	Percentage	137	0.116	0.19	0	1
ALTERNATIVE REVENUE	Binary variable	137	0.255	0.438	0	1
DENSITY	Individuals per hectare	137	0.26	0.118	0.12	0.56
DISTANCE	Kilometer	137	1.4	0.815	0	3
DISTANCE TO LARGE CITY	Kilometer	137	15.43	5	7	25
DRIP	Percentage	137	0.3	0.13	0.1	0.6
EDUCATION	Year	137	5.63	1.93	3	10.33
EQUIPPED SURFACE (ES)	Hectare	137	234.2	172.34	20	706
HILLY AREA	Percentage	137	0.0572	0.0463	0	0.18
PREVIOUS SPRINKLER	Percentage	137	0.23	0.06	0.1	0.34
PRICE	Tunisian Dinar per m^3 of water reported	137	0.1033	0.027	0.05	0.14
PUNISHMENT RATE (PR)	Days (for which farmers are denied access to water feeding the cooperative) per 10,000 m^3 of water stolen in the cooperative	137	26.25	9.36	12	42
RAINFALL	Index	137	0.956	0.77	0	2
RED SOILS	Percentage	137	0.2	0.127	0	0.7
REVENUE SHOCK	Index	137	0.073	0.863	−2	1
SIZE	Farmer	137	43.07	39.1	3	251
WATER SOURCE	Index	137	1.85	1.37	0	4
WATER THEFT	Percentage	137	0.376	0.19	0	0.876
YEAR	Year	137	2	0.804	1	3
CODE		1 37	25.13	14.2	1	49
log(*EQUIPPED SURFACE*)		137	5.204	0.743	3	6.56
log(*SIZE*)		137	3.43	0.84	0.7	5.52

such as schools, public hospitals, water systems, bridges, roads, and other public buildings.

- DRIP: The percentage of land irrigated by a cooperative equipped with drip irrigation systems.
- EDUCATION: The average number of years of schooling of farmers who are in charge of running the cooperative's affairs.
- EQUIPPED SURFACE: The surface of the cooperative area (measured in hectares). This area is equipped with irrigation network, for example, primary and secondary water tubes, measuring devices, and so on.
- HILLY AREA: The percentage of the cooperative area that is hilly.
- PREVIOUS SPRINKLER: The percentage of the land irrigated by the cooperative that was equipped with sprinkler systems in the previous year.
- PRICE: The price of one unit of water (i.e., the number of Tunisia Dinars per m^3 of water used by the farmer) charged by the WA to the cooperative.
- PUNISHMENT RATE: The number of days for which farmers are denied access to irrigation, expressed per 10,000 m^3 of divergence between the estimated water used by cooperatives members[25] and the total amount of water indicated by the members' meters. This divergence represents the total liability that will be shared between members who are caught stealing.

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[25] See the definition of WATER THEFT.

- SIZE: The number of active farmers who grow crops on land irrigated by the cooperative.
- RAINFALL: This is a somewhat crude measure of the variation in annual precipitation in the region where the cooperative area is located. It scores (+2) when it faces high annual precipitation (higher than 600 mm), (+1) when it faces normal annual precipitation (between 600 mm and 200 mm), (0) when it faces lower than normal annual precipitation (lower than 200 mm).
- RED SOILS: The percentage of the cooperative area with red soil.
- REVENUE SHOCK: This is an index drawn up in discussion with the representatives of each cooperative which captures whether the cooperative had experienced a good or bad previous year relative to what is perceived as normal. It scores (-2) when more than 50% of the cooperative area was ravaged in the previous year by some natural catastrophes such as floods, scorching heat, and crop diseases, and there was also a decrease in the prices of the main farm goods produced by the cooperative. It scores (-1) when up to 50% of the cooperative area was ravaged by some natural catastrophe such as floods, scorching heat, and crop disease, and there was no major change in the prices of the main farm goods produced by the cooperative. It scores (0) when farmers enjoy favorable environmental conditions and there was no rise in the prices of the main farm goods produced by the cooperative. It scores (+1) when farmers enjoy favorable environmental conditions and there was a small rise in the prices of the main farm goods produced by the cooperative. It scores (+2) when farmers enjoy favorable environmental conditions and there was a significant rise in the prices of the main farm goods produced by the cooperative.
- WATER SOURCE: Scores (+4) when the source is a dam with a storage capacity between 400 and 700 millions of m^3 of water (a large dam). It scores (+3) when the source is a dam with storage capacity between 50 and 400 millions of m^3 of water (a medium dam). It scores (+2) when the source is a dam with storage capacity between 10 and 50 millions m^3 of water (a small dam). It scores (+1) when the source is a dam with storage capacity between 1 and 10 millions of m^3 of water (a very small dam) or is a hilly lake. It scores (0) when the source is a borehole.[26]
- WATER THEFT: The differential between estimated water used by cooperative members and that indicated by cooperative members' meters, expressed as a percentage of the estimated water used by members.

Testing the Model: Results

In this section, we report the determinants of water theft using various specifications, including the instrumental variables' regression, to deal with the endogeneity of the institutional characteristics and technological adoption. We then report more detailed econometric evidence about how people involved in the cooperative determine the institutional characteristics, notably the punishment rate and the cooperative size.

3.2.1 Estimation of the Determinants of Water Theft. Here we report the determinants of theft—particularly the predictions that theft is increasing with the price of water, decreasing with the punishment rate, and increasing with the cooperative size and monitoring costs. We regress water theft on the following independent variables:

- PRICE

Institutional Variables:
- PUNISHMENT RATE
- SIZE

Variable Controlling for Water Productivity:
- DRIP

Proxy Measure of Monitoring Costs:
- DISTANCE

Control Variables:
- AGE
- EQUIPPED SURFACE
- REVENUE SHOCK

This index captures the broad characteristics of a shared revenue shock and can thereby be considered as a proxy measure of cooperative members' liquidity constraints. As shown below, this variable is

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[26] We did not use a continuous variable here because we do not have the exact storage capacities of boreholes.

Table 2. Determinants of *WATER THEFT* - Ordinary Least Squares

Independent Variable	First OLS Specification	Second OLS Specification	With Cooperative Fixed Effects
AGE	0.0047 (0.0015)***	0.0044 (0.0016)***	0.029 (0.0076)***
DENSITY	–	0.138 (0.14)	–
DISTANCE	0.084 (0.0156)***	0.077 (0.0174)***	0.032 (0.076)
DRIP	−0.384 (0.106)***	−0.379 (0.1024)***	−1.626 (0.1853)***
log(ES)	−0.071 (0.0177)	−0.077 (0.018)***	−0.069 (0.46)
log(SIZE)	0.124 (0.0125)***	0.118 (0.0135)***	0.124 (0.0342)***
PRICE	1.029 (0.452)***	1.107 (0.486)**	1.35 (1.492)
PUNISHMENT RATE (PR)	−0.0031 (0.001)***	−0.0029 (0.001)***	0.0116 (0.0057)**
REVENUE SHOCK	−0.034 (0.0114)***	−0.033 (0.0112)***	0.0038 (0.015)
CONSTANT	0.068 (0.0912)	0.096 (0.098)	1.715 (2.39)
R^2	0.741	0.743	0.01

Notes: Robust standard errors (for the OLS specification) and standard errors (for the fixed effects specification) are in parentheses; *, **, and *** denote variables significance at the 10%, 5%, and 1% levels, respectively.
1: R^2 between is reported for the fixed effects specification.

associated with water theft in an entirely intuitive direction.

Table 2 illustrates an Ordinary Least Squares estimation of the determinants of water theft. The two first equations (which are OLS regressions with clustering on cooperatives) show that theft increases with the price of water, the cooperative size, and the distance of the cooperative from the village, and is decreasing with the punishment rate. These four effects are all predicted by theory, and all are significant at the 1% level, except the price effect, which is significant at 5%.

The third equation shows that the qualitative findings prove reasonably robust to the inclusion of cooperative fixed effects, although this is a very demanding test since there are only three years of data and not all cooperatives are included. Under fixed effects the standard errors increase, reducing the price effect to insignificance (though without very much modifying the coefficient). Overall, the results clearly support the predictions of the theory, and the remaining coefficients show various controls for which theory provides no unambiguous predictions. The presence of drip irrigation, which increases the productivity of water, lowers theft. The age of the cooperative manager has a positive effect on theft but this is reversed under fixed effects. The presence of a positive revenue shock lowers theft, though not in the fixed effects specification, as does the size of the equipped surface.

We now turn to concerns about the possible endogeneity of some of the right-hand side variables using the IV regression with clustering on cooperatives. The most likely variable to suffer from this problem is PUNISHMENT RATE because higher rates of theft might lead to increased punishment rates. This would bias upward the absolute value of the OLS parameter estimate, since the causal association of high punishment rates with low rates of theft would be offset by a reverse-causal association of high punishment rates with high rates of theft. Similar considerations might apply to Log(SIZE): high rates of theft could lead to smaller-sized cooperatives, especially if members realize that a large organization is prone to free-riding and are more likely to form breakaway organizations. A variable that may be endogenous for different reasons is DRIP: members who expect to steal their water will have weaker incentives to adopt water-saving technologies. This would bias upward the OLS parameter estimate, since a causal association of high drip technology adoption with low rates of theft would be reinforced by a reverse-causal association of high rates of theft with low rates of technology adoption.

To explore these possibilities, our instrumenting strategy is as follows. Beginning with PUNISHMENT RATE, we use the idea that personal characteristics of the cooperative society managers may lead them to be more likely to inflict harsher punishments, and supplement these with geographical characteristics of the localities that may make harsher punishments either more or less costly to inflict. Relevant personal characteristics are captured by the variable EDUCATION. Our use of this variable is inspired by earlier evidence collected by Seabright (1997) that education plays an important role in helping individuals to understand the importance of incentives and devise institutional responses to incentive problems. Seabright (1997) reports evidence from milk producers' cooperative societies in South India that more educated managers are more likely to use incentive-based methods to deter cheating by society members. We use DENSITY for geographical characteristics, that is, the idea is that higher population density may increase the costs in social discord of inflicting punishments, both because people depend more intensely on the land and because the punishers and the punished have to live more closely together. It is possible, however, that DENSITY also proxies for ease of monitoring, and may therefore affect theft directly and not just via PUNISHMENT RATE. We test for this below, and find the exclusion restriction justified. Finally, we use WATER SOURCE as an instrument, as it seems likely that larger sources of water make it easier to exclude individuals who steal since there are more third parties who are likely to be affected, and therefore more pressure exists to sanction water theft. As an instrument for Log(SIZE) we use the geographical variable HILLY AREA, that is, areas that are hilly are more likely to be limited by topographical constraints.

Finally, as instruments for DRIP we use one geographical and two climatic variables that influence the productivity of the technology, and two variables that capture the ability of farmers to afford the necessary investment. The variable RED SOILS are those with lower water retention on which drip technology therefore saves more water. The variables RAINFALL and ADVERSE CLIMATE[27] capture the relative abundance and scarcity of water to the cooperative, respectively. The ALTERNATIVE REVENUE variable captures the greater economic ability of the farmers to afford investments in drip technology, while PREVIOUS SPRINKLER captures the farmers' awareness of the benefits of water-saving technologies.

A word of caution is in order. Although we find the exclusion restrictions plausible, we cannot rule out a priori that the proposed instruments do in fact affect theft directly, so we pay particular attention to the statistical tests of overidentifying restrictions that we report in all the instrumental variable specifications below.

Table 3 reports the results of these instrumental variables estimations. We first instrument for PUNISHMENT RATE, then for PUNISHMENT RATE and DRIP, and finally for both of these variables, as well as for Log(SIZE). In the final equation we replace EDUCATION[28] by the distance of the cooperative from the nearest large city,[29] which is a more clearly exogenous variable, and which is a significant predictor of education. Results provide a striking confirmation of our hypotheses about the determinants of theft, even when we control for the endogeneity of institutional rules and technology adoption. All the variables that were significant in our OLS specification remain significant in the 2SLS specification at a 5% level at least, and in most cases at a 1% level. The variables also show that our concerns about endogeneity are justified, though more for some variables than for others. The coefficient on PUNISHMENT RATE more than doubles in absolute magnitude compared to the OLS specification, suggesting that there is indeed a reverse causality effect of theft that tends to increase punishment rates. The Durbin-Wu-Hausman tests reject exogeneity of PUNISHMENT RATE at less than 5% significance level. The coefficient on DRIP falls a bit in absolute magnitude, confirming our conjecture that the OLS estimate is biased away from zero. A Durbin-Wu-Hausman test on this variable alone (not reported) rejects exogeneity at around a 33% level of significance. The coefficient on SIZE, however, does not change in a consistent way—the effect of instrumenting relative to OLS depends on the specification in question, and the coefficient does not change very much. Indeed, a Durbin-Wu-Hausman test on this variable alone (not

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[27] This captures a more general range of adverse climatic conditions than simple water scarcity, and which have been found by other researchers to be associated with technology adoption (see Koundouri et al. 2006).

[28] Which may not be quite appropriate as an instrument for Log(SIZE) since larger cooperatives are more likely to have educated individuals to call upon meaning that the proportion of educated farmers in the team of cooperative members in charge of running the cooperative's affairs is likely to increase.

[29] This is a plausible positive proxy for education infrastructure or/and for proximity to schools.

Table 3. Determinants of *WATER THEFT* - Instrumental Variables

Variable	Eq.3.1[a]	Eq.3.2[b]	Eq.3.3[c]	Eq.3.4[d]
Instrumented:	*PR*	*+DRIP*	*+log(SIZE)*	as 3.3
Independent variable:				
PRICE	1.576 (0.523)***	1.335 (0.467)***	1.0498 (0.4605)**	0.982 (0.48)**
log(SIZE)	0.1043 (0.016)***	0.1078 (0.0142)***	0.132 (0.0193)***	0.132 (0.019)***
PUNISHMENT RATE (PR)	−0.0079 (0.002)***	−0.0071 (0.0017)***	−0.0055 (0.0013)***	−0.0048 (0.00138)***
DISTANCE	0.079 (0.019)***	0.0788 (0.0178)***	0.0772 (0.0163)***	0.0785 (0.016)***
DRIP	−0.403 (0.11)***	−0.352 (0.124)***	−0.3122 (0.116)***	−0.314 (0.1189)***
AGE	0.0069 (0.002)***	0.0066 (0.0017)***	0.0055 (0.0016)***	0.0052 (0.0015)***
REVENUE SHOCK	0.0293 (0.0113)***	−0.0286 (0.0114)**	−0.0272 (0.01137)**	−0.0285 (0.0111)***
log(ES)	−0.087 (0.023)***	−0.0824 (0.0207)***	−0.0834 (0.0198)***	−0.0797 (0.0189)***
CONSTANT	0.197 (0.12)*	0.162 (0.101)	0.1154 (0.09)	0.096 (0.0927)
Hansen J-stat (% sig)	1.085 (0.58)	2.836 (0.83)	4.326 (0.74)	5.751 (0.57)
Durbin-Wu-Hausman test(%sig)	6.02 (0.014)	6.547 (0.0378)	6.27 (0.099)	3.65 (0.301)

Notes: Robust standard errors are in parentheses, clustered on cooperatives; *, **, and ***denote significance at the 10%, 5%, and 1% levels, respectively.

a. The excluded instruments are education[30], density, and water source.

b. The excluded instruments are as in 3.1 plus red soils, rainfall, adverse climate, previous sprinkler, and alternative revenue.

c. The excluded instruments are as in 3.2, plus hilly area and alternative source.

d. The excluded instruments are as in 3.3 minus education plus distance to large city.

Tables 3.b, 3.c and 3.d below report the first-stage IV estimates of the instrumented variables in the estimation of WATER THEFT. In table 3.b, equation 3.1 reports the estimates of PUNISHMENT RATE (PR), and equation 3.2 reports the estimates of PR and DRIP. In table 3.c, equation 3.3 reports the estimates of PR, DRIP, and log(SIZE). In table 3.d, equation 3.4 reports the estimates of the same instrumented variables as in equation 3.3 (table 3.c), except that in the set of excluded instruments we replace EDUCATION by DISTANCE TO LARGE CITY.

reported) fails to reject exogeneity at anything close to conventional significance levels, although the joint test of the exogeneity of all three variables is clearly rejected. Further, the coefficient on PRICE increases when we instrument for the other variables, suggesting that the impact of PRICE on theft is even stronger before institutional responses act to mitigate it.

The rest of the variables have the expected signs and are significant at a 5% or better level of confidence. The coefficient on DISTANCE is positive, because it reduces the expected level of monitoring, thereby increasing the scope for theft. The coefficient on REVENUE SHOCK is negative as expected. We are not sure how to interpret the positive coefficient on AGE, which is significantly associated with higher punishment rates, and which themselves reduce theft. This positive coefficient may indicate that the older the cooperative managers are[31], the less inclined they are to personally monitor the other members (preferring to rely instead on more stringent punishment) to reduce their incentives of theft. This is in line with the findings of Niels Hermes, et al. (2000). who report evidence that peer-monitoring by group leaders helps to reduce cheating by borrowers and increase their repayment performance. Similarly, it is not clear how to interpret the negative coefficient on EQUIPPED SURFACE. This variable may well be associated with the wealth of the region where the cooperative is located, which will tend to be positively associated with the productivity of investment by the Water Authority in the region concerned. If so, EQUIPPED SURFACE may be negatively associated with liquidity constraints, and thereby be associated with lower incentives of theft.

Finally, the instruments comfortably pass the Hansen test of overidentifying restrictions. Our exploration of the link between

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[30] The variable education suffers from endogeneity, and in equation 3.4 we instrument for it using a more exogenous variable, namely, the distance of the cooperative to the nearest large city.

[31] The managers' age might well be interpreted as a positive proxy for costs of monitoring performed by this former.

Table 4. First-Stage IV Estimates of the Instrumented Variables in the Estimation of *WATER THEFT* (Equation 3.1 and Equation.3.2)

	Equation 3.1	Equation 3.2	
Instrumented Variable	*PR*	*PR*	*DRIP*
Independent variable			
PRICE	49.45 (38.23)	74.28 (40.352)*	1.043 (0.448)**
log(SIZE)	−0.333 (1.967)	0.0832 (1.79)	0.0034 (0.012)
PUNISHMENT RATE (PR)	–	–	–
DRIP	−6.87 (7.87)	–	–
DISTANCE	0.07 (2.15)	−0.412 (1.912)	−0.0152 (0.018)
AGE	0.473 (0.179)**	0.497 (0.1794)***	−0.0002 (0.0012)
REVENUE SHOCK	0.673 (0.77)	0.617 (0.823)	0.00313 (0.0068)
log(ES)	−3.235 (1.97)	−3.42 (1.86)*	−0.0143 (0.0175)
EDUCATION	2.13 (0.63)***	2.198 (0.59)***	0.00446 (0.00325)
DISTANCE TO LARGE CITY	–	–	–
DENSITY	−40.4 (13.78)**	−31.217 (13.25)**	−0.084 (0.15)
WATER SOURCE	2.84 (1.352)**	2.48 (1.23)**	0.009 (0.013)
RED SOILS	–	3.98 (9.28)	0.23 (0.0475)***
ADVERSE CLIMATE	–	−0.059 (1.79)	0.066 (0.018)***
PREVIOUS SPRINKLER	–	14.87 (14.89)	0.709 (0.173)***
ALTERNATIVE REVENUE	–	−6.48 (2.43)***	0.0445 (0.023)*
RAINFALL	–	0.535 (0.675)	−0.024 (0.0086)***
HILLY AREA	–	–	–
ALTERNATIVE SOURCE	–	–	–
CONSTANT	11.53 (12.95)	1.79 (12.82)	−0.0045 (0.0734)
F-statistic (excluded instruments)	$F(3, 48) = 6.58$	$F(8, 48) = 3.11$	$F(8, 48) = 26.61$

EDUCATION and institutional rules has an important and intuitive interpretation whose importance goes far beyond this particular context (and is supported by the work reported in Seabright (1997)); namely, education has a powerful effect on the choice of institutions in a direction that tends to reduce theft, but has no direct effect on theft apart from this.

Institutional Characteristics

In this section we report the determinants of institutional characteristics, notably the punishment rate and the cooperative size.

Endogenous Punishment

Here we report the results of our estimates of the determinants of the PUNISHMENT RATE. The independent variables we use are the three discussed above, plus two controls:

Personal characteristics:

- EDUCATION

Physical characteristics affecting the ease of inflicting punishment:

- DENSITY
- WATER SOURCE

Control variables:

- AGE
- DISTANCE

Table 7 reports two OLS (equations 7.1 and 7.2) and a 2SLS (equation 7.3) estimation regressions with clustering on cooperatives. In equation 7.1, we use just the first four variables. In equation 7.2, we add the control for DISTANCE. The purpose of controlling for DISTANCE is twofold. The first is to determine whether monitoring costs directly influence the choice of punishment. The answer is that they are not. The second is to determine whether its inclusion changes the coefficient on DENSITY, which might indicate that the latter is in fact proxying for monitoring costs and may therefore have a direct impact on theft. In fact, DISTANCE is insignificant in the second equation, and its inclusion leaves the coefficient on DENSITY almost unchanged; this increases our confidence in its validity as an instrument in the theft equations reported above, as well as in the conclusion that monitoring costs do not directly affect the choice of punishment rate. The negative coefficient on DENSITY may well indicate that monitoring costs do increase the required level of punishment. The latter instead responds to factors that affect the cost of inflicting punishment, as well as the ability of cooperative managers to understand the significance of incentives in the effective running of the organization.

The variable AGE is indeed significant and has a positive coefficient. One plausible interpretation for the coefficient's sign is that older cooperative managers are likely to be more experienced in the use of incentives. It may also indicate that they are less inclined to perform monitoring themselves.

We also undertook a two-stage least squares estimation (equation 7.3) with clustering on cooperatives, instrumenting EDUCATION with DISTANCE TO LARGE CITY, but this did not change the coefficient significantly.[32]

Cooperative Size

Here we report the results for the determinants of Log(SIZE). Once again we use an approach based on both personal characteristics and geographical characteristics. We use the same variables as for PUNISHMENT RATE, plus two additional geographical variables that are likely to be particularly relevant for determining cooperative size. The first is ALTERNATIVE SOURCE, which measures the proportion of farmers who have access to water sources that are not controlled by the Water Authority (this is likely to reduce cooperative size for any given population since it decreases the incentive for farmers to join the cooperative). The second is HILLY AREA, which is likely to have a negative effect on cooperative size by reducing the populated area in a given community. We expect WATER SOURCE to have a positive coefficient since larger sources make it easier to support more cooperative members.

As with PUNISHMENT RATE, we shall also try to determine whether DISTANCE is a significant regressor. Unlike in the case of PUNISHMENT RATE, there are some reasons to fear that EDUCATION may be endogenous since it is likely that larger cooperatives will have more educated members to call upon in the course of managing the cooperative. This would tend to bias downward the OLS parameter estimate (since a negative causal link would be offset by a positive reverse-causal link). We therefore try endogenizing EDUCATION using DISTANCE TO LARGE CITY as an instrument.

This leaves us with the following variables in the main equation:

- ALTERNATIVE SOURCE
- EDUCATION
- DENSITY
- DISTANCE
- HILLY AREA
- WATER SOURCE

Table 8 (which illustrates two OLS and a 2SLS estimation regressions with clustering on cooperatives) shows our results. The findings are consistent with those for PUNISHMENT RATE. The variable EDUCATION has an important influence on cooperative size in the expected direction, which is that more educated members choose smaller cooperatives (in the sense that more educated individuals may better understand the use of incentives and adapt cooperative rules to make theft more difficult). This finding is strengthened when we instrument for EDUCATION, since there is an effect of reverse causality making larger cooperatives contain more educated members. Instrumenting increases the absolute magnitude of the coefficient on EDUCATION by more than one half, a difference that is significant under a 5% level.

Once again, DISTANCE is insignificant and makes no difference to the coefficients on the other explanatory variables, including DENSITY. This implies that cooperative size is not influenced directly by monitoring costs, but rather by the various geographical constraints that directly influence the costs and benefits of size, with more educated managers of the society appreciating the benefits of smaller size in terms of theft reduction. The insignificance of DISTANCE and its lack of correlation with DENSITY also strengthens our confidence in the exclusion restrictions in the theft equations in table 3.

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[32] The positive coefficient on EDUCATION (as reported in table 4) is unlikely to be due to the fact that more educated individuals are richer and can afford to pay higher fines, since the punishment is measured in terms of the length of time for which water is cut off from a cheating member - a measure whose cost is increasing in the amount of land cultivated by the concerned farmer.

Table 5. First-Stage IV Estimates of the Instrumented Variables in the Estimation of *WATER THEFT* (Equation 3.3)

	Equation 3.3		
Instrumented Variable	*PR*	*DRIP*	*log(SIZE)*
Independent variable			
PRICE	69.765 (42.55)	1.027 (0.43)**	2.976 (2.615)
log(SIZE)	–	–	–
PUNISHMENT RATE (PR)	–	–	
DRIP	–	–	–
DISTANCE	−0.36 (1.74)	−0.016 (0.02)	−0.072 (0.087)
AGE	0.501 (0.188)**	0.0005 (0.0015)	0.0007 (0.0089)
REVENUE SHOCK	1.005 (0.853)	0.0002 (0.0068)	−0.055 (0.093)
logES	−3.36 (1.77)*	−0.0104 (0.0175)	0.974 (0.108)
EDUCATION	2.373 (0.46)***	0.003 (0.003)	−0.092 (0.036)**
DISTANCE TO LARGE CITY	–	–	–
DENSITY	−37.78 (12.64)***	0.006 (0.14)	1.82 (0.86)**
WATER SOURCE	2.803 (1.236)**	0.0049 (0.0133)	0.109 (0.076)
RED SOILS	6.29 (8.74)	0.212 (0.045)***	0.108 (0.46)
ADVERSE CLIMATE	0.32 (1.69)	0.058 (0.0164)***	−0.082 (0.0906)
PREVIOUS SPRINKLER	17.71 (14.24)	0.697 (0.168)***	0.77 (0.53)
ALTERNATIVE REVENUE	−6.02 (2.32)**	0.042 (0.02)*	0.23 (0.104)
RAINFALL	−0.42 (0.66)	−0.025 (0.0085)**	−0.005 (0.029)
HILLY AREA	−14.745 (22.004)	0.313 (0.22)	−4.08 (1.81)**
ALTERNATIVE SOURCE	−8.267 (3.128)**	0.044 (0.0216)**	−1.52 (0.416)***
CONSTANT	2.094 (12.56)	−0.055 (0.093)	2.76 (0.655)***
F-statistic (excluded instruments)	$F(10, 48) = 6.63$	$F(10, 48) = 20.99$	$F(10, 48) = 11.85$

Table 6. First-Stage IV Estimates of the Instrumented Variables in the Estimation of *WATER THEFT* (Equation 3.4)

	Equation 3.4		
Instrumented Variable	*PR*	*DRIP*	*log(SIZE)*
Independent variable			
PRICE	150.18 (49.003)***	0.97 (0.47)**	0.104 (2.69)
log(SIZE)	–	–	–
PUNISHMENT RATE (PR)	–	–	–
DRIP	–	–	–
DISTANCE	−2.78 (1.84)	−0.013 (0.0175)	0.0126 (0.094)
AGE	0.49 (0.182)***	0.0005 (0.0014)	0.0013 (0.009)
REVENUE SHOCK	0.94 (0.88)	0.0007 (0.007)	−0.044 (0.036)
loges	−5.42 (1.86)***	−0.0077 (0.018)	0.17 (0.12)
EDUCATION	–	–	–
DISTANCE TO LARGE CITY	−1.047 (0.244)***	0.0014 (0.0022)	0.036 (0.015)**
DENSITY	−25.1 (14.42)*	−0.0144 (0.144)	1.39 (0.89)
WATER SOURCE	3.65 (1.27)***	0.00013 (0.012)	0.086 (0.087)
RED SOILS	11.47 (7.69)	0.19 (0.04)***	−0.045 (0.58)
ADVERSE CLIMATE	0.32 (1.81)	0.058 (0.017)***	−0.08 (0.097)
PREVIOUS SPRINKLER	19.72 (15.92)	0.71 (0.17)***	0.68 (0.55)
ALTERNATIVE REVENUE	−5.48 (2.62)**	0.042 (0.022)*	0.21 (0.105)*
RAINFALL	−0.64 (0.74)	−0.025 (0.0082)***	0.0029 (0.032)
HILLY AREA	1.27 (28.77)	0.042 (0.022)*	−4.66 (1.72)***
ALTERNATIVE SOURCE	−9.52 (3.34)***	0.055 (0.026)**	−1.49 (0.43)***
CONSTANT	30.92 (14.56)**	−0.057 (0.09)	1.705 (0.76)**
F-statistic (excluded instruments)	$F(10, 48) = 4.43$	$F(10, 48) = 24.10$	$F(10, 48) = 12.80$

Table 7. Determinants of *PUNISHMENT RATE*

Independent Variable Specification	Eq.7.1	Eq.7.2	Eq.7.3
	OLS	OLS	2SLS
AGE	0.457 (0.1502)***	0.438 (0.167)**	0.452 (0.149)***
DENSITY	−55.07 (9.926)***	−53.965 (10.73)***	−56.098 (10.254)***
DISTANCE	–	−0.525 (1.965)	–
EDUCATION	2.195 (0.599)***	2.197 (0.607)***	1.928 (0.806)**
WATER SOURCE	2.662 (1.072)**	2.837 (1.22)**	2.561 (1.056)**
CONSTANT	1.303 (8.36)	2.33 (9.545)	3.511 (9.786)
R^2	0.543	0.544	0.541
Durbin-Wu-Hausman test(%sig)	–	–	0.445 (0.5048)

Note: Robust standard errors are in parentheses, clustered on cooperatives; *, **, and *** denote variables significant at 10%, 5%, and 1%, respectively.

Table 8. Determinants of Log(*SIZE*)

Independent Variable Specification	Eq.8.1	Eq.8.2	Eq.8.3
	OLS	OLS	2SLS
ALTERNATIVE SOURCE	−1.413 (0.37)***	−1.415 (0.369)***	−1.343 (0.41)***
DENSITY	1.762 (0.76)**	1.835 (0.61)***	1.69 (0.798)**
DISTANCE	0.023 (0.926)	–	0.0232 (0.094)
EDUCATION	−0.0874 (0.042)**	−0.08742 (0.0418)**	−0.136 (0.045)***
HILLY AREA	−3.854 (1.83)**	−3.761 (1.69)**	−3.597 (1.947)*
WATER SOURCE	0.185 (0.566)***	0.190 (0.0623)***	0.161 (0.06)***
CONSTANT	3.471 (0.247)***	3.47 (0.246)***	3.784 (0.31)***
R^2	0.806	0.8058	0.797
Durbin-Wu-Hausman test (%sig)	–	–	4.946 (0.026)

Note: Robust standard errors are given in parentheses, clustered on cooperatives; *, **, and ***denote variables significant at the 10%, 5%, and 1% levels, respectively.

Table 9 reports the first-stage IV estimates of the instrumented variables in the estimation of PUNISHMENT RATE and log(SIZE). In equations 7.3 (PR) and 8.2 (log(SIZE)), we report the estimates of EDUCATION.

Table 9. First-Stage IV Estimates of the Instrumented Variables in the Estimation of *PUNISHMENT RATE* (*PR*) and log(*SIZE*)

Independent Variable Specification	Eq.7.3(*PR*)	Eq.8.2(*log*(*SIZE*))
	EDUCATION	EDUCATION
Independent variable		
DISTANCE	−0.3076 (0.37)	0.466 (−0.416)
AGE	−0.021 (0.033)	–
EDUCATION	–	–
DISTANCE TO LARGE CITY	−0.27 (0.042)***	−0.28 (0.043)***
DENSITY	−4.454 (1.93)**	−0.766 (3.39)
WATER SOURCE	0.377 (0.27)	0.283 (0.271)
ALTERNATIVE SOURCE	–	0.35 (1.116)
HILLY AREA	–	11.021 (7.687)
CONSTANT	11.72 (1.75)***	9.704 (1.178)***
F-statistic (excluded instruments)	$F(1, 48) = 41.03$	$F(1, 48) = 44.17$

Conclusions on Institutional Characteristics

The results of these two exercises on the determinants of PUNISHMENT RATE and Log(SIZE) can be summarized as follows.

The choice of PUNISHMENT RATE and Log(SIZE) do seem to be influenced by geographical factors that affect the costs and benefits of making these respective choices. The variable DENSITY makes punishment more difficult to be implemented and larger cooperatives easier to form. These choices are also clearly influenced by the education levels of the farmers who run the cooperatives. The latter appear to be aware of the importance of their choices for effective cooperative management, and more educated people make these choices in ways that tend to reduce theft. We have found, however, no direct evidence that high monitoring costs in themselves lead to theft-reducing choices of these institutional variables. This may of course be due to the fact that DISTANCE is a very imperfect proxy for monitoring costs. We have considered whether our variable DENSITY could in fact be proxying for monitoring costs, which would suggest a role for such costs in both the choices of PUNISHMENT RATE and Log(SIZE). However, the results of our regressions on the determinants of water theft show that DENSITY is insignificant in all specifications, which is inconsistent with the hypothesis that this variable is an alternative proxy for monitoring costs. We are thus left to conclude that while monitoring costs directly affect theft, they do not directly affect institutional characteristics, which are responsive to other factors that influence their costs and benefits as well as to the education levels of the farmers who manage the organization.

Conclusion

This paper has investigated how cooperative members choose their institutional rules in terms of the cooperative size and the level of punishment inflicted on farmers who are caught stealing water. We also show how the institutional rules and formal incentives affect farmers' decisions in terms of water theft. Based on survey data from irrigation cooperatives in five governorates in the north of Tunisia, the econometric evidence supports the findings of the theoretical models in that the size of the cooperatives and the levels of punishment inflicted on members caught stealing water depend on the perceived costs and benefits of such choices. We also find support for the role of higher cooperative size in increasing the incentives for theft and of a higher level of punishment in reducing them. Moreover, the econometric evidence lends credence to the fact that monitoring costs and the price of water increase theft, and drip-irrigation technology in turn reduces it.

Overall, these results provide strong confirmation of the ability of well-designed incentives to reduce theft, and that institutions are not just exogenously given features of the social environment but adapt to the perceived costs and benefits of designing them in particular ways. Our results also show that higher monitoring costs have a positive effect on the incidence of theft, though various institutional innovations can counteract such effect.

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APPENDIX

Proof of Proposition 1

In the absence of monitoring, cooperative members would share the fine equally. By monitoring each other, members reallocate the burden of the fine between themselves. Denote by $s_i^{\exp}(a_i, m_i; a_j, m_j)$ the farmer i's expected share of such a fine, where $a_k = (q_k - q_k^r)$ is the amount of water stolen by farmer k, for $k = i, j$. In what follows we will focus only on symmetric equilibria. Suppose that both farmers steal, that is, $a_k > 0$. The expected share[33] of farmer i is lowered by the likelihood of discovering her peer cheating, and is in turn increased by the likelihood that she herself is discovered stealing by her peer:

$$\text{(A.1)} \quad s_i^{\exp} = \frac{1}{2}(1 - \kappa m_i a_j + \kappa m_j a_i).$$

The subgame perfect equilibrium for this case corresponds to the profile (m_1^c, m_2^c, q_1^c, q_2^c, q_1^{rc}, q_2^{rc}) of monitoring efforts $m_i^c \in 0, +\infty)$, water use levels $q_i^c : [0, +\infty)^2 \to 0, +\infty)$ mapping from the set of monitoring decisions into the set of water use decisions and water reports[34] $q_i^{rc} : [0, +\infty)^2 \to [0, q_i]$ mapping from the set of monitoring decisions into the set of reports. The objective function of farmer i is thus given by:

(A.2)

$$\begin{aligned} &U_i\left(m_i, q_i, q_i^r\right) \\ &\quad = g(q_i) - cq_i - tq_i^r - \frac{1}{2}f \\ &\quad \times \left\{ \begin{matrix} \left(1 - \kappa m_i \left(q_j - q_j^r\right) + \kappa m_j \left(q_i - q_i^r\right)\right) \\ \left(\left(q_i - q_i^r\right) + \left(q_j - q_j^r\right)\right) \end{matrix} \right\} \\ &\quad - \psi(m_i). \end{aligned}$$

We solve the game by backward induction. At stage 2 of the game, farmer i optimally chooses the amount of water to use, $q_i^c \equiv q_i^c(m_i, m_j)$ and the report to file, $q_i^{rc} \equiv q_i^{rc}(m_i, m_j)$, which maximize her expected payoff, given the levels of monitoring performed by the two members, m_i and m_j, and that farmer j chooses $q_j^c \equiv q_j^c(m_i, m_j)$ and $q_j^{rc} \equiv q_j^{rc}(m_i, m_j)$,

$$\max_{(q_i, q_i^r)} U_i(m_i, q_i, q_i^r).$$

The first-order conditions with respect to q_i and q_i^r are, respectively, given by:

$$\begin{aligned} \text{(A.3)} \quad & q_i^c : g'(q_i) - c - \frac{1}{2}\kappa m_j f \left(\sum_{k=i,j} (q_k - q_k^r) \right) \\ & - \frac{1}{2} f \left(1 - \kappa m_i \left(q_j - q_j^r\right) \right. \\ & \left. + \kappa m_j \left(q_i - q_i^r\right)\right) = 0 \end{aligned}$$

and

$$\begin{aligned} \text{(A.4)} \quad & q_i^{rc} : -t + \frac{1}{2}\kappa m_j f \left(\sum_{k=i,j} (q_k - q_k^r) \right) + \frac{1}{2} f \\ & \times \left(1 - \kappa m_i (q_j - q_j^r) + \kappa m_j (q_i - q_i^r)\right) \\ & = 0. \end{aligned}$$

Rewriting equation (A.4) gives the price of water t:

$$\begin{aligned} \text{(A.5)} \quad & t = \frac{1}{2}\kappa m_j f \left(\sum_{k=i,j} (q_k - q_k^r) \right) + \frac{1}{2} f \\ & \left(1 - \kappa m_i (q_j - q_j^r) + \kappa m_j (q_i - q_i^r)\right). \end{aligned}$$

Replacing the expression

$$\begin{aligned} & \left\{ \frac{1}{2}\kappa m_j f \left(\sum_{k=i,j} (q_k - q_k^r) \right) + \frac{1}{2} f \right. \\ & \left. \times \left(1 - \kappa m_i (q_j - q_j^r) + \kappa m_j (q_i - q_i^r)\right) \right\} \end{aligned}$$

by t (as shown by equation (A.5)) into equation (A.3) yields

$$\text{(A.6)} \quad g'(q_i) = c + t.$$

This means that the amount of water used by farmer i is independent of monitoring and punishment levels. The objective function $U_i(.,.)$ is strictly concave since its

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[33] The set of reports is reduced to $[0, q_i]$ because it is assumed throughout this paper that there are no rewards for over-reporting.

[34] The expected share of farmer i from the cooperative fine when everyone steals is given by:

$$\begin{aligned} s_i^{\exp} &= \frac{1}{2}(\kappa m_i a_j)(\kappa m_j a_i) + \kappa m_j a_i (1 - \kappa m_i a_j) \\ &\quad + \frac{1}{2}(1 - \kappa m_i a_j)(1 - \kappa m_j a_i) \end{aligned}$$

where the first term corresponds to her share when both farmers are caught stealing, the second term is her share when she is caught and farmer j is not, and the last term is her share when noone is caught.

Rearranging the equation above gives the expression in (A.1).

Hessian matrix

$$\text{(A.7)}\quad \mathbf{D}^2\mathbf{U}_i(\mathbf{q}_i, \mathbf{q}_i^r) = \begin{pmatrix} \mathbf{g''(q_i)} - \kappa\mathbf{fm_j} & \kappa\mathbf{fm_j} \\ \kappa\mathbf{fm_j} & -\kappa\mathbf{fm_j} \end{pmatrix}$$

is negative definite (since its first and second principal minors are negative and positive, respectively). Therefore, the first-order conditions are both necessary and sufficient to identify a global maximum.

It follows from equations (A.3) and (A.4) that the two expressions below are equal to zero:

$$\left\{ g'(q_i) - c - \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k - \frac{1}{2} f\left(1 - \kappa m_i a_j + \kappa m_j a_i\right) \right\} = 0$$

$$\text{(A.8)}\quad \frac{\partial U_i^c}{\partial m_i} = \left\{ \begin{array}{c} \left(g'(q_i) - c - \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k - \frac{1}{2} f\left(1 - \kappa m_i a_j + \kappa m_j a_i\right) \right) \frac{\partial q_i}{\partial m_i} \\ + \left(-t + \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k + \frac{1}{2} f\left(1 - \kappa m_i a_j + \kappa m_j a_i\right) \right) \frac{\partial q_i^r}{\partial m_i} \\ + \frac{1}{2}\kappa f(a_i + a_j)\left(a_j + m_i \frac{\partial a_j}{\partial m_i} \right) \\ - \frac{1}{2} f(1 - \kappa m_i a_j + \kappa m_j a_i) \frac{\partial a_j}{\partial m_i} - \psi'(m_i) \end{array} \right\}.$$

To simplify our calculations in the remainder of this proof, we will replace in equations (A.3) and (A.4) the amount of water stolen by farmer k, notably $(q_k - q_k^r)$ by a_k for $k = i, j$

$$\text{(A'3)}\quad q_i^c : g'(q_i) - c - \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k - \frac{1}{2} f(1 - \kappa m_i a_j + \kappa m_j a_i) = 0,$$

and

$$\text{(A'4)}\quad q_i^{rc} : -t + \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k + \frac{1}{2} f(1 - \kappa m_i a_j + \kappa m_j a_i) = 0.$$

At stage 1 of the game, farmer i chooses the monitoring effort, m_i^c (given that farmer j chooses m_j^c) so as to solve

$$\max_{m_i} g(q_i) - cq_i - tq_i^r - \frac{1}{2} f \times (1 - \kappa m_i a_j + \kappa m_j a_i)(a_i + a_j) - \psi(m_i) \text{ for } i \neq j$$

the first-order condition of which is:

and

$$\left\{ -t + \frac{1}{2}\kappa m_j f \sum_{k=i,j} a_k + \frac{1}{2} f\left(1 - \kappa m_i a_j + \kappa m_j a_i\right) \right\} = 0.$$

This reduces (A.8) to the following expression:

$$\text{(A.9)}\quad \frac{\partial U_i^c}{\partial m_i} = \frac{1}{2}\kappa f(a_i + a_j)\left(a_j + m_i \frac{\partial a_j}{\partial m_i} \right) - \frac{1}{2} f\left(1 - \kappa m_i a_j + \kappa m_j a_i\right) \times \frac{\partial a_j}{\partial m_i} - \psi'(m_i).$$

Given that the problem is symmetric for player j, the first-order condition with respect to the report filed by player j immediately follows from equation (A.4) above:

$$\text{(A.10)}\quad q_j^{rc} : -t + \frac{1}{2}\kappa m_i f \sum_{k=i,j} a_k + \frac{1}{2} f\left(1 - \kappa m_j a_i + \kappa m_i a_j\right) = 0.$$

Rewriting and rearranging equations (A.4) and (A.10) yields the following system of two equations as functions of the levels of water stolen by the two cooperative members, notably a_i and a_j

$$\text{(A.11)}\quad \begin{cases} 2\kappa m_j a_i + \left(\kappa m_j - \kappa m_i\right) a_j = \frac{2t-f}{f} \\ \left(\kappa m_i - \kappa m_j\right) a_i + 2\kappa m_i a_j = \frac{2t-f}{f} \end{cases}.$$

Solving system (A.11) gives the respective amounts of water stolen by farmers i and j as functions of their respective levels of monitoring m_i and m_j:

$$\text{(A.12)}\quad a_i = \left(\frac{2t-f}{\kappa f}\right)\frac{(3m_i - m_j)}{(m_i+m_j)^2}$$

and

$$\text{(A.13)}\quad a_j = \left(\frac{2t-f}{\kappa f}\right)\frac{(3m_j - m_i)}{(m_i+m_j)^2}.$$

Differentiating (A.13) with respect to cooperative members monitoring efforts m_i and m_j, respectively, gives:

$$\text{(A.14)}\quad \frac{\partial a_j}{\partial m_i} = \left(\frac{2t-f}{\kappa f}\right)\frac{(m_i - 7m_j)}{(m_i+m_j)^3}$$

and

$$\text{(A.15)}\quad \frac{\partial a_j}{\partial m_j} = \left(\frac{2t-f}{\kappa f}\right)\frac{(5m_i - 3m_j)}{(m_i+m_j)^3}.$$

Differentiating (A.14) with respect to the monitoring effort performed by farmer i, notably m_i yields

$$\text{(A.16)}\quad \frac{\partial^2 a_j}{\partial m_i^2} = \left(\frac{2t-f}{\kappa f}\right)\frac{(-2m_i + 22m_j)}{(m_i+m_j)^4}.$$

Since we look only at the symmetric subgame perfect equilibrium, then the equilibrium level of theft is $a_i^c = a_j^c \equiv a^c$, and the equilibrium monitoring effort is $m_i^c = m_j^c \equiv m^c$, which are given, respectively, by:

$$\text{(A.17)}\quad a^c = \frac{(2t-f)}{2\kappa m^c f}$$

and

$$\text{(A.18)}\quad m^c : \frac{(2t-f)(2f-t)}{4\kappa f m^2} = \psi'(m).$$

Depending on the stringency of the punishment rate, f, two cases arise.
Case 1: If the punishment rate is stringent enough, that is, when $f \geq 2t$, the equilibrium amount of water stolen for a given level of monitoring will be non positive, that is,

$$\text{(A.19)}\quad a^c = \frac{(2t-f)}{2\kappa m^c f} \leq 0$$

meaning that farmers may well over-report, that is, $a^c < 0$. However, since there are no rewards for over-reporting (by assumption), farmers will never gain by doing so. This implies that theft does not occur in equilibrium

$$\text{(A.20)}\quad a^c = 0.$$

Plugging equation (A.17) into equation (A.18) yields the equilibrium intensity of monitoring, which is implicitly given by

$$\text{(A.21)}\quad \frac{(2f-t)}{2} a^c = m^c \psi'(m^c).$$

Using the fact that theft does not occur in equilibrium and the fact that $\psi'(0) = 0$ yields that farmers do not monitor in equilibrium

$$\text{(A.22)}\quad m^c = 0.$$

$$\text{(A.23)}\quad \frac{\partial^2 U_i}{\partial^2 m_i^2} = \left\{ \begin{array}{c} \frac{1}{2}\kappa f\left(\left(2\frac{\partial a_j}{\partial m_i} + m_i\frac{\partial^2 a_j}{\partial m_i^2}\right)(a_i + a_j) + \left(a_j + m_i\frac{\partial a_j}{\partial m_i}\right)\left(\frac{\partial a_i}{\partial m_i} + \frac{\partial a_j}{\partial m_i}\right)\right) \\ +\frac{1}{2}f\left(\kappa\left(a_j + m_i\frac{\partial a_j}{\partial m_i} - m_j\frac{\partial a_i}{\partial m_i}\right)\frac{\partial a_j}{\partial m_i} - (1 - \kappa m_i a_j + \kappa m_j a_i)\frac{\partial^2 a_j}{\partial m_i^2}\right) - \psi''(m_i) \end{array} \right\}.$$

Case 2: If the punishment rate is less stringent than in the previous case, but exceeds the price of water, that is, when $t < f < 2t$.

Now let us check whether the first-order condition for the level of monitoring m^c given by (A.18) is sufficient. Differentiating (A.9) with respect to m_i provides

Replacing a_k and m_k by the equilibrium levels of theft and monitoring, respectively, a^c and m^c for $k = i, j$ yields that the second partial derivative of the farmer's utility function is strictly negative:

(A.24)
$$\frac{\partial^2 U_i}{\partial m_i^2}(m^c, a^c) = \left(\frac{2t - f}{\kappa f}\right)\left(\frac{t - 3f}{4(m^c)^3}\right) - \psi''(m^c) < 0.$$

This means that the first-order condition for the monitoring level is necessary and also sufficient to identify a global maximum. This completes the proof of proposition 1. ■

B. Centralized Water Management

We assume that under centralized management the WA can commit, before farmers choose their actual and reported levels of water use, to a level m of monitoring its members' activities, at a cost $\Psi(m)$, which is increasing and convex.[35] We assume that monitoring cannot be conditioned on the farmer's report and must be the same for all reports. The probability that a farmer is discovered stealing is given by[36]

(B.1) $$P(m, a) = \min\{\kappa m \max\{a, 0\}, 1\}.$$

When the farmer is caught stealing, her true intake is established without error and she pays tq^r plus a penalty proportional to the amount of water stolen, F^{cs} (the solution to this scheme will be indexed with the superscript "*cs*"). It is the nature of the monitoring system that makes it possible to use a punishment device based on individual levels of theft. The punishment is measured in terms of the length of time for which water is cut off from a cheating member. This length is proportional to the farmer's level of theft. The punishment is assumed to take the form:

(B.2) $$F^{cs} = f \max\{a, 0\}$$

where the punishment rate f is positive, and greater than t (because otherwise farmers will have an interest in stealing everything, see footnote 11).

The order of events is that the WA sets m, and t, then each farmer chooses the quantity of water to use q^{cs} and the report to file q^{rcs}. In what follows we focus on the subgame perfect equilibrium and solve the model by backward induction. In stage 2 of the game, the farmer chooses q^{cs} and q^{rcs} to maximize her expected payoff, that is:

(B.3) $$\max_{(q - q^r)} U^{cs}(q, q^r) = g(q) - cq - tq^r - \kappa m f (q - q^r)^2.$$

Whose first-order conditions with respect to q and q^r are given by (B.4) and (B.5) respectively

(B.4) $$q^{cs} : g'(q^{cs}) = c + 2\kappa m f (q^{cs} - q^{rcs})$$

and

(B.5) $$q^{rcs} : t = 2\kappa m f \left(q^{cs} - q^{rcs}\right).$$

Plugging equation (B.4) into equation (B.5) implies that q^{cs} is independent of m and f

(B.6) $$g'(q^{cs}) = c + t.$$

Now we turn to the initial contracting stage, where the WA anticipates the farmer's behavior and picks a monitoring effort[37] m and a price of water t that maximize the social benefit. Specifically, this benefit function is the sum of the farmers' surpluses $2\left(g(q^{cs}) - (c + t)q^{cs} - \kappa m f (q^{cs} - q^{rcs})^2\right)$ and the water supplier surplus equal to the revenue from water proceeds $2tq^{rcs}$, from which is deduced the cost of water provision to $2\gamma q^{cs}$ and the cost incurred by monitoring

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[35] The cost of monitoring should be understood as including not only the wages of monitors, but other costs as measurement devices aiming to make water intakes observable.

[36] Detecting a cheating farmer is based on detecting her meter's manipulation, which is not based on the amount recorded by the meter (the report), but rather on evidence of manipulation observed on the meter, or catching this farmer while manipulating her meter.

[37] The WA is able to control the punishment rate, f, in addition to controlling the monitoring and pricing decisions. When punishment is endogenous and costly, some level of punishment is always required in equilibrium. However, because punishment is costly, the optimal response of the WA is to tolerate some theft in order to save in punishment costs.

$2\Psi(m)$

$$\text{(B.7)}\quad W^{cs}(m,t) = 2\left(g\left(q^{cs}\right) - (c+\gamma)q^{cs} - \kappa m f\left(q^{cs} - q^{rcs}\right)^2 - \Psi(m)\right).$$

We can then show:

Proposition 2. *The optimal monitoring and pricing policy used by the WA* $\{m^{cs}, t^{cs}\}$ *satisfies*

$$\text{(B.8)}\quad m^{cs}: \frac{(t^{cs})^2}{4\kappa(m^{cs})^2 f} = \Psi'(m^{cs}),$$

$$\text{(B.9)}\quad t^{cs} = \gamma\left(\frac{2\kappa m^{cs} f}{2\kappa m^{cs} f - g''(q^{cs})}\right)$$

and yields a level of theft by each farmer given by

$$\text{(B.10)}\quad a^{cs} = \frac{t^{cs}}{2\kappa f m^{cs}}.$$

Proof. See below after the interpretation of the proposition.

$$\text{(B.11)}\quad \frac{\partial W^{cs}(m,t)}{\partial m} = 2\begin{pmatrix} \left(g'\left(q^{cs}\right) - (c+\gamma) - 2\kappa m f\left(q^{cs} - q^{rcs}\right)\right)\dfrac{\partial q^{cs}}{\partial m} \\ +2\kappa m f\left(q^{cs} - q^{rcs}\right)\dfrac{\partial q^{rcs}}{\partial m} - \kappa f\left(q^{cs} - q^{rcs}\right)^2 - \Psi'(m) \end{pmatrix} = 0.$$

The proposition says that some level of monitoring is always required in equilibrium. However, because monitoring is costly, the optimal response of the WA is to tolerate some theft in order to save in monitoring costs. Moreover, in the presence of theft, the optimal second-best price of water is typically lower than in its absence, that is, $t^{cs} < \gamma$. It is worth tolerating some allocative inefficiency in water use in return for a reduction of theft occurrence.

How feasible it is for the authority to charge below γ for its water will depend on circumstances and particularly the extent to which it is constrained to avoid making losses. In the presence of theft, the authority would make losses in any case if it charged at marginal cost, since this would imply a positive level of theft and therefore an average revenue well below marginal and average cost. If the authority were able to pursue the goal of maximizing social welfare it could set a price that balanced the need to raise revenue with the need to diminish incentives for theft, as we have described. Otherwise it might take explicit account of the shadow price of public funds. We have not pursued these complications here and do not believe they would fundamentally affect the qualitative nature of our calculations. ■

Proof of Proposition 2:

At the initial contracting stage, the WA picks the monitoring level, m and the price of water, t, which maximize the following social welfare function

$$\text{(P)}\quad \max_{(m,t)} W^{cs}(m,t) = 2\left(g(q^{cs}) - (c+\gamma)q^{cs} - \kappa m f(q^{cs} - q^{rcs})^2 - \Psi(m)\right)$$

whose first-order conditions are derived as follows.

1. We take the first partial derivative of the social welfare function, $W^{cs}(m,t)$ with respect to m

We take the first partial derivatives of the farmer's water use and report levels, $q^{cs}$and q^{rcs} (given by equations (B.4) and (B.5) with respect to m

$$\text{(B.12)}\quad \frac{\partial q^{cs}}{\partial m} = 0 \text{ and } \frac{\partial q^{rcs}}{\partial m} = \frac{1}{m}\left(q^{cs} - q^{rcs}\right).$$

Replacing $\frac{\partial q^{cs}}{\partial m}$ and $\frac{\partial q^{rcs}}{\partial m}$ by their expressions into equation (B.12) yields

$$\text{(B.13)}\quad \frac{\partial W^{cs}(m,t)}{\partial m} = 2\left(\kappa f(q^{cs} - q^{rcs})^2 - \Psi'(m)\right) = 0.$$

Moreover, plugging the expression of the level of theft $(q^{cs} - q^{rcs}) = \frac{t}{2\kappa m f}$ into equation (B.13) results in

$$\text{(B.14)}\quad \frac{\partial W^{cs}(m,t)}{\partial m} = 2\left(\frac{t^2}{4\kappa f m^2} - \Psi'(m)\right) = 0.$$

Rearranging equation (B.14) yields the equilibrium monitoring effort which is implicitly given by:

$$\text{(B.15)}\quad \frac{t^2}{4\kappa f (m^{cs})^2} = \Psi'(m^{cs}).$$

2. Second, we take the first partial derivative of $W^{cs}(m,t)$ with respect to t

$$\text{(B.16)}\quad \frac{\partial W^{cs}(m,t)}{\partial t} = 2\left\{\begin{array}{c} \left(g'\left(q^{cs}\right) - (c+\gamma) - 2\kappa mf\left(q^{cs} - q^{rcs}\right)\right)\dfrac{\partial q^{cs}}{\partial t} \\ +2\kappa mf\left(q^{cs} - q^{rcs}\right)\dfrac{\partial q^{rcs}}{\partial t} \end{array}\right\} = 0.$$

Recall that $g'(q^{cs})$ and the first partial derivatives of the farmer's water use and report levels, q^{cs} and q^{rcs} with respect to t are given by:

$$\text{(B.17)}\quad g'(q^{cs}) = c + t;\ \frac{\partial q^{cs}}{\partial t} = \frac{1}{g''(q^{cs})} \quad \text{and} \quad \frac{\partial q^{rcs}}{\partial t} = \frac{1}{g''(q^{cs})} - \frac{1}{2\kappa m^{cs} f}.$$

Substituting $g'(q^{cs})$, $\frac{\partial q^{cs}}{\partial t}$ and $\frac{\partial q^{rcs}}{\partial t}$ by their expressions above into (B.17) yields

$$\text{(B.18)}\quad \frac{\partial W^{cs}(m,t)}{\partial t} = 2\left(\frac{(t-\gamma)}{g''(q^{cs})} - \frac{t}{2\kappa m^{cs} f}\right) = 0.$$

Rearranging equation (B.18) gives the equilibrium price of water

$$\text{(B.19)}\quad t^{cs} = \gamma\left(\frac{2\kappa m^{cs} f}{2\kappa m^{cs} f - g''(q^{cs})}\right).$$

$$\text{(B.20)}\quad \mathbf{D^2W(m,t)} = \begin{pmatrix} -\dfrac{\mathbf{t}^2}{\boldsymbol{\kappa}\mathbf{fm}^3} - \mathbf{2\Psi''(m)} & \dfrac{\mathbf{t}}{\boldsymbol{\kappa}\mathbf{fm}^2} \\ \dfrac{\mathbf{t}}{\boldsymbol{\kappa}\mathbf{fm}^2} & \mathbf{2}\left(\dfrac{\mathbf{1}}{\mathbf{g''}}\mathbf{(q)} - \dfrac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\kappa}\mathbf{mf}\right) \end{pmatrix}$$

The objective function $W(.,.)$ is strictly concave since its Hessian matrix is negative definite for every (m,t). The first and second principal minors are negative and positive respectively (i.e., $H_1 = \left(-\frac{t^2}{\kappa f m^3} - 2\Psi''(m)\right) < 0$ and $H_2 = \det D^2W(m,t) - \frac{t^2}{\kappa f m^3}\frac{2}{g''(q)} - 4\frac{\Psi''(m)}{g''(q)} + 2\Psi''(m)\frac{1}{\kappa mf} > 0.$). Moreover, their signs are independent of where they are evaluated.

The first-order conditions are both necessary and sufficient to identify a global maximum. This completes the proof of proposition 2.

C. Definition of the Estimated water Used by Cooperative Members

The estimated water used by cooperative members is equal to the total amount of water delivered to the cooperative area from which the WA deduces an estimate of likely losses due to leakage, that varies with the age of the irrigation system – these losses are measured as a proportion of water distributed to the cooperative minus 10 percent for systems under 10 years old and 15 percent for older systems, as well as an estimate by the WA of leakages due to known breakages in pipes.