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ADOPTION OF MODERN IRRIGATION TECHNOLOGIES IN THE PRESENCE OF WATER THEFT AND CORRUPTION: EVIDENCE FROM PUBLIC IRRIGATED AREAS IN MEDJEZ EL BAB

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Abstract

In this paper we investigate the potential advantages and limitations encountered by adoption of modern irrigation technologies in the presence of water theft (by simple manipulation of water meters). We propose a mechanism in a centralized management framework combining the use of monitoring, punishment, and subsidies. We show that water theft and technology adoption interact in two competing ways. On the one hand, new technology adoption does reduce theft by enhancing the WA's monitoring capabilities. On the other hand, savings incurred from simple water theft reduce the farmers' desire and willingness to absorb the cost of implementing these new irrigation technologies. We show that technological adoption is more likely, when monitoring costs are low and punishment levels are high. Moreover, the adoption of water-saving technologies such as drip systems increases with increasing water prices, though within the range of low to medium prices. The basic analysis is extended to deal with the problem of regulatory capture when monitoring responsibility is delegated to a monitor whose expertise allows her to hide information from the Water Authority in order to identify with the cheating farmer. We demonstrate that collusion is more likely when monitoring costs are high and punishments rates are low. We test the model's predictions on data from two public irrigated areas in Medjez El Bab (Tunisia). The results give strong confirmation about most of the theoretical findings. But, various economic, socioeconomic, physical and geographical factors can either counteract or supplement these effects.

ملخص

في هذه الورقة نبحث المزايا المحتملة إلى جانب نقاط النقص التي تواجه الاعتماد علي تقنيات الري الحديثة في ظل سرقة المياه (عن طريق التلاعب في عدادات المياه). ونقترح آلية في إطار إدارة مركزية تعتمد علي استخدام الرقابة والعقاب، وأشكال الدعم. ونبين أن هناك تفاعلا وبين سرقة المياه والاعتماد علي تقنيات الري الحديثة من خلال طريقتين متناقضتين. فمن ناحية نجد أن الاعتماد علي تقنيات الري الحديثة تقلل من سرقة المياه وذلك عن طريق تعزيز قدرات الرصد للسلطات المسئولة عن مصادر المياه.ومن ناحية أخري نجد أن المدخرات من سرقة المياه تقلل من رغبة المزارعين واستعدادهم لتحمل تكلفة تنفيذ هذه التقنيات الجديدة للري. ونبين أن احتمالات الاعتماد علي التقنيات الحديثة يزداد عندما تكون تنخفض تكاليف المراقبة وتشدد العقوبات. أضف إلي ذلك أن الاعتماد علي تقنيات توفير المياه، مثل نظام الري بالتنقيط, يزداد مع زيادة أسعار المياه، دون تجاوز تلك المعدلات المنخفضة و المتوسطة للأسعار. ويمتد التحليل الأساسي ليتعامل مع مشكلة هيئات الضبط التنظيمي (regulatory capture) عندما يتم تفويض المسؤولية الرقابية إلي مراقبة لديها الخبرة التي تتيح لها إخفاء المعلومات عن السلطة المسئولة عن الموارد المائية تعاطفا مع المزارعين الغشاشين. وقد تبين أن احتمالات حدوث مثل هذا التواطؤ بين المراقبين والمزارعين تزداد حين ترتفع تكاليف الرقابة وتقل غرامات العقوبات. واختبرنا بتطبيق نموذج التنبؤ هذا علي بيانات من منطقتي ري عامتين في مدينة مجاز الباب الواقعة في شمال تونس. وتؤكد النتائج صدق الحقائق النظرية. ولكن يجب الأخذ في الاعتبار أن العوامل الاقتصادية والاقتصادية الاجتماعية والطبيعية والجغرافية يمكن أن توازن مثل هذه التأثيرات أو تكون مكملة لها .

1. Introduction

The growing scarcity of fresh water in many parts of the world, in particular for the agricultural sector, has led to an urgent search for solutions. These include pricing policies to encourage conservation and the use of modern irrigation technologies that reduce water loss, by allowing a larger fraction of diverted water to be used by the plant and increase the revenue per unit of water, such as sprinkler and drip irrigation systems. However, it is becoming apparent that when farmers are in a position to steal water, typically by manipulating their water meters, pricing policies may not only fail to encourage conservation, but 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 its absence: it is worth tolerating some inefficiency of allocation in water use in return for a lower incidence of theft. This issue has been tackled in a previous paper[1]. We focus more in this paper on the interactions between theft and irrigation technology adoption[2]. Theft interacts with technology adoption in two ways. First, the adoption of the new technology does directly affect theft by increasing the ease of detection[3] (because the settings of such technologies as drip and sprinkler systems reveal more easily the amount of water being used). Secondly, the expected incidence of theft is likely to affect the incentives for adoption - why adopt an expensive new technology to reduce the cost of a resource which the farmer does not expect to pay for anyway.

We broadly distinguish between new technologies of "Type I " (namely, those which save in water use at all values of the marginal cost of water) from other technologies, we call technologies of "Type II ", which may or may not save in water use, depending on the values of the marginal cost of water. We develop a model in a centralized management framework, where the Water Authority (hereafter WA) designs a policy scheme intended to reduce the occurrence of theft and to encourage adoption of modern irrigation technologies. The WA tries to reduce theft by monitoring the farmer's behavior punishing observed instances of theft, in an economic environment in which monitoring and punishment are costly. Adopting the new technology incurs a fixed cost, and farmers may choose not to adopt it when the perceived gains from adoption do not outweigh the costs. The WA then designs a subsidy scheme to encourage technology adoption.

The model centers around the idea that the WA's policy instruments chosen by the WA in response to the struggle between the farmer's incentives (described above) may well interact. We show this by comparing two settings: in the first, the farmer has enough incentives to adopt the new technology on her own without the need for subsidies. The WA has then to focus only on the incentives of theft. In the second setting, the farmer may not find it profitable to adopt the new technology without external support; the WA devises then a mechanism combining the use of monitoring, punishment and subsidies which can promote (and facilitate) the adoption of new irrigation technologies while reducing incentives of water theft. More precisely, we show that the adoption of modern irrigation technologies is more likely when monitoring costs are low and punishment levels are high. To the extent that these variables do not explain the full range of variation in water theft, one should realize that theft reduces technology adoption incentives. We also examine how a variation in the price of water affects the incentives for theft and those for technology adoption. It is found that a

[1] Mattoussi, W., and Seabright, P., "On the design of irrigation cooperatives with peer monitoring." Working paper, 2007.

[2] Our model is related to the interlinked contract literature (for instance, see Ghatak, M. and Pandey, P., 2000) and to the literature dealing with the introduction of innovations which save on water input use or limit unwanted environmental effects of agricultural production (for instance see Caswell and Zilberman (1985), Jeremy D, Foltz (2003), Koundouri P., et al (2003) and Awudu A., et al (2005)).

[3] Our model is distinct from the model developed by Ghatak and Pandey (2000). In their model the technology reduces agency costs, while in our model the technology improves efficiency in a farming resource use, namely water use.

higher water price increases the incentives of theft and unambiguously reduces the incentives for adopting the non water-saving technologies (which include technologies of "Type II " when they do not save in water use at a given water price). However, the adoption of water-saving technologies (which include both technologies of "Type I" and those of "Type II" when they save in water use at a given water price) such as drip systems increases with increasing water prices, though within the range of low to medium prices. However, this result may not hold at higher price levels.

We extend the basic model by investigating the problem of regulatory capture when monitoring responsibility is delegated to monitors who have conflicting interests with the WA. The monitor's expertise allows her to hide information from the WA in order to identify with the cheating farmer. We demonstrate that the likelihood of collusion between the farmer and the monitor is more likely when monitoring costs are high and punishment rates are low. We should expect to see empirically that collusion varying both with observed factors that increase the likelihood of theft and (to the extent that other unobserved factors increase that likelihood) as a function of the level of theft itself. Similar implications apply to technology adoption incentives, thus we should expect water-saving technologies to reduce the likelihood of collusion.

We test the model's predictions using data coming from an original survey conducted in two public irrigated areas in Medjez El Bab (a small town in Tunisia located at 54 km northwest of the capital). Our procedure is to use theory to focus attention on the underlying determinants of farmers' behavior in terms of water theft, the adoption of water-saving technologies and collusion with monitors. The theory guides our search for proxies for unobserved variables, and instruments for endogenous variables, that enable us to identify the appropriate causal relationships in our data. 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 theft is affected by the aspects of the institutions - the rules specifying how severely farmers will be punished for theft, and the pricing policy for water use which increases the incentives for theft. Also a higher water price is associated with greater adoption of water-saving technologies, and in turn a higher incidence of theft reduces the incentives of adoption. Moreover, the evidence supports that higher monitoring costs and lower punishment rates are associated with lower incidence of collusion, and a higher incidence of theft is associated with increased opportunities for collusion. Finally, the use of water-saving technologies reduces the incentives for collusion. Nevertheless, other economic, socioeconomic, physical, personal and geographical factors seem to be relevant to farmers' decisions, and some of these factors are considered in this analysis.

The remainder of the paper is organized as follows. Section 2 introduces the model and derives the first-best outcome as a benchmark. Section 3 considers the case of asymmetric information. Comparative static results are derived in section 4. We study the issue of regulatory capture in section 5. We use the propositions derived in previous sections to make predictions that can be tested empirically. Section 6 describes our data and tests the empirical predictions. Section 7 concludes.

2. The Model and the First-Best Outcome

Consider a risk neutral farmer who uses water as an input q in the production of a homogenous farm good. The production technology may be described by the following logistic function:

$$g(q;\beta) = \frac{1}{d + e^{-\beta q}} \quad where \ \ 0 < d < 1 \tag{1}$$

The technological parameter β takes on two values { $\underline{\beta},\overline{\beta}$ } with $\overline{\beta} > \underline{\beta}$. We will refer $\underline{\beta}$ to an old or traditional technology (such as furrow and flooding irrigation) and $\overline{\beta}$ - to the new or modern one[4] (such as drip and sprinkler systems).

The new technology incurs a fixed cost C_T and the cost of the old technology is normalized to zero. The private cost borne by the farmer for using a unit of water is c (e.g., the cost of delivering water from the public canal to the farmer's field). The social marginal cost of water exceeds the private cost by the amount γ referred to as the external cost of water (all components not directly borne by the farmer). It may cover operation and maintenance (O&M) cost to which one can add investment cost and interest and depreciation on borrowed capital, or the scarcity cost of water, or extraction externalities associated with pumping from a shared aquifer, or any combination of these). In addition, the farmer pays a linear price, t per unit *omf* water used, a price which is set by the WA.

The farmer will choose the quantity of water which maximizes her net return from water application, equal to $g(q;\underline{\beta})-(c+t)q$ when the old technology is used and equal to $g(q;\overline{\beta})-(c+t)q-C_T$ when the new technology is instead adopted. The corresponding optimal water input level for a given technology equates the marginal value product of water[5] to the marginal cost of generating such a quantity

$$q(\beta): g_q(q;\beta) = c+t \qquad (2)$$

The logistic function, $g(q;\beta)$, well describes the different stages in the plant's growth. The initial stage of growth is approximately exponential (the marginal yield response to water increases with the quantity of water). Then, as saturation begins, the growth slows (the marginal yield response to water decreases in the quantity of water), and at maturity, growth stops. The above function is particularly suitable to the present context, where the marginal productivity associated with any extra water use offered by the new technology can be lower than that associated with the old one. This implies that the new technology may increase yields, while using less water. Formally, by taking the first and second-order derivatives of $g(q;\beta)$ we obtain

$$g_q(q;\beta) = \frac{\beta e^{-\beta q}}{(d+e^{-\beta q})^2} \quad and \quad g_{qq}(q;\beta) = \frac{\beta^2 e^{-\beta q}(e^{-\beta q}-d)}{(d+e^{-\beta q})^3}$$

The marginal yield, $g_q(q;\beta)$ has an inverted U-shape, with a maximum value of $\frac{\beta}{4d}$ reached at $q_{\max}(\beta) = -\frac{\ln d}{\beta}$. For extremely small amounts of water, the marginal yield is $\sim \frac{\beta}{d^2}$ (i.e., $\lim_{q\to 0} g_q(q;\beta) = \frac{\beta}{d^2}$). It immediately follows that for small q,

[4] It is easy to verify that $g_\beta(q;\beta) = \frac{qe^{-\beta q}}{(d+e^{-\beta q})^2} > 0$, so the specification $\overline{\beta} > \underline{\beta}$ reflects the fact that the new technology increases the yield response to water. Modern irrigation technologies are credited with increasing yields because they are more responsive to crop and field conditions (Fishelson and Reymon, 1989, Dinar and Zilberman, 1991; Shrestha and Gopalakrishnan,1993). However, this may not always be the case. Indeed, Mourshed, M., 1995, brings an econometric evidence about public-reclamation in the Egyptian desert, where farmers discovered that hand-move sprinkler is actually yield-decreasing with respect to vegetables (because of leaf-scorch and fungi) as compared to traditional flooding (with the association of livestock or/ and chicken manure). A layer of manure is placed near the root zone (acting as a binding agent between sand and water), water that would filter through the sand is held in place, keeping the moisture of the soil until next irrigation.

[5] An implicit assumption here is that the price of the farm good is normalized to 1.

$\lim_{q \to 0} g_q(q;\overline{\beta}) > \lim_{q \to 0} g_q(q;\underline{\beta})$ *and* $q_{\max}(\overline{\beta}) < q_{\max}(\underline{\beta})$, which implies that the two curves associated with the use of new and old technologies overlap when $g_{qq}(0;\overline{\beta}) < 0$; the two functions may intercept at least once. In economic terms what matters is whether the new technology uses more or less water than the old technology for a given water price, which mathematically corresponds to whether $g_q(q;\beta)$ is monotonic in β or not. This will affect the impact of water price upon the farmer's incentives to adopt the new technology. In particular, we would like to test if a small increase in water price will affect the farmer's desire to adopt new technology that is expected to save in water use. We broadly distinguish between two modern technologies described as follows:

1. First, the new technology is of "type I" if both $g_{q\beta}(q;\beta)$ and $g_{qq}(q;\overline{\beta})$ are negative (< 0). The marginal yield curves $g_q(q;\underline{\beta})$ and $g_q(q;\overline{\beta})$ intercept each other only once at $\hat{q}$ that strictly lies below $q_{\max}(\underline{\beta}) = -\frac{\ln d}{\underline{\beta}}$ (the input level that maximizes the yield of the old technology). It saves in water use at all values of the social marginal cost of water, $c + \gamma$ as shown by Figure 1.

2. Second, the new technology is of "Type II" when the marginal product curve, $g_{q\beta}$ does not have a constant sign[6]. The two curves, $g_q(q;\overline{\beta})$ and $g_q(q;\underline{\beta})$ can intercept either once at $\hat{q}$ that strictly lies above $q_{\max}(\underline{\beta}) = -\frac{\ln d}{\underline{\beta}}$ (as depicted by Figure 2). This implies that

$$g_q(q,\overline{\beta}) > g_q(q,\underline{\beta}) \;\; \textit{if} \;\; \overline{q}_{\max} < q < \hat{q},$$

and

$$g_q(q,\overline{\beta}) > g_q(q,\underline{\beta}) \;\; \textit{if} \;\; q > \hat{q}\,.$$

or more than once (as depicted by Figure 3).

The technology of "Type II" may or may not save in water use, depending on the values of the social marginal cost of water.

It immediately follows that the distinction between the new technologies can be based on their water saving abilities:

(i) We can refer to new technologies that save in water use at a given price (which include both technologies of "Type I" and those of "Type II" when they save in water use at a given water price) as "water-saving" ones.

(ii) We refer to new technologies that do not save in water use at a given price (which include technologies of "Type II" when they do not save in water use at a given water price) as "non water-saving" technologies.

In the absence of asymmetric information, and abstracting from any transaction cost related to pricing implementation and any shadow cost of public funds that might imply Ramsey-pricing considerations, water proceeds will be a mere transfer from the farmer to the WA. If the irrigation technology and the quantity of water used by the farmer were fully contractible, the first-order condition to maximize social surplus would be

$$g_q(q^{FB}(\beta);\beta) = c + \gamma \qquad (3)$$

[6] The marginal yield of water, g_q is non monotonic in the technological parameter, β.

For a given technology β, the first-best efficient water use $q^{FB}(\beta)$ equates the marginal product value of water to its social marginal cost.

We establish in lemma 1 that if it were not the fixed costs attached to technology adoption, using the new technology would be always socially beneficial in the first-best world. This implies that the new technology undoubtedly improves efficiency in water use.

LEMMA 1: Let $\underline{\beta} < \overline{\beta}$ then,

$$\overline{w}^{FB} > \underline{w}^{FB} \tag{4}$$

where, $w^{FB}(\beta) = g(q(\beta);\beta) - (c+\gamma)q(\beta)$.

Proof: By using the envelope theorem one gets $\frac{\partial w(\beta)}{\partial \beta} = \frac{\partial g(q;\beta)}{\partial \beta} = q\frac{qe^{-\beta q}}{(d+e^{-\beta q})^2} > 0$.

For the WA, inducing the adoption of the new technology yields the payoff

$$\overline{W}^{FB} = \overline{g}(\overline{q}^{FB}) - (c+\gamma)\ \overline{q}^{FB} - C_T$$

Had the WA decided to let the farmer use her old technology, she would save in the fixed cost related to adoption. In this scenario, the WA would instead obtain the payoff

$$\underline{W}^{FB} = \underline{g}(\underline{q}^{FB}) - (c+\gamma)\ \underline{q}^{FB} - C_T$$

Inducing technology adoption is thus optimal from the WA's point of view when $\overline{W}^{FB} \geq \underline{W}^{FB}$; and to put it differently when

$$\Delta w^{FB} \geq C_T\ , \tag{5}$$

where, $\Delta w^{FB} = \overline{w}^{FB} - \underline{w}^{FB} > 0$. Inequality (5) states that technology adoption is socially beneficial in the first-best world when it brings about efficiency gains in water use that exceed the first-best social cost related to adoption. This implies that in the fully centralized economy the new technology is the most desirable, and thereby the first-best outcome is $\{\overline{\beta}, \overline{q}^{FB}\}$.In complete information, if condition (5) is satisfied, the WA can implement its preferred policy, $\{\overline{\beta}, \overline{q}^{FB}\}$ with appropriate *out-of-equilibrium penalties*.

3. Asymmetric Information

In this section water use and technology adoption are unobservable to the WA and hence, cannot be contracted on[7]. The farmer who is equipped with an individual water meter can send a report of the amount used, denoted by $q^r(\beta)$, that may differ from the true quantity $q(\beta)$ when technology β is used. The amount of water stolen is equal to $a(\beta) = q(\beta) - q^r(\beta)$. In what follows, a few assumptions necessary to the analysis will be listed.

- The Water Authority sets up monitoring systems aiming at providing a precise measurement of the farmer's water consumption. We assume that monitoring cannot be conditioned on the farmer's report and must be the same for all reports. The function $\psi(m)$ designates the monitoring cost, which accounts for measurement devices and wages $\psi(m)$ is strongly

[7] While it seems plausible to assume that water use is not contractible, the case of non contractibility of technology adoption is less strong and therefore needs more justification. The type of technology used can be verified at a cost. Verification requires visiting the plots of lands of each farmer apart. This turns out to be very costly especially when the number of farmers operating in the area is very high and when they are growing a great variety of crops and using different irrigation technologies.

convex, i.e., $\psi'''(m) > 0$ in addition to $\psi''(m) > 0$: This assumption is based on the complexity and difficulty in measuring the true quantity of water used by a farmer.

- If the farmer is not monitored, then she pays the mandated water fee associated with her report, $tq^r(\beta)$. Otherwise, she is discovered stealing with a probability $P(m; a(\beta); \beta)$ which increases in the intensity of monitoring and in her level of theft. To simplify the exposition the probability $P(.)$ is assumed to be commonly known and takes the form

$$P(m, a(\beta), \beta) = \min\{\kappa(\beta)m \ \max\{a(\beta), 0\}, 1\}, \tag{6}$$

where $\kappa(\beta) > 0$ (we assume henceforth that it is sufficiently small to generate an interior solution).

- When the farmer is detected stealing, her true intake is established without error and she pays $tq^r(\beta)$ plus a penalty proportional to the amount of water stolen. It is the nature of the monitoring system which 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 o¤ from a cheating member. This length is proportional to the farmer's level of theft. The punishment is assumed to take the form

$$F = f \ \max\{a(\beta), 0\}, \ \ where \ f > 0 \tag{7}$$

where the punishment rate f is positive.

- We assume that it is costly to inflict the punishment rate f and we denote by $\varphi(f)$ the associated cost which can be pecuniary in nature when farmers put up a resistance to closing their water meters $\varphi(f)$ is increasing and strongly convex, i.e., $\varphi'''(f) > 0$ in addition to $\varphi''(f) > 0$. This assumption is based on the increased complexity and difficulty of enforcing increasingly stringent punishments. There are no rewards for over-reporting.
- The new technologies, such as sprinkler and drip systems, make it easier to irrigate and reduce monitoring costs. These technologies give farmers superior control over the scheduling and release of moisture relative to flooding or any other traditional irrigation. For example, following a learning phase of how the dripping system operates, the use of drip system requires less effort and time. Indeed, drippers with controllable flow rates (e.g., liters or m^3 per hour) can be easily installed to effectively accommodate the optimal needs of any crop (e.g., choosing the optimal distance between dripper and plant). This may also allow farmers the additional flexibility to irrigate at any time of the day, particularly when activity is less intensive (dawn or late in the night). We might add that irrigation at specific (low activity) time windows are also associated with higher theft opportunities, since inspections are expected to be less frequent. In the counterpart, this might well give monitors a higher scope to detect theft. Moreover, because of their repeated relationship with farmers, and their know-how in the agricultural sector (as a result of their long experience), government agencies (and even skilled farmers) can determine the approximated water being used by casual observation. To abstract the advantages offered by the new technology, we introduce a weighing parameter λ (essentially a monitoring advantage coefficient) and define a new monitoring cost as $\lambda\psi(m), \ with \ 0 \le \lambda \le 1$.
- *Assumption 7*: $\overline{\kappa} > \underline{\kappa}$.

By increasing the ease of detection, this assumption essentially implies that the new technology provides less scope for theft. For example, the installation of drip and sprinkler-irrigation systems provided more effective monitoring of water use (revealing more easily the amount of water being used). Furthermore, the dripper and sprinkler system may well signal whether farmers are using only the needed levels of water or carelessness is involved. Thus, for example placing the drippers quite far from the lines of plants or the observation of a salt residue around plants roots (meaning that the plant has been over-irrigated) means that carelessness is involved.

- *Assumption 8*: $c + \gamma \le \frac{\beta}{4d}$, *where* $0 < d < 1$

This assumption states that both technologies new and old are privately profitable. The farmer decides then which technology to use by comparing the utility level generated by each of them.

- *Assumption 9*: $\bar{\phi}(c + \gamma) > \underline{\phi}\left(\frac{\ln d}{\underline{\beta}}\right)$, *where* $\bar{\phi} \equiv (\bar{g}_q)^{-1}$, $\underline{\phi} \equiv (\underline{g}_q)^{-1}$ *and* $0 < d < 1$

This assumption states that the second partial derivative of the production function is negative for both technologies new and old, i.e., $g_{qq}(q; \beta) < 0$, for $\beta \in \{\underline{\beta}, \bar{\beta}\}$.

- The WA may wish to subsidize the farmer by the amount $S(\alpha) = \alpha\ C_T$, *where* $\alpha \in [0,1]$ is the subsidization rate.

Let Σ denote the set of regulatory instruments used by the WA, i.e., $\Sigma = \{m, f, \alpha\}$. Treating the WA's mechanism parametrically, the farmer derives the utility

$$u(q, q^r; \Sigma, \underline{\beta}) \equiv \underline{u}(q, q^r; \Sigma) = \underline{g}(q) - cq - tq^r - \underline{\kappa} mf(q - q^r)^2, \qquad (8)$$

if she uses the old technology, and the utility

$$u(q, q^r; \Sigma, \bar{\beta}) \equiv \bar{u}(q, q^r; \Sigma) = \bar{g}(q) - cq - tq^r - \bar{\kappa} mf(q - q^r)^2 - C_T + S(\alpha) \qquad (9)$$

if she instead adopts the new technology.

The social welfare function associated with the use of the new technology is defined as the sum of the farmer and water supplier's surpluses

$$\overline{W}(q, \Sigma) = \bar{u}(q, q^r; \Sigma) + [tq^r - \gamma q - (1 + \eta_s)S(\alpha) - \lambda\psi(m) - \varphi(f)] \qquad (10)$$

The parameter $\eta_s \ge 0$ is the transaction cost related to the implementation of subsidies. For feasibility requirements, we assume that $\eta_s < 1$. By rearranging the terms of (10), one obtains

$$\overline{W}(q, \Sigma) = \bar{g}(q) - (c + \gamma)q - \bar{\kappa} mf(q - q^r)^2 - (1 + \eta_s\alpha)C_T - \lambda\psi(m) - \varphi(f) \qquad (11)$$

Where, $\eta_s \alpha C_T$ is the social cost incurred by technology adoption.

By the same token, the social welfare function in case the old technology is instead used corresponds to

$$\underline{W}(q, \Sigma) = \underline{g}(q) - (c + \gamma)q - \underline{\kappa} mf(q - q^r)^2 - \psi(m) - \varphi(f) \qquad (12)$$

The order of events is that the WA fixes m, f and α; then the farmer chooses whether to adopt the new technology and chooses the amount of water to use and the report to file. Once monitoring takes place the choice of the technology used becomes publicly observed[8]. Then, subsidies, if any, are paid and payoffs are realized.

[8] Alternatively, we could assume that while claiming for subsidies the farmer can provide a hard evidence that the new technology was adopted.

For the purpose of the analysis, we will focus on punishment rates which strictly lie above the price of water, i.e., $f > t$; because otherwise the farmer will always have an interest in stealing everything[9].In what follows we focus on the subgame perfect equilibrium and solve the model by straight backward induction. In stage 2, for a given technology β, the farmer chooses the amount of water to use $q^*(\beta)$ and to report $q^{r*}(\beta)$ that maximize her expected payoff, i.e.,

$$\max_{(q,q^r)} u(q\,, q^r; \Sigma, \beta)$$

Whose first-order conditions are

$$g_q\left(q^*\left(\beta\right);\beta\right) = c + 2\kappa(\beta)mf\left[q^*\left(\beta\right) - q^{r*}\left(\beta\right)\right] \tag{13}$$

$$t = 2\kappa(\beta)mf\left[q^*\left(\beta\right) - q^{r*}\left(\beta\right)\right] \tag{14}$$

By rewriting (14), we obtain the value of the optimal level of theft.

$$a^*(\beta) = \frac{t}{2\kappa(\beta)fm} \tag{15}$$

As we can see the level of theft is not directly influenced by the productivity of water but only by such variables as the price of water and the levels of punishment and monitoring. Water use is, of course affected by productivity, but theft is the difference between the actual water use and the reported one. Clearly, an increase in the levels of punishment and monitoring reduce theft. However, the impact of water price on theft is ambiguous since this latter directly increases theft and affects it indirectly through its influence on monitoring and punishment.

Comparing the levels of theft associated with the use of the alternative technologies new and old, shows that the new technology reduces theft because it increases the ease of detection, i.e.,

$$\overline{a}^* < \underline{a}^*. \tag{16}$$

One may then expect the policy instruments chosen in response to a perceived interaction between theft and technology adoption to interact; For instance, the levels of monitoring and punishment which are primarily designed to reduce the occurrence of theft might influence the incentives of technology adoption.

Denote by $u^*(\Sigma, \beta) \equiv u(q^*\,, q^{r*}; \Sigma, \beta)$ the farmer's maximum utility under technology β; when she faces the WA's policy scheme, Σ: By using (15) and (16), we rewrite the inequality which makes the farmer better off by adopting the new technology, $\overline{u}^*(\Sigma) \geq \underline{u}^*(\Sigma)$ (namely, the farmer's participation constraint in the WA's program aiming at the implementation of an irrigation regime where the new technology is used) as

$$G\left(t\right) - L\left(m, f, t\right) \geq (1 - \alpha)C_T, \tag{17}$$

where $G(t)$ designates the efficiency gain in water use offered by the new technology; it is expressed as:

$$G\left(t\right) \equiv \left[\overline{g}\left(\overline{q}^*\right) - (c + t)\,\overline{q}^*\right] - \left[\underline{g}(\underline{q}^*) - (c + t)\,\underline{q}^*\right] > 0, \tag{18}$$

[9] The net return of water theft is equal to (t- $\kappa mf\, a$) a; with the probability $\kappa ma < 1$: If $f < t$; one gets $\kappa ma\, f < f < t$, and therefore theft is strictly beneficial; this essentially implies that the net return is maximized when the farmer is stealing everything.

$L(m, f, t)$ represents the utility cost to the farmer associated with reduced opportunities for theft when using the new technology; it is equal to the difference between the net returns to theft (old versus new technology).

$$L(m,f,t) \equiv B\left(m,f,t,\underline{\beta}\right) - B\left(m,f,t,\overline{\beta}\right),$$

where $B(m,f,t,\beta) = [t - \kappa(\beta) m a^*(\beta) f]\, a^*(\beta)$. Rearranging the above expressions yields

$$L(m,f,t) \equiv \frac{1}{4}\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{fm} > 0. \tag{19}$$

In summary, inequality (17) implies that the after-subsidy cost of the new technology (defined as $(1 - \alpha)\, C_T$) is lower than the net benefit associated with switching to the new technology (defined as $G(t) - L(m, f, t)$).

It is worth examining at this stage how variation in the levels of monitoring and punishment would affect the farmer's utility cost associated with the use of the new technology. We found that the partial derivatives of L with respect to m and f are negative.

$$\frac{\partial L(m,f,t)}{\partial m} = -\frac{1}{4}\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{fm^2} < 0, \tag{20}$$

$$\frac{\partial L(m,f,t)}{\partial f} = -\frac{1}{4}\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{f^2 m} < 0. \tag{21}$$

In economic terms this implies that the higher level of monitoring (and punishment) by the WA, the less farmers have to loose in opportunities of theft by switching to the new technology.

In stage 1 of the game, the WA anticipates the farmer's behavior when designing its policy scheme, Σ. If technology adoption is encouraged, the WA optimally solves[10]

$$\begin{aligned} &\overline{\Sigma}^* \in \arg\max_{\Sigma} \overline{W}(\overline{q}^*, \Sigma) \\ &\text{s. t. } \overline{u}^*(\Sigma) \geq \underline{u}^*(\Sigma). \end{aligned} \qquad (P_{New})$$

On the other hand, if the WA wants the farmer to stay with the old technology, it optimally solves

$$\begin{aligned} &\underline{\Sigma}^* \in \arg\max_{\Sigma} \underline{W}(\underline{q}^*, \Sigma) \\ &\text{s. t. } \underline{u}^*(\Sigma) \geq \overline{u}^*(\Sigma). \end{aligned} \qquad (P_{Old})$$

The dilemma of the WA is whether or not it should induce farmers to adopt the new technology and which policy scheme to implement in each case. It bases its decision on the comparison of the social welfare levels of the alternative programs P_{New} and P_{Old}; i.e.,

$$\max\left\{\overline{W}\left(\overline{\Sigma}^*\right), \underline{W}\left(\underline{\Sigma}^*\right)\right\} \tag{22}$$

The existing literature has always assumed that modern irrigation technologies are socially desirable, and we will follow this assumption. We analyze the WA's problem when it induces the farmer to adopt the new technology in two economic situations. We first consider the situation when the participation constraint (17) is slack (i.e., when the farmer makes strictly

[10] We make the standard assumption that if the farmer is indifferent between the two types of technologies she will finally adopt the one which is most preferable to the WA.

higher profits through adopting the new technology, and without the need for incentives from the WA). This case will serve as a useful benchmark in the subsequent analysis. Afterwards, we proceed with the case when constraint (17) is binding (i.e., when the farmer should be given sufficient incentives to adopt new technologies).

3.1. When technology adoption is privately profitable

When constraint (17) is strictly satisfied, it can be omitted in the maximization problem P_{new}. Proposition 1 characterizes the solution to this case.

PROPOSITION 1: Suppose that assumptions (7), (8) and (9) hold and constraint (17) is slack. Then, the second-best policy scheme is such that $\alpha_0 = 0$ and $(m_0; f_0)$ solves

$$m_0 : \frac{t^2}{4\overline{\kappa} f_0 m_0^2} = \lambda \psi' (m_0) \, , \tag{23}$$

and

$$f_0 : \frac{t^2}{4\overline{\kappa} m_0 f_0^2} = \varphi' (f_0) \, , \tag{24}$$

Proof: See the appendix.

The WA does not use subsidies and relies entirely on the regulatory instruments, monitoring and punishment, because the only problem the WA faces is water theft. The proposition says that some monitoring and punishment are always required to counteract the incentives of theft. Since monitoring and punishment are costly, the WA has to tolerate some theft in order to save in the costs of its policy instruments. This solution, $(m_0; f_0; \alpha_0)$ is valid only if

$$G(t) - L(m_0, f_0, t) > C_T.$$

That is, the net benefit associated with switching to the new technology (defined as $G(t) - L(m_0; f_0; \alpha_0)$) outweighs the fixed cost of adoption, C_T .

3.2. When technology adoption is privately unprofitable

Now we solve problem P_{New} taking into account that constraint (17) is binding, which defines the subsidization rate α as a function of the levels of monitoring and punishment. It is easily shown that α is negatively related to m and f,

$$\frac{\partial \alpha}{\partial m} = \frac{1}{C_T} \frac{\partial L(m, f, t)}{\partial m} = -\frac{1}{4C_T} \left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}} \right) \frac{t^2}{f m^2} < 0, \tag{25}$$

$$\frac{\partial \alpha}{\partial f} = \frac{1}{C_T} \frac{\partial L(m, f, t)}{\partial f} = -\frac{1}{4C_T} \left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}} \right) \frac{t^2}{f^2 m} < 0. \tag{26}$$

This means that monitoring (respectively, punishment) and subsidies are substitutes. The explanation is straightforward: a more intense monitoring and a higher level of punishment increase the net gain from using the new technology. They reduce the utility cost to the farmer incurred by its use, since she has less to lose in opportunities of theft by switching to the new technology, while leaving the efficiency gains in water use unchanged. Overall, more intense monitoring and a higher level of punishment reduce the levels of required subsidies to encourage technology adoption.

Taking into account that (17) is binding, the new irrigation regime (problem P_{New}) can be described by this maximization program:

(P1)

$$\max_{\Sigma} \overline{g}\left(\overline{q}^*\right) - (c+\gamma)\,\overline{q}^* - \overline{\kappa} m f \overline{a}^{*2} - (1+\eta_s\alpha)C_T - \lambda\psi(m) - \varphi(f)$$
$$\text{s.t. } G(t) - L(m,f,t) = (1-\alpha)C_T \ .$$

The solution to (P1) is summarized by proposition 2.

PROPOSITION 2: Suppose that assumptions (7), (8) and (9) hold, then the WA uses the policy scheme $\{m_1, f_1, \alpha_1\}$ which solves

$$m_1 : \frac{t^2 z}{4m_1^2 f_1} = \lambda\psi'(m_1)\,, \tag{27}$$

$$f_1 : \frac{t^2 z}{4m_1 f_1^2} = \varphi'(f_1)\,, \tag{28}$$

and

$$\alpha_1 = 1 - \frac{G(t) - L(m_1, f_1, t)}{C_T} > 0. \tag{29}$$

$$Where,\ z = \left[(1-\eta_s)\frac{1}{\kappa} + \eta_s \frac{1}{\underline{\kappa}}\right] > 0.$$

Proof: See the Appendix.

In this economic environment, it is clear that the water authority would design a higher subsidy level, because farmers do not find it profitable to adopt new technologies on their own. Moreover, our findings allow us to shed light on the potential interactions between the various regulatory instruments, by comparing the policy schemes used by the WA in the binding setting (described by Eqs. 27 and 28) versus non-binding one (described by Eqs. 23 and 24). Since the two settings discussed above do not allow the explicit determination of monitoring (m_1 and m_0) and punishment levels (f_1 and f_0), we will adopt two particular functions, $\psi(m) = \frac{1}{3}bm^3$ and $\varphi(f) = \frac{1}{3}\omega f^3$(where $b > 0$ and $\omega > 0$ denote monitoring and punishment enforcement transaction costs, respectively) to carry out the desired comparison.

LEMMA 2: Suppose that assumptions (7) and (8) hold, then, we have

$$m_1 > m_0 \text{ and } f_1 > f_0. \tag{30}$$

Proof: See the appendix.

Higher levels of monitoring and punishment clearly reduce the opportunities of theft. This will undoubtedly increase the farmer's willingness to pay the cost associated with the new technology, which in turn brings additional savings in water use. Alternatively, subsidies encourage farmers to adopt new technologies and indirectly reduce incidence (and need) of theft.

4. Comparative statics

We now determine how the key parameters (of the model) affect the farmer's incentives for theft and technology adoption, on the one hand, and on the design of the three regulatory instruments (i.e., monitoring, punishment and subsidies) on the other hand. We first explore the effects of water price variation on the equilibrium monitoring, punishment and subsidy levels when the particular functions,

$\psi(m) = \frac{1}{3}bm^3$ and $\varphi(f) = \frac{1}{3}\omega f^3$ (where $b > 0$ and $\omega > 0$) are adopted. We found that monitoring and punishment are positively related.

$$\frac{\partial m}{\partial t} = \frac{6m}{15t} > 0 \text{ and } \frac{\partial f}{\partial t} = \frac{6f}{15t} > 0, \tag{31}$$

Higher water price increases the incentives for theft, and therefore higher monitoring and punishment levels are required to reduce them. We also found that the effects of water price on subsidies and incentives to adopt new technologies are negatively related.

$$\frac{\partial \alpha}{\partial t} = -\frac{1}{C_T}\frac{\partial\left[G\left(t\right) - L\left(m, f, t\right)\right]}{\partial t}. \tag{32}$$

This is expected, because, for instance, an increase in water price may make technology adoption more attractive. The WA would thus not need large subsidies to encourage the adoption of such technologies, incurring substantial savings. For a given water price, the punishment rate increases in monitoring costs.

$$\frac{\partial f}{\partial b} = \frac{f}{15b} > 0. \tag{33}$$

This is a clearly expected result since an increase in monitoring costs reduces monitoring, increasing thereby the opportunities of theft and then, greater punishment is required to counter the incentives of theft. We also found similar effects of punishment costs, ω on the intensity of monitoring.

$$\frac{\partial m}{\partial \omega} = \frac{m}{15\omega} > 0. \tag{34}$$

This implies that monitoring and punishment are indeed substitute instruments. We now explore how variations in water price affect the incentives of theft and those of technology adoption. First, the incentives of theft are positively related to water price.

$$\frac{\partial a\left(\beta\right)}{\partial t} = \frac{1}{10\kappa\left(\beta\right)mf} > 0. \tag{35}$$

This is the case because for a given technology *β*; a higher water price increases the net benefit from theft (defined as $\frac{t^2}{4\kappa(\beta)mf}$), making it attractive.

We have shown that the levels of monitoring and punishment reduce the farmer’s utility cost associated with the use of the new technology, while leaving efficiency gains accrued to its use unchanged. However, the price of water affects both utility cost and efficiency gains, i.e. an increase in t unambiguously increases *L*:

$$\frac{\partial L\left(m, f, t\right)}{\partial t} = \left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t}{2fm} > 0,$$

In economic terms this implies that the higher the price of water is, the lesser the gain in opportunities of theft farmers would have by switching to the new technology. However, the impact of overall water price on *G*(*t*) is ambiguous; it depends on the water-saving abilities of the new irrigation technologies.

$$\frac{\partial G\left(t\right)}{\partial t} = -(\overline{q}^* - \underline{q}^*),$$

If the new technology is a "non water-saving" one, an increase in t reduces *G*(*t*), and thus the incentives for adopting such technology are reduced. However, when the new technology is rather a "water-saving" one, then an increase in t increases *G*(*t*), and therefore the overall impact of t on the net benefit from switching to this technology, *G*(*t*) − *L*(*m*, *f*, *t*) is not straightforward. To gain insights into these effects, we will start with the reference case where theft does not occur. There is no utility cost to the farmer from switching to the new technology (i.e., $L(m, f, t) \equiv 0$), and the farmer will indeed react to an increase in the price of water by switching to a "water-saving" technology. The question now is whether or not the occurrence of theft would affect this finding and how. Intuitively, the answer is very likely to be related to the rates of efficiency gains and utility cost to the farmer incurred from using the new technology.

- (a) The function $L(m, f, t)$ increases with t at an increasing rate (i.e., $\frac{\partial^2 L(m,f,t)}{\partial t^2} = \frac{3}{50fm}\left(\frac{1}{\underline{\kappa}} - \frac{1}{\kappa}\right) > 0$), meaning that this function is convex in t;
- (b) As for the shape of function G(t) it is given by the following lemma:
- LEMMA 3: Suppose that assumptions (7), (8) and (9) hold, than for a given water price, $0 \leq t \leq \gamma$, efficiency gains from switching to the water-saving technology (defined by G(t)) increase with t at deceasing rate i.e.,
-

$$\frac{\partial G(t)}{\partial t} = \underline{q}^* - \overline{q}^* > 0, \tag{36}$$

and

$$\frac{\partial^2 G(t)}{\partial t^2} = \frac{1}{\underline{g}_{qq}(\underline{q}^*)} - \frac{1}{\overline{g}_{qq}(\overline{q}^*)} < 0. \tag{37}$$

Proof: See the appendix.

The difference in curvature between the two functions $G(t)$ and $L(m, f, t)$ and the fact that $G(t) \geq L(m, f, t)$ (which is a straightforward implication of inequality (17)), essentially implies that there exists a threshold price of water, $\bar{t}$, satisfying $G(\bar{t}) = L(m(\bar{t}), f(\bar{t}), \bar{t})$ (i.e., the net gain from using the water- saving technology is equal to zero) such that:

- For any $t \leq \bar{t}$, $G(t)$ lies above $L(m, f, t)$ as depicted by Figures 4A and 4B. In economic terms, this means that in a relevant range of low to intermediate water prices, the efficiency gains from using the new technology exceed costs, implying that an increase in t increases the incentives for adopting water-saving technologies, but at a lower rate compared to the case without theft; this is reflected in the trend shown in Figures 5A and 5B.
- For any $\bar{t} < t \leq \gamma$, $G(t)$ lies below $L(m, f, t)$, meaning that in the regime of high water prices, the utility cost to the farmer from switching to the new technology becomes sufficiently large and outweighs any gains. This reduces the incentives for technology adoption.

5. Extension: Regulatory capture

Thus far we have ignored the problem of regulatory capture[11] - the eventual collusion between the monitor and farmers (the so called interest group). In this section we allow the monitor to collude with the farmer. To use standard agency methodology, we assume that side contracts between the monitor and the farmer are enforceable[12]. The regulatory structure is two-tiered: the agency (the "monitor" or "supervisor") and the regulator (the "WA"). In contrast to the

[11] Up to this point we have assumed that there is no conflictual interest between the WA and its monitor.

[12] Side contracts should not generally be thought of as being enforced by a court of law. Rather, enforcement comes from the parties' willingness to abide by their promise to cooperate.

WA, the monitor has time, resources and expertise to obtain information about the farmer's true water use. The WA relies on information supplied by the monitor. The monitor's expertise allows her to hide information from the WA in order to identify with the cheating farmer. That is, the farmer can bribe the monitor to withold the information about her theft. To keep the model tractable, we assume that a monetary equivalent of \$1.00 received by the monitor costs $(1 + \rho)$ \$ to the farmer. The shadow price of transfer ρ reflects the fact that transfers to the monitor are not fully efficient (a monetary bribe exposes the parties to the possibility of legal sanctions).

We consider a three-tier hierarchy: farmer/monitor/WA. All parties are risk neutral.

1. The Farmer: The farmer is detected stealing with the probability, $\kappa(\beta)\, m\left[q(\beta) - q^r(\beta)\right]$ for $\beta \in \{\underline{\beta}, \overline{\beta}\}$. The monitor files then a report to the WA about the information she has learned about the farmer. In case she decides to collude with the farmer, she makes a false report with a probability, υ and asks in return for bribe, B: Collusion can arise only if the retention of information benefits the two parties: the bribe must not exceed the farmer's expected cost of theft which is equal to $\kappa(\beta)\, mf\left[q(\beta) - q^r(\beta)\right]^2$:

$$B \leq \kappa(\beta)\, mf\left[q(\beta) - q^r(\beta)\right]^2 . \tag{38}$$

The WA discovers collusion with a probability π: The farmer's problem is given by

$$\begin{cases} \max\limits_{(\overline{q},\overline{q}^r)} \overline{g}(\overline{q}) - c\overline{q} - t\overline{q}^r - (1+\rho)(1-\pi)\nu B - C_T \\ \qquad s/t \\ B \leq \overline{\kappa} mf\left[\overline{q} - \overline{q}^r\right]^2 \end{cases} \tag{P3}$$

2. The Monitor: The monitor receives income from the WA for her monitoring activity, $w(m) = wm$ (the linearity of income in monitoring is quite plausible since in practice monitors receive wages for their activity). Monitoring incurs the cost $\lambda\psi(m)$: Furthermore, when the monitor is discovered lying she is punished with the level F which occurs with the probability $\pi\upsilon$ We consider here an endogenous[13] punishment, F which cannot be greater than the monitor's stake from collusion (benefit from her false announcement to the WA)

$$F \leq (1-\pi)\,\nu\overline{\kappa} mf\left[\overline{q} - \overline{q}^r\right]^2 . \tag{39}$$

In this case, the monitor may have no asset to be seized by the WA. Only her profit from collusion can now be taken back. The monitor's problem is the following)

$$\begin{cases} \max\limits_{m} wm + (1-\pi)\nu B - \lambda\psi(m) - \pi\nu F \\ \qquad s/t \\ B \leq \overline{\kappa} mf\left[\overline{q} - \overline{q}^r\right]^2 \\ F \leq (1-\pi)\,\nu\overline{\kappa} mf\left[\overline{q} - \overline{q}^r\right]^2 \end{cases}, \tag{P4}$$

3. The Water Authority: At the initial contracting stage, the WA picks f; F and α that maximize the social benefit. Specifically this benefit function is the sum of the farmers' surplus, $\left[\overline{g}(\overline{q}) - c\overline{q} - t\overline{q}^r - (1+\rho)(1-\pi)\nu B - C_T\right]$, the monitor's surplus, $\left[wm + (1-\pi)\nu B - \lambda\psi(m) - \pi\nu F\right]$ and the water supplier surplus which is equal to the

[13] We could consider the case of exogenous punishment where, F cannot be greater than some exogenous threshold l; so that $F \leq l$. This exogenous punishment can be viewed as the maximum amount of the monitor's asset that can be seized in the case of a detected lie.

revenue from water proceeds, $t\overline{q}^r$, from which is deduced the cost of water provision to the irrigated area, $\gamma\overline{q}$, the wage given to the monitor for her monitoring activity, the cost incurred by

monitoring, $\lambda\psi(m)$; the cost of inflicting punishment to the farmer $\varphi(f)$, the cost of inflicting punishment to the monitor $\phi(F)$ and the social cost of implementing the new irrigation regime $\eta_s\alpha C_T$:

$$W(f,F,\alpha) = \left\{ \begin{array}{c} \overline{g}(\overline{q}) - (c+\gamma)\overline{q} - \rho(1-\pi)\nu B - \lambda\psi(m) \\ -(1+\eta_s\alpha)C_T - \phi(F) - \varphi(f) \end{array} \right\}. \tag{40}$$

The WA's problem is

$$\left\{ \begin{array}{c} \max_{(f,F,\alpha)} W(f,F,\alpha) \\ s/t \\ G(t) - L(m,f,\alpha) \geq (1-\alpha)C_T \\ F \leq (1-\pi)\nu\overline{\kappa}mf\left[\overline{q}-\overline{q}^r\right]^2 \end{array} \right. , \tag{P5}$$

Collusion can occur only if the transaction cost of collusion is not very high[14], i.e.,

$$\rho < \frac{1}{(1-\pi)\nu} - 1. \tag{41}$$

Before solving this model, let us present the setting when collusion does not occur. This case will serve as a useful benchmark in the subsequent analysis. Afterwards, we proceed with the regulatory capture setting. We do not need to present the optimization problem of each actor in the three-tier hierarchy in details. We will use modified versions of the above programs. As one would expect, the terms in the bribe, B and the level of punishment F conceal. Hence, no evidence of bribe and punishment shows in this setting. Furthermore, the two constraints (38) and (39) are omitted in these programs. Lemma 5 characterizes the solution.

LEMMA 5: Suppose that assumptions (7), (8) and (9) hold, then

(i) The optimal punishment inflicted to the farmer and subsidies used by the

WA[15] $\left\{f^{ARC},\alpha^{ARC}\right\}$ *satisfy*

$$f^{ARC}: \left[-\lambda\psi'(m) + \eta_s\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{4m^2f}\right]\frac{\partial m}{\partial f} + \eta_s\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{4mf^2} = \varphi'(f), \tag{42}$$

and

$$\alpha^{ARC} = 1 - \frac{G(t) - L\left(m^{ARC}, f^{ARC}, t\right)}{C_T} > 0. \tag{43}$$

(ii) The optimal monitoring effort performed by the monitor is implicitly given by

$$m^{ARC}: w = \lambda\psi'(m). \tag{44}$$

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[14] The assumption, $\rho < \frac{1}{(1-\pi)\nu} - 1$ is feasible because $\upsilon < 1$ and $(1-\pi) < 1$; this essentially implies that $\upsilon(1-\pi)$ is smaller than 1 and therefore, $\frac{1}{\nu(1-\pi)}$ is higher than 1.

[15] The subscript "ARC" is to indicate the absence of regulatory capture (=non-collusive setting) by contrast to "RC" which will be used for the regulatory capture setting (=collusive model).

(iii) The level of theft by each farmer is given by

$$a^{ARC} = \frac{t}{2\overline{\kappa}m^{ARC}f^{ARC}}. \tag{45}$$

As for the results of the RC setting[16] they are summarized by the following proposition:

PROPOSITION 4: Suppose that $2(1+\rho)(1-\pi)\nu - 1 > 0$, and that assumptions (7), (8), (9) and (41) hold, then

(i) The optimal punishments and subsidies used by the $WA\{f^{RC}, F^{RC}, \alpha^{RC}\}$ satisfy

$$F^{RC} = \frac{t^2}{4(1+\rho)^2(1-\pi)\nu m^{RC}f^{RC}}, \tag{46}$$

$$f^{ARC}: \left\{ \begin{array}{c} \frac{\rho t^2}{4(1+\rho)^2(1-\pi)\nu\overline{\kappa}m^2 f} \\ -\lambda\psi'(m) \\ +\phi'(F)\frac{t^2}{4(1+\rho)^2(1-\pi)\nu\overline{\kappa}m^2 f} \\ +\eta_s\left[\frac{2(1+\rho)(1-\pi)\nu-1}{2(1+\rho)(1-\pi)\nu}\right]\frac{Bt^2}{m^2 f} \end{array} \right\} \frac{\partial m}{\partial f}$$

$$+\left\{ \begin{array}{c} \frac{\rho t^2}{4(1+\rho)^2(1-\pi)\nu\overline{\kappa}m f^2} \\ +\phi'(F)\left(\frac{t^2}{4(1+\rho)^2(1-\pi)\nu\overline{\kappa}m f^2}\right) \\ +\eta_s\left(\frac{2(1+\rho)(1-\pi)\nu-1}{2(1+\rho)(1-\pi)\nu}\right)\frac{Bt^2}{m f^2} \end{array} \right\} = \varphi'(f), \tag{47}$$

and

$$\alpha^{RC} = 1 - \frac{G(t) - L\left(m^{RC}, f^{RC}, t\right)}{C_T} > 0. \tag{48}$$

(ii) The optimal monitoring effort performed by the monitor is implicitly given by

$$m^{RC}: w - \left(\frac{1}{\nu} - \pi\right)\frac{t^2}{4(1+\rho)^2(1-\pi)\overline{\kappa}m^2 f^{RC}} = \lambda\psi'(m) \tag{49}$$

(iii) The level of theft by each farmer is given by

$$a^{RC} = \frac{1}{(1+\rho)(1-\pi)\nu}\left(\frac{t}{2\overline{\kappa}m^{RC}f^{RC}}\right) \tag{50}$$

Proof: (See the Appendix).

A mere comparison between Eqs. (44) and (49) yields that a lower level of monitoring is necessary in the RC setting compared to ARC (i.e., $m^{RC} < m^{ARC}$). Monitoring here does not only reduce the incidence of theft (incentive effect), but may allow the monitor to benefit from colluding with the farmer (rent seeking effect). This second effect acts as a disincentive to undertaking a higher level of monitoring - A lower monitoring effort in addition to the cost savings it brings about, gives a higher scope for theft, therefore increasing the expected stake from collusion.

[16] Here we do not consider "collusion proof" schemes, namely schemes that do not induce the monitor and the farmer to collude and lead the monitor to report truthfully, and hence there is no bribe in equilibrium.

By using the envelope theorem, we derive the impact of the level of punishment inflicted to the farmer[17] on monitoring

$$\frac{\partial m^{RC}}{\partial f} = -\frac{\left(\frac{1}{\nu} - \pi\right)\left(\frac{t^2}{4(1+\rho)^2 \overline{\kappa} m^2 f^2}\right)}{\frac{d^2 V(m)}{dm^2}} > 0. \qquad (51)$$

(Where $\left(\frac{1}{\nu} - \pi\right) > 0$ since $\pi\upsilon < 1$). In the presence of collusion, monitoring and punishment become complement instruments, meaning that a lower level of punishment f is required in the RC setting, i.e., $f^{RC} < f^{ARC}$. This is because in addition to the cost savings it brings about, a lower level of punishment increases the opportunities of theft increasing thereby the stake from collusion and thereafter the amount of money that can be seized from the monitor by the WA through the punishment inflicted to the former. This acts as a disincentive for the monitor from colluding.

Collusion reduces the level of instruments that counteract the incentives of theft, affording the farmer with more opportunities of stealing, i.e., $\overline{a}^{RC} > \overline{a}^{NRC}$. Finally, monitoring levels and subsidies are substitute instruments with respect to increasing the incentives for technology adoption

$$\frac{\partial \alpha}{\partial m} = \frac{1}{C_T}\frac{\partial L(m,f,t)}{\partial m} = -\left(\frac{2(1+\rho)(1-\pi)\nu - 1}{2(1+\rho)(1-\pi)\nu}\right)\frac{1}{C_T}\left(\frac{1}{\underline{\kappa}} - \frac{1}{\overline{\kappa}}\right)\frac{t^2}{fm^2} < 0, \qquad (52)$$

A higher subsidy is then required in the *RC* setting, i.e., $\alpha^{RC} > \alpha^{NRC.}$ This is the case because a lower monitoring increases the incentives of theft lowering thereby the incentives for technology adoption. Hence, a higher subsidy is required to compensate.

Our findings are summarized as follows: the collusive behavior is more likely when punishment rates are low and monitoring costs are high. We should expect to see empirically that collusion varying both with observed factors that increase the likelihood of theft and (to the extent that other unobserved factors increase that likelihood) as a function of the level of theft itself. Similar implications apply to technology adoption incentives: to the extent that punishment levels, monitoring efforts and subsidies do not explain all the variation in technology adoption, we should expect *water-saving* technologies to reduce the likelihood of collusion. We test these predictions below.

5.1. Summary of empirical hypotheses

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

Determinants of individual water theft:

- The individual level of theft increases in the price of water
- The individual level of theft decreases in punishment levels
- The individual level of theft increases in monitoring costs
- The individual level of theft decreases in the adoption of water-saving technologies
- The individual level of theft increases in collusion

The adoption of water-saving technologies:

- Adoption of water-saving technologies increases in the level of punishment
- Adoption of water-saving technologies decreases in monitoring costs

[17] The level of punishment inflicted to the farmer is chosen in the first stage of the game, and is therefore a parameter in the second stage when the monitor chooses the level of monitoring.

- Adoption of water-saving technologies increases in the price of water in a relevant range of low to medium water prices
- Adoption of water-saving technologies decreases in the equilibrium incidence of theft

Determinants of collusion:

- Collusion decreases in the level of punishment
- Collusion increases in monitoring costs
- Collusion increases in the expected level of theft
- Collusion decreases in the adoption of water-saving technologies

Finally, a word of caution is in order. In the following analysis we will focus only on the determinants of drip technology and skip those of sprinkler systems. Sprinklers actually limit production flexibility because they confine farmers to growing low value fodder and grain crops such as sorghum and wheat. Moreover, the price of water for these crops is heavily subsidized reducing greatly the incentives for theft and thereby for collusion.

6. Testing the Model

6.1. Data sources:

We now test the predictions of our model against data compiled from interviews of 58 farmers active in two public irrigated areas in Medjez-El-Bab. Our set of data though limited is representative, because the survey was conducted in every small village within the county. We are not aware of any biases that might be introduced by this partial availability of data, but evidently the possibility of selection bias cannot be ruled out.

Medjez-El-Bab is a small town in Tunisia located at 54 km northwest of the capital, with a total area of 46,975 hectares of which 41,900 hectares are devoted to agricultural activity and 1,570 hectares essentially reserved for pastures. The total irrigated areas is ~ 8,000 hectares divided between public and private sectors, with 6,696 hectares and 1,304 hectares, respectively.

Medjez-el-Bab is located in a semi-arid superior climate area of the country, and receives moderate and erratic rainfalls averaging 412 mm per year, mainly concentrated during four months from December to Mars. Thus, farmers rely heavily on water sources controlled by government agencies for most of the year. The region is mostly flat, with hills in only 40% of its total area. In this agroclimatic zone, wheat, olives and gardening products are the main crops in the winter season, with wheat by far the most important in terms of cultivated area (64%). Tomatoes, watermelon, potatoes, apples, pears, peaches and almonds are the main crops in the summer season, with tomatoes by far being the most important in terms of cultivated area (40%). The percentage of workers who are permanently employed in the agricultural sector amounts to 40% of the population while those who work in part-time is 30%.

Government policies for the last three decades have promoted irrigated cropping patterns at the expense of dry land farming in the whole country, through the creation of several public irrigated areas (=farm land equipped with network irrigation such as primary and secondary water tubes, measuring devices and so on). When the region relies mainly on water surface, the ministry of Agriculture builds pumping stations to carry water to these areas.

The Medjerda river, which also feeds Sidi Salem – the largest dam in the country (with a storage capacity about 700 millions m^3) is the main source of water for the whole agricultural area of Medjez El Bab. Prior to 1984 the areas immediately adjacent to the river (about 1,780 hectares) were irrigated directly using water provided by small diesel pumps (motors) stationed along the river bed. This has left a large areas of fertile farm lands either partially used or not at all, in particular those located in higher elevation. Two pumping stations that required substantial public investments, were built, one in the village of El Heri and the other next to the agglomeration of Medjez El Bab, and were used to provide irrigation of these areas.

The key question for investigation is what determines the rate of individual theft of water, the diffusion of modern irrigation technologies such as drip systems and collusion. Among the difficulties in 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 the collusion captured by the variable corruption defined below) are very likely to be endogenous. There is also the difficulty that theft as such is not directly observable by the managing authority. The determination of the true amount of water stolen required the major investigation of this survey (as explained below).

The survey was carried out in 2009 during the months of June and half of July in two public irrigated areas in Medjez El Bab. These areas are run by a regional authority, the so called "Agricultural Regional Development Commission (ARDC) of Medjez El Bab." It should be stressed that the ARDC's mission is the management of water distribution to the targeted areas, maintenance of irrigation network as a whole, monitoring farmers to reduce the occurrence of theft when the irrigated area is equipped with water measuring devices, collecting water proceeds and making recommendations about water tariffs. This holds even though the exact prices are usually set by the ministry of agriculture.

The first public area called "Medjez El Bab - Mattisse - Sidi Nasser," was created in 1985. The surface is equipped with network irrigation of 3,791 hectares. The area is intensely exploited (i.e. land is cultivated throughout the year). The landscape is mostly flat, with hills and valleys constituting less than 15% of the area. Currently, typical winter crops are wheat, olives and vegetables (with wheat by far the most important in terms of cultivated area, 72.3%), while typical summer crops include tomatoes, potatoes, peppers, and fruits such as apples, peaches, pears and almonds; tomatoes are by far the most important in terms of cultivated area (31.3%).

The cultivated areas can be divided into four categories:

1. Small parcels (less than 3 hectares)
2. Medium size plots with areas ranging from 3 to 6 hectares
3. Large plots ranging from 6 to 25 hectares
4. Very large plots exceeding 25 hectares.

Medium and large plots are the most common – these plots represent respectively 47% and 28% of the total number of cultivated land, while small and very large plots represent 19% and 6%, respectively.

while small and very large plots represent 19% and 6%, respectively. The second area called "El Heri - Grish - Griaat", was created more recently (in 1994). The equipped surface with network irrigation is equal to 2,905 hectares. The area is cultivated at 95%. The area is mostly .at, with hills in only 15% of its total area. In this zone, wheat, olives and vegetables are the main crops in the winter season, with wheat by far the most important in terms of cultivated area (65%). Tomatoes, watermelon, potatoes and fruits including apples, peaches, pears and almonds are the main crops in the summer season, with tomatoes taking the lion share of the cultivated area (22,2%).

The cultivated areas are essentially divided in four categories as described above: small and medium plots represent the highest percentage (32% for each category), and all the others combine the remaining 26%.

Our information consists of the price of water charged to farmers as well as about their socioeconomic characteristics such as their off-farm incomes and their personal characteristics such as their levels of education and age. We also have information about pedologic characteristics such as the percentage of farmers' plots of land in which the soil is red. In addition, there are data about the farmers' cultivation processes, namely cropping patterns and the diffusion of drip-irrigation systems. The major difficulty we were expecting to face was the determination of the individual level of theft (defined as the difference between the true amount of water used by the farmer and the amount indicated by her water meter). The strategy we have adopted to discover the value of this key variable is the following: to determine the true individual quantity of water used we asked the farmer about her cropping patterns, the surface devoted to each crop, the type of soil of such surface and also the irrigation technology used. Then, we asked the farmer about the amount of water necessary for each crop per hectare and whether she actually used such a quantity. As for the quantity indicated by the farmer's water meter, we got it directly from the Agricultural Regional Development Commission, ARDC. To our great surprise and pleasure several farmers claimed that they have stolen water and gave us the amount stolen (These confessions were cross-checked with the data we have collected as described previously). They also gave information about the bribe paid to monitors.

Almost all farmers we have interviewed were complaining seriously about the high price of water, the increased prices of the other production inputs and the severe climate conditions they were facing (in particular the repeated Medjerda floods[18] which ravaged their harvests and for which they were not indemnified). Farmers recognized that among the fewest ways to reduce production costs is to steal water (since it is the only production input they can use without paying for it fully or partially).

The data are of an unbalanced panel type, for four years from 2004-08 for 57 farmers and for three years from 2004-07 for the remaining farmer. Almost all data were jointly provided by farmers themselves, the Agricultural Regional Development Commission (ARDC) of Medjez El Bab, the Cells of Agricultural Development (CAD) of the county's villages.

Before proceeding with the econometric analysis it is important to clarify the way in which we propose to measure the monitoring costs faced by the monitor.

6.2. Proxy measure of monitoring costs

Given that monitoring levels are not directly observable, we need to find a suitable proxy measure. The one we have chosen is:

- DISTANCE: the length measured in kilometers of the portion of the main road which separates the plot of land the farmer is irrigating and the Agricultural Regional Development Commission, ARDC of Medjez El Bab.

This is likely to increase monitoring costs because it reduces the ability of monitors to observe the behavior of farmers. It is important to note that monitoring costs by themselves cannot be used as excluded instruments for the endogenous variables, since the theory predicts that monitoring costs will determine both the collusive behavior and the use of drip technology and also the level of theft conditional on the incentives of collusion and technology adoption.

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[18] The more severe floods the region experienced were those of 2003 and 2006. But the major riverside farmers' lands were fully or partially ravaged by floods almost each year. This is due to the poor investment in dredging the Medjerda river whose width narrowed from one year to the other.

However, we can nevertheless investigate whether monitoring costs also directly influence the incentives for collusion and technology adoption; we do this in subsections (7.3.2) and (7.3.3).

Table 1 presents the descriptive statistics of our empirical variables.

The variables we will use in the subsequent empirical analysis[19] are defined as follows:

- WATER THEFT: is the differential between the amount of water used by the farmer and that indicated by her water meter, expressed as a percentage of the total amount used by the farmer.
- PUNISHMENT RATE: is the number of days for which the farmer is denied access to irrigation, expressed per 1.000 m^3 of water stolen.
- DRIP: is the percentage of the land irrigated by the farmer equipped with drip irrigation systems.
- ALTERNATIVE SOURCE: is the distance measured in kilometers between the plot of land the farmer is irrigating and the river "Oued Medjerda".
- REVENUE SHOCK: is the percentage of losses in the harvest incurred by the farmer in the previous year. It is the ratio of the losses in the harvest measured in hectares and the total surface irrigated. These losses are either due to natural catastrophes such as "Oued Medjerda" floods or/and crop diseases or/and problems of harvest distribution etc.
- RED SOILS: is the percentage of the farmer’s land which soil is red.
- EDUCATION: is the average number of years of schooling of the farmer.
- AGE: is the average age of the farmer.
- DISTANCE TO LARGE CITY: is the distance between the county where the farmer spent her childhood and the nearest large city where there are public infrastructures such as schools (primary and secondary), public hospitals, water systems, bridges, roads and other public buildings.
- ALTERNATIVE REVENUE: it scores (0) when the only source of income the farmer has is that generated by the irrigation activity. It scores a further 1, when in addition to her irrigation activity, the farmer has an off-irrigation income such as having moderate livestock. It scores an additional 1, when the farmer has both off-irrigation income and a moderate off-farm income such as having a salary (between 500 TD and 700 TD) or she is receiving some monetary aid from her children. It scores (3) when in addition to her irrigation activities, the farmer has a salary (between 800 TD and 1200 TD) and also has some moderate personal properties generating a moderate fixed revenue. It scores (4) when the farmer possesses several personal properties generating a large fixed revenue; and scores (5) when the farmer is very rich - she has several personal properties and several highly profitable commercial projects.
- WATER PRICE: is the price of one unit of water charged by the ministry of agriculture to the farmer.
- CORRUPTION: is the amount of money in Tunisian Dinars given by the farmer to the monitor(the bribe). This is a positive measure of collusion.
- IRRIGATION NETWORK: is the period of time (in years) between the date of creation of the irrigated area and the year the survey was conducted.
- INFLUENTIAL POSITION: it scores (1) when the farmer has a prestigious social position or/and has political relations or/and belongs to the most powerful family in the village or the agglomeration were the survey is conducted, and scores (0) otherwise.
- DIVERSIFICATION: is the number of crops grown by the farmer.

[19] Except the proxy for monitoring costs which has already been defined above.

- ADVERSE PRICING: is the differential between the price of water charged to farmers in the irrigated areas of Medjez El Bab and the price of water for irrigation charged to farmers of Cap Bon's county[20] (a governmental project diverts the Medjerda river water to the region of Cap Bon at lower prices than those assigned to Medjez's farmers), expressed as a percentage of the price charged to farmers of Medjez El Bab.
- WATER LOGGING: it measures the aquifer inflow level (in meters) because of a bad draining.

6.3. Testing the model

6.3.1. Estimation of individual water theft

We report here that theft increases or decreases relative to the other factors, notably, the price of water, the level of punishment and the monitoring costs. We also investigate how theft is affected by the regulatory capture behavior and the use of water-saving technologies.

We regress the individual level of theft on the following independent variables.

- WATER PRICE

Institutional variable

- PUNISHMENT RATE

Variable controlling for regulatory capture

- CORRUPTION

Variable controlling for the productivity of water

- DRIP

Proxy of monitoring costs

- DISTANCE

Control variables

- ADVERSE PRICING

- ALTERNATIVE SOURCE
- IRRIGATION NETWORK

Table 2 illustrates an Ordinary Least Squares of the determinants of theft. The first equation shows that theft increases with the price of water, with the incidence of collusion and with the distance of the farmer's plot of land from the water government agency, ARDC (a positive proxy of monitoring costs). It decreases with the use of drip technology. These effects are all those predicted by the theory and all are significant at 1% except the drip effect which is significant at 7,4%. A word of caution is in order. Although the coefficient on PUNISHMENT RATE is the opposite to what is expected, this finding is far from counterintuitive. The explanation on the face of it is that corruption interacts with punishment implementation - higher bribes lead monitors to report lower theft rates and therefore to implement lower punishment levels. The second equation is the initial OLS specification from which we drop WATER PRICE and replace it by ADVERSE PRICING (since the two variables are perfectly correlated, their inclusion together in the same equation makes one them to drop). The positive coefficient on ADVERSE PRICING is along expected lines. Theft is a way to react to

[20] This county is located at 80 km northeast of the capital. Medjerda water is mobilized for irrigation to the towns of Hammamet, Nabeul, Bni Khaled, Bni Khiar, Menzel Bourgiba, Hawariaa, Grombalia etc.

the Governmental "injustice": why the Government charges the Medjerda river water to farmers of the county at a price that is twice as high as the price charged to farmers of the Cap Bon's region who are richer and grow high value crops such as strawberries and citrus fruits. For the rest of variables the results are exactly the same as in the first equation, confirming the perfect correlation between WATER PRICE and ADVERSE PRICING. The third equation shows that the qualitative findings prove reasonably robust to the inclusion of farmers fixed effects, although this is a very demanding test since there are only four years of data and not for all farmers (in addition some important variables in the regression such as WATER PRICE which varies a little in time and other controls such as ALTERNATIVE SOURCE which is completely invariant in time are dropped from the regression). Under fixed effects the standard errors increase for some variables and decrease for others, reducing the effect of the monitoring costs' proxy to insignificance (though without very much modifying the standard error). Overall, though, the results clearly support the predictions of the theory.

The remaining coefficients show various controls for which theory provides no unambiguous predictions. The presence of drip (which increases the productivity of water by bringing about higher yields per cubic meter of water applied) reduces theft. The presence of alternative sources of water not controlled by government agencies lowers theft since diverting water directly from the river seems to be more profitable for farmers than paying for it when it is provided by the ARDC. As for the age of the irrigation network it is very likely to be positively correlated to theft.

We now turn to the concerns about the possible endogeneity of some of the right-hand side variables. The most likely variable to suffer from this problem is CORRUPTION: higher rates of theft might lead to increased incentives for collusive behavior that might reduce the punishment inflicted to the farmer. The causal association of high corruption levels with high rates of theft leaves the coefficient on CORRUPTION almost the same. A variable that might be endogenous for different reasons is DRIP: the farmer who expects to steal water will have weaker incentives to adopt water-saving technologies. This would bias upward the absolute value of the OLS estimate, since a causal association of high adoption of drip technology with low rates of theft would be reinforced by a reverse-causal association of high rates of theft with low rates of adoption of the technology.

To explore these possibilities our instrumenting strategy is as follows: beginning with CORRUPTION, we use the idea that farmers' personal characteristics captured by the variables, EDUCATION and AGE may be associated with lower corruption. We are not sure how to interpret the negative coefficient on AGE. It may indicate that the older the farmers are, the more risk averse they are to engaging in any illegal activity. An alternative explanation of this result may rely on religious biases - older farmers who are generally more religious are very likely to consider corruption as a sin. Moreover, more educated farmers may have a higher public spiritual appeal and fear spoiling their reputation by engaging in illegal activities. An alternative interpretation is that more educated individuals may understand better the use of incentives (as for older farmers they may be more experienced in the use of incentives) and are therefore more aware about the consequences in engaging in risky activities. We also use two other variables: the first one, INFLUENTIAL POSITION is a positive proxy for collusion enforcement since monitors may well take the bribe and breach the informal side contract with the farmer. The second, ALTERNATIVE REVENUE may well capture the farmers' ability to afford the necessary funds to pay bribes to monitors.

Finally, we control for the endogeneity of DRIP using a geographical variable that influences the productivity of the technology. RED SOILS are rich soils requiring less production inputs (except water) per unit of output, leading to production cost reduction. However, these soils have lower water retention on which drip technology therefore saves more water. A word of caution is in order. Although we find the exclusion restrictions plausible, we cannot rule out a priory that the proposed instruments do in fact affect theft directly, so we pay particular attention to the statistical tests of over identifying restrictions that we report in all the instrumental variables specifications below.

Table 3 shows the results of these instrumental variables estimations. We instrument first for CORRUPTION, then for DRIP and finally for both CORRUPTION and DRIP. In the final equation (Eq. 3.4) we replace EDUCATION (which may also suffer from endogeneity) by the distance between the county where the farmer spent her childhood and the nearest large city which is a more clearly exogenous variable, and which is a significant predictor of education as we show in table 5.

These results provide a striking confirmation of our hypotheses about the determinants of theft, even when we control for the endogeneity of regulatory capture and technology adoption. All the variables that were significant in our OLS specification remain significant in the 2SLS specification at 5% at least and in most cases at 1%. They also show that our concerns about endogeneity are justified, though more for some variables than for others. The value of the OLS estimate on CORRUPTION did not change significantly, confirming that the causal association of the increased incentives of theft with high rates of corruption would be almost exactly compensated for by the positive causal effect of corruption on theft in an increasing-theft direction. A Durbin-Wu-Hausman test on this variable alone fails to reject exogeneity at anything close to conventional significance levels, although the joint test of the exogeneity of the two variables (CORRUPTION and DRIP) is clearly rejected. The coefficient on DRIP more than doubles in absolute magnitude compared to the OLS specification, confirming our conjecture that the OLS estimate is biased away from zero. A Durbin-Wu-Hausman test on this variable alone rejects exogeneity at less than 21%.

The coefficients of all variables (except that on DRIP) did not change significantly. Moreover, the variables have the expected signs and are significant at a 6% or a better level of confidence. The coefficient on DISTANCE is positive, because it reduces the expected level of monitoring, increasing thereby the scope for theft. The coefficient on ALTERNATIVE SOURCE is negative as expected. We are not sure how to interpret the positive coefficient on IRRIGATION NETWORK. It may indicate that farmers who were equipped with measuring devices for longer periods may become more experienced in their manipulation, facilitating thereby the activity of theft. Finally, the instruments comfortably pass the Hansen test of over identifying restrictions.

6.3.2. Adoption of drip-irrigation technology

We report here the results for the estimation of DRIP. Our model predicts that adoption of water-saving technologies will be increasing in the price of water with and in the level of punishment, and decreasing in the equilibrium incidence of theft and in monitoring costs. In testing these predictions, we shall want to control for factors that affect the productivity of the technology (which may vary from one place to another according to agro-climatic conditions and cropping patterns) and for factors that affect the ability of farmers to afford the capital investments involved (access to capital may be positively correlated with adoption incentives). We also control for the production flexibility (captured by the variable DIVERSIFICATION) and the degree of risk aversion to using innovative technologies.

Our independent variables are the following:

- WATER PRICE

Institutional variable

- PUNISHMENT RATE

Variables controlling for the productivity of the technology

- RED SOILS

- WATER LOGGING

Variable capturing farmers' liquidity constraints

- REVENUE SHOCK

Variable capturing risk aversion

- AGE

Other control

- DIVERSIFICATION

In addition we test the hypothesis that expected levels of theft will influence the incentives to adopt water-saving technology (in the sense that people who expect to steal water will be less likely to invest in the technology). We do this by including the variable WATER THEFT, but since we expect this may be endogenous we instrument it using DISTANCE, which we know from Table 3 to be an important determinant of theft, and one which is not significant directly in the DRIP equation (Eq. 4.2 in table 4). Table 4 illustrates the results.

In Equations (4.1), (4.2), (4.3) and (4.4), the coefficient on WATER PRICE is positive[21] as expected. The coefficient on RED SOILS is positive. This soil has poor water-holding capacity, requiring a greater amount of irrigation to maintain soil moisture. Hence, higher is the need for water-saving technologies. The coefficient on REVENUE SHOCK is negative: the higher the losses in previous years are, the less likely farmers are to have the necessary funds for investing in new technologies. The positive coefficient on WATER LOGGING is along expected lines: the lower the aquifer inflow level is the less severe the problem of salinity threatening the deterioration of the planting area, and the higher is the productivity of drip technologies on such areas.

The interpretation of the positive coefficient on DIVERSIFICATION is twofold. First, this variable may well capture the farmer's liquidity constraints. The greater variety of crops the farmer grows allows them to hedge the risk of production shocks or/and crop price fluctuations. Second, capital-intensive technologies are generally assumed to increase production flexibility, so we expect drip technology (in the context of irrigation this technology is relatively more capital intensive than traditional methods) to increase the farmer's production flexibility captured by the greater crop variety. Drip technology which allows for the more efficient use of production inputs per unit of output, may well increase the planting area and hence growing more crops. The greater crop variety may then signal the high production flexibility indicating the increased farmer's responsiveness to the market fluctuations. This finding is in line with the findings of Mourshed, M. (1995) who reports evidence from 53 participants in an Egyptian desert land reclamation project that the larger variety of crops grown by farmers is associated with higher adoption of drip systems. DIVERSIFICATION is likely to suffer from endogeneity, we instrument it using REVENUE SHOCK which is not significant directly in the estimation of DRIP (see equations 4.2 and 4.3). REVENUE SHOCK measuring the losses incurred by the farmers in the previous year is

[21] This finding is in line with findings reported by Caswell and Zilberman (1985) who examined the determinant factors in the adoption of furrow, sprinkler and drip irrigation by fruits growers in the San Joaquin Valley of California. They find that an increase in water tax would encourage fruit growers to adopt modern technologies associated with water cost-saving.

a more clearly exogenous variable, and is a significant predictor of DIVERSIFICATION (not reported here): the coefficient is negative as expected since REVENUE SHOCK can be considered as a positive proxy of liquidity constraints reducing the farmer's funds necessary for enlarging the cropping patterns.

The results of equation (4.4) show that our concerns about endogeneity are justified, though more for some variables than for others. Indeed, the coefficient on DIVERSIFICATION almost doubles compared to the OLS specification (Eq.4.2). A Durbin-Wu-Hausman test on this variable alone (not reported here) rejects exogeneity at a conventional level (~20%). The coefficient on WATER THEFT almost doubles in absolute magnitude compared to the OLS specification, confirming our conjecture that the OLS estimate is biased away from zero. A Durbin-Wu-Hausman test on this variable alone rejects exogeneity at less than 12,6% and the joint test of exogeneity of all variables passes the Durbin Wu-Hausman test at conventional level (less than 11,2% level).

The variable AGE may be interpreted as a positive proxy for the farmer's degree of risk aversion. Older farmers who are likely to be more rooted in traditional practices may be less receptive to innovative techniques. The negative coefficient on AGE is thus along expected lines. The theoretical predictions are therefore supported by the evidence, except for the coefficient on DISTANCE, for which no support is found. The remaining variables have the expected signs and are significant at less than 6% or a better level of confidence.

In Equations (4.2), (4.3) and (4.4), the striking findings are that predicted water theft has a negative impact on technology adoption, as expected, and that including this regressor increases the coefficient on WATER PRICE. This implies that the effect of water price on technology adoption would be even stronger than it is if it were not for the fact that higher prices also encourage theft. The second point is that the inclusion of WATER THEFT as regressor reduced the coefficient on DISTANCE insignificantly confirming that this variable is indeed a strong instrument for theft.

6.3.3. CORRUPTION

We report here the results for the estimation of CORRUPTION. Our model predicts that corruption will be increasing in monitoring costs and in the equilibrium incidence of theft, and decreasing in the punishment rate and in the use of water-saving technologies. We use an approach based on personal characteristics captured by two variables, EDUCATION and AGE and on factors that affect the enforcement of the side informal contract between the monitor and the farmer (monitors are more fearful from reneging agreements with individuals with high powerful social and political relationships). We shall also control for factors that influence the ability of farmers to afford the necessary funds to pay bribes to monitors (access to capital may be positively correlated with corruption).

Our independent variables are as follows:

Personal characteristics

- EDUCATION
- AGE

Institutional variable

- PUNISHMENT RATE

Variable capturing farmers' liquidity constraints:

- ALTERNATIVE REVENUE

Proxy of monitoring costs

- DISTANCE

Other control

- INFLUENTIAL POSITION

We also test the hypothesis that expected levels of theft will influence the incentives for corruption (in the sense that farmers who expect to steal water will be more likely to bribe monitors to reduce the punishment inflicted on them in case they are detected stealing). This will be done by including the variable WATER THEFT, but since we expect this may be endogenous we instrument it using DISTANCE, which we know from Table 2 to be an important determinant of theft (DISTANCE is also an important determinant of CORRUPTION). Similarly, we test the hypothesis that the use of drip technology will affect the incentives for corruption in the corruption-decreasing direction (using drip technology saves in the amount of irrigation thereby reducing their incentives for theft). However, DRIP suffers from endogeneity, we instrument for it using RED SOILS which we know from table 3 to be a strong determinant of drip adoption. Another variable which is likely to suffer from endogeneity is EDUCATION. More educated farmers are likely to be less prone to engage in illegal activities because they may fear more for their reputation or because they understand better the bad consequences of these activities. The higher scope for corruption calls upon less educated individuals who may have a short run vision of things and are attracted by seemingly easy gains.

Table 5 illustrates the results.

In all equations the coefficients on ALTERNATIVE REVENUE and INFLU- ENTIAL POSITION are positive as expected. The results of equations (5.2), (5.3) and (5.4) show that our concerns about endogeneity are justified, though more for some variables than for others. Indeed, when we control for the endogeneity of EDUCATION alone (not reported here) its coefficient increases in absolute magnitude by almost one third compared to the OLS specification. Similarly controlling for the endogeneity of both EDUCATION and DRIP increases the absolute magnitude of the coefficient on EDUCATION by more than one third compared to the OLS specification, and increases the absolute magnitude of the coefficient on DRIP by more than seven times compared to OLS (and also increases the significance level which passes from 16,9% to 2%). A Durbin-Wu-Hausman test on both variables DRIP and EDUCATION rejects exogeneity at a highly significant level (less than 2,5%). Moreover, controlling for the endogeneity of WATER THEFT and EDUCATION, though it reduces the coefficient on WATER THEFT (although the coefficient remains significant at less than 5%), it increases the absolute magnitude of the coefficients on EDUCATION and DRIP compared to OLS. The joint test of exogeneity of these variables passes the Durbin-Wu-Hausman test at less than 1%. However, controlling for the three variables; EDUCATION, WATER THEFT and DRIP (not reported here) reduces the coefficient on WATER THEFT to insignificance.

Overall, the theoretical predictions are supported by the evidence. The rest of variables have the expected signs and are significant at less than 10% or a better level of confidence.

Nevertheless, to test the robustness of these results to alternative specifications, particularly bearing in mind the endogeneity of theft and technology adoption (respectively, theft and corruption) in each others' equations, we estimate a system of three equations using three-stage least squares regression; the results are reported in table 6. As one can see the 3SLS results are qualitatively almost identical to the 2SLS results. This is entirely supportive of the theoretical predictions.

7. Conclusion

We have investigated the potential advantages and limitations encountered by adoption of new irrigation technologies in the presence of water theft applied to the agricultural sector. In particular, our theoretical treatment has shown that water theft and technology adoption interact in two competing ways. On the one hand, new technology adoption does reduce theft by enhancing the WA's monitoring capabilities; new technology allows easier detection of theft incidence. On the other hand, accessing water resource via simple theft may very well reduce the farmers' willingness to pay for the technology adoption, because this means of access though risky is still essentially much lower than the true value.

Each policy instrument chosen by the WA in response to the competition between the farmer's incentives – described above – may well produce one solution but often creates a new problem. Monitoring and punishment – which are primarily designed to fight theft – also increase technology adoption incentives. Moreover, larger subsidies entice the farmer to adopt new technologies to reduce theft, confirming that monitoring (respectively, punishment) and subsidies are indeed substitute instruments. We also examined the impact of few additional key parameters (of the model) on the farmer's decisions in terms of theft and technology adoption, notably the price of water. We found that incidence of water theft and the adoption of water-saving technologies increase with increasing water prices. We extended the basic model allowing for collusion between monitors and cheating farmers. We show that the likelihood of collusion is more likely when monitoring costs are high and punishment rates are low.

The main theoretical predictions were tested empirically using a survey based on data from two public irrigated areas in Medjez El Bab (Tunisia). The econometric evidence supports most of our findings in that monitoring costs, the price of water and the higher scope for collusion all increase theft and the adoption of drip irrigation in turn reduces it. Moreover, the evidence lends credence to the fact that punishment rates increase the adoption of drip irrigation and the expected incidence of theft reduces it. Finally, we found that the expected incidence of theft increases the incentives for collusion and in turn, punishment levels and the use of drip irrigation reduces them.

Overall these results give a strong confirmation that water theft is an important constraint for the implementation of two solutions recognized to be effective in improving water use efficiency, namely pricing policies and the use of modern irrigation technologies. In addition water theft gives rise to opportunistic behavior through regulatory capture, increasing therefore the inefficiency of water use by increasing the opportunities of theft itself. The last striking finding is the negative effect of the collusive behavior or corruption on the effectiveness of institutions: corruption reduces the productivity of institutional rules in that higher levels of punishment primarily designed to reduce the incentives of theft instead increase them.

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Table 1: Summary of Descriptive Statistics

Variable	Unit of measure	Obs.	Mean	Std. Dev	Min	Max
FARMER	individual	231	-	-	-	-
YEAR	Year	231	2.5	1.12	1	4
WATER THEFT	Percentage	231	0.176	0.32	0	0.8
WATER PRICE	Tunisian Dinar per $m^3$of water reported	231	0.1245	0.00086	0.124	0.126
PUNISHMENT RATE	Days access denied per 1.000 m^3 of water stolen	231	1.5	1.23	0	5
EDUCATION	Year	231	10.844	4.6	2	22
AGE	Year	231	50.94	11.246	28	76
REVENUE SHOCK	percentage	231	0.232	0.178	0	1
DIVERSIFICATION	Integer	231	2.433	1.006	1	5
ALTERNATIVE REVENUE	Index	231	1.775	1.12	0	5
DRIP	Percentage	231	0.5	0.23	0	1
CORRUPTION	Tunisian Dinar	231	241.13	341.16	0	3500
RED SOILS	Percentage	231	0.46	0.33	0	1
INFLUENTIAL POSITION	Binary variable	231	0.636	0.48	0	1
WATER LOGGING	meter	231	4.547	1.9	0.4	8
DISTANCE	Kilometer	231	8.77	3.601	3	16
ALTERNATIVE SOURCE	Kilometer	231	2.1125	1.1035	0.3	5
IRRIGATION NETWORK	Year	231	17.034	4.0345	15	25
DISTANCE TO LARGE CITY	Kilometer	231	6.0216	5.1266	0	16
REVENUE SHOCK	Percentage	231	0.232	0.18	0	1
ADVERSE PRICING	Percentage	231	0.5	0.00345	0.492	0.5
CODE		231	111.4	64	1	223

Table 2: Determinants of WATER THEFT - Ordinary Least Squares

Independent variable	Eq. 2.1	Eq. 2.2	Eq. 2.3
Specification	OLS	OLS	Farmers with fixed effects
WATER PRICE	37.45 (0.912)***	-	-
ADVERSE PRICING	-	9.362 (0.978)***	-
DRIP	- 0.049 (0.027)*	- 0.049 (0.027)*	- 0.047 (0.0117)**
CORRUPTION	0.0001 (0.00003)***	0.0001 (0.00003)***	0.00032 (0.00008)**
PUNISHMENT RATE	0.0364 (0.0062)***	0.0364 (0.0062)***	0.0235 (0.0093)*
DISTANCE	0.026 (0.003)***	0.026 (0.003)***	- 0.0031 (0.0026)
ALTERNATIVE SOURCE	- 0.036 (0.011)**	- 0.036 (0.011)**	-
NETWORK IRRIGATION	0.007 (0.0014)***	0.007 (0.0014)***	0.0047 (0.0011)**
CONSTANT	- 4.67 (0.988)***	- 4.63 (0.980)***	0.176 (0.028)***
R^2	0.77	0.77	0:136[1]

Note: Robust standard errors (for the OLS specification) and standard errors (for the fixed effects specification) are in parentheses; *, **, and *** indicate that the estimated coefficients are significant at 10%, 5%, and 1% level.

1: R2 between is reported for the fixed effects specification.

Table 3: Determinants of WATER THEFT - Instrumental Variables

	Eq.3.1[a]	Eq.3.2[b]	Eq.3.3[c]	Eq.3.4[d]
Variable instrumented:	**CORRUPTION**	**DRIP**	**CORRUPTION+DRIP**	**as 4.3**
Independent variable:				
WATER PRICE	38.23 (8.23)***	37.766 (7.87)***	37.523 (8.21)***	40.895 (8.506)***
PUNISHMENT RATE	0.035 (0.0083)***	0.038 (0.00567)***	0.0386 (0.007)***	0.032 (0.0081)***
CORRUPTION	0.0001 (0.00005)*	0.000109 (0.00003)***	0.00011 (0.00004)***	0.000049 (0.00005)
DISTANCE	0.026 (0.003)***	0.024 (0.00345)***	0.0239 (0.00347)***	0.0244 (0.00365)***
DRIP	- 0.0503 (0.03)*	- 0.134 (0.077)*	- 0.136 (0.0712)*	- 0.147 (0.0706)**
ALTERNATIVE SOURCE	- 0.0375 (0.01143)***	- 0.0307 (0.012)**	- 0.0303 (0.0123)**	- 0.035 (0.0132)***
IRRIGATION NETWORK	0.007 (0.0014)***	0.00646 (0.0016)***	0.00642 (0.0016)***	0.0068 (0.00166)***
CONSTANT	- 4.76 (1.02)***	- 4.65 (0.973)***	- 4.626543 (1.0005)***	- 5.016 (1.04)***
Hansen J-stat (% sig)	1.48 (0.687)	equation exactly identified	1.54 (0.67)	1.82 (0.61)
Durbin-Wu-Hausman test(%sig)	0.162 (0.687)	1.57 (0.21)	3.317 (0.19)	0.61 (0.069)

Note: Robust standard errors are in parentheses; *, **, and *** indicate that the estimated coefficients are significant at 10%, 5%, and 1% level.

a: The excluded instruments are education, age, alternative revenue, influential family.

b: The excluded instrument is red soils.

c: The excluded instruments are as in 4.1 plus red soils.

d: The excluded instruments are as in 4.3 minus education plus distance to large city

Table 4: Determinants of DRIP

Independent variable	Eq. 4.1	Eq. 4.2	Eq. 4.3e	Eq. 4.4f
Specification	OLS	OLS	2SLS (WATER THEFT)	2SLS (+DIVERSIFICATION)
WATER THEFT	-	- 0.368 (0.107)***	- 0.587 (0.12)***	- 0.56 (0.148)***
WATER PRICE	3.75 (12)	19.43 (0.59)*	28.77 (0.75)**	27.8 (14)**
PUNISHMENT RATE	0.015 (0.009)*	0.027 (0.01)***	0.035 (0.01)***	0.031 (0.012)**
DISTANCE	- 0.018 (0.003)***	- 0.0067 (0.005)	-	-
RED SOILS	0.126 (0.048)***	0.115 (0.045)**	0.109 (0.045)**	0.127 (0.053)**
AGE	- 0.0024 (0.001)**	- 0.002 (0.0001)**	- 0.002 (0.001)**	- 0.0016 (0.0011)
DIVERSIFICATION	0.0595 (0.0156)***	0.059 (0.016)**	0.059 (0.016)***	0.101 (0.0559)*
REVENUE SHOCK	- 0.12 (0.067)*	- 0.08 (0.068)	- 0.056 (0.08)	-
WATER LOGGGING	0.036 (0.008)***	0.037 (0.008)***	0.037 (0.008)***	0.031 (0.011)***
CONSTANT	- 0.05 (0.5)	- 2.017 (0.444)	- 3.19 (0.717)*	- 3.2 (1.66)*
R^2	0.56	0.58	0.57	0.55
Hansen J-stat (% sig)	-	-	equation exactly identified	equation exactly identified
Durbin-Wu-Hausman test (% sig)	-	-	2.35 (0.125)	4.4 (0.11)

Note: Robust standard errors are in parentheses; *, **, and *** indicate that the estimated coefficients are significant at 10%, 5%, and 1% level.

e: The excluded instrument is distance

f: The excluded instruments are as in 5.2 plus revenue shock

Table 5: Determinants of CORRUPTION

Independent variable	Eq. 5.1	Eq. 5.2[g]	Eq. 5.3[h]	Eq. 5.4[i]
Specification	OLS	2SLS (WTH)	2SLS (WTH+EDU)	2SLS (DRIP+EDU)
WATER THEFT (WTH)	1164.62 (346.94)***	301.4 (141.81)**	281.06 (135.3)**	851.8 (278.9)***
DRIP	- 104.46 (75.7)	- 210.16 (115.53)*	- 214.23 (116.32)*	- 776.06 (333.1)*
PUNISHMENT RATE	- 89.6 (32.44)*	- 54.42 (20.97)***	- 52.12 (20.55)**	- 58.7 (27.76)**
DISTANCE	- 24.7099 (10.5614)**	-	-	- 37.3 (13.926)***
INFLUENTIAL POSITION	114.02 (42.76)***	89.58 (35.97)**	91.88 (37.35)**	135.2 (50.08)***
AGE	- 4.487 (1.485)***	- 4.556 (1.53)***	- 4.73 (1.64)***	- 7.88 (2.62)***
EDUCATION (EDU)	- 19:105 (3.372)***	- 22:71 (3.72)***	- 24:86 (5.77)***	- 27.58 (6.81)***
ALTERNATIVE REVENUE	61.48 (25.16)**	73.8 (23.37)***	74.8 (23.7)***	72.66 (23.97)***
CONSTANT	527.1 (112.15)***	621.19 (143.22)***	655.15 (158.25)***	1256.23 (401.84)***
R^2	0.56	0.58	0.57	0.55
Hansen J-stat (% sig)	-	-	-	-
Durbin-Wu-Hausman test (% sig)	-	10.5 (0.00119)	13.24 (0.00133)	7.545 (0.0229)

Note: Robust standard errors are in parentheses; *, **, and *** indicate that the estimated coefficients are significant at 10%, 5%, and 1% level.

g: The excluded instrument is distance

h: The excluded instruments are as in 5.2 plus distance to large city

i: The excluded instruments are red soils and distance to large city

Table 6: Determinants of WATER THEFT, DRIP and CORRUPTION

	WATER THEFT	DRIP	CORRUPTION
WATER THEFT	-	- 1.122 (0.204)***	2068.5 (289.9)***
WATER PRICE	30.55 (0.002)***	49.212 (0.626)***	-
PUNISHMENT RATE	0.041 (0.006)***	0.0537 (0.0122)***	- 132.4 (19.61)***
DRIP	- 0.1108 (0.045)**	-	122.3 (154.67)
CORRUPTION	0.00014 (0.00003)***	-	-
DISTANCE	0.0245 (0.0023)***	0.0174 (0.0072)**	- 49.3 (10.44)***
ALTERNATIVE SOURCE	- 0.028 (0.0067)***	-	-
ALTERNATIVE REVENUE	-	-	45.35 (15.6)***
REVENUE SHOCK	-	- 0.171 (0.062)***	-
DISTANCE TO LARGE CITY	-	-	13.122 (3.446)***
AGE	-	- 0.0035 (0.0009)***	-
WATER LOGGGING	-	0.0358 (0.0066)***	-
IRRIGATION NETWORK	0.00625 (0.00127)***	-	-
INFLUENTIAL POSITION	-	-	118.07 (35.367)***
RED SOILS	-	0.1168 (0.038)***	-
CONSTANT	- 3.79 (0.747)***	- 5.505 (1.95)***	79.156 (156.337)

Appendix

The details of mathematical demonstrations are available from the author upon request.