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Self-selecting agri-environmental policies with an application to the Don watershed

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Abstract

We consider a model of regulation for nonpoint source water pollution through non linear taxation/subsidization of agricultural production. Farmers are heterogenous along two dimensions, their ability to transform inputs into final production and the available area they possess. Asymmetric information and participation of farmers to the regulation scheme put constraints on the optimal policy that we characterize. We show that a positive relationship between size of land and ability may exacerbate adverse selection effects. We calibrate the model using data on a French watershed and we simulate the optimal second-best policy and characterize the allocation of the abatement effort among the producers.

Keywords: Non Linear Taxation - Asymmetric Information - Non Point Source Pollution - Water Pollution.

JEL classification: D82, Q19.

Résumé

Nous présentons un modèle de régulation de la pollution diffuse des eaux par un mécanisme de taxation/subvention de la production agricole. Les agriculteurs sont hétérogènes selon deux dimensions, leur habileté à transformer les inputs en production finale, et la surface disponible qu'ils possèdent. L'asymétrie d'information et la participation des agriculteurs au mécanisme de régulation ajoutent des contraintes à la politique optimale, que nous caractérisons. Nous montrons qu'une relation positive entre la taille de l'exploitation et l'habileté peut intensifier les effets de la sélection adverse. Le modèle est calibré avec des données provenant d'un bassin versant français, ce qui nous permet de simuler la politique de second rang et de caractériser la répartition de l'effort de dépollution entre les producteurs.

Mots clefs : Taxation non-linéaire - Asymétrie d'information - Pollution diffuse - Pollution des eaux

Classification JEL : D82, Q19.

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1 Introduction

While the developments of the Agency theory to the regulation of nonpoint source (NPS) pollution are numerous, empirical applications remain rare (Shortle and Horan, 2001). The aim of this paper is to provide such an application, through the characterization of an optimally differentiated regulation for NPS water pollution from a population of heterogeneous farmers on a French watershed. This paper deals with two mains issues, first the design of efficient policies when the regulator has to allocate the pollution control effort among heterogeneous polluters, and second the choice of feasible actions when the special features of NPS pollution make difficult the policy design (Shortle *et al.*, 1998).

Asymmetric information problems occur when the regulator looks for providing measures to control pollution, but has little information on the cost savings to the firms from emitting pollutants. Using a single instrument to mitigate the pollution inevitably induces some firms to pollute too much, and others to pollute too little; more importantly no single (uniform) instrument can eliminate these distortions. Moreover, the special features of NPS pollution can explain why, among all polluting sources, little has been undertaken by environmental agencies to provide adequate measures to control them. This is especially true for agricultural pollution from fertilizers or pesticides in developed countries, when environmental agencies generally face multiple and heterogenous possible polluters, whose individual emissions cannot be currently measured with good accuracy at reasonable cost. This pollution problem is also made more complex because of the presence of uncertainty on both production and pollutant emissions, related with weather conditions and run-off events.

Literature merely compared different policies to mitigate NPS pollution. Lots of studies conclude that the choice of instrument base can significantly influence the cost-effectiveness of agri-environmental policy (Larson *et al.,* 1996, Weinberg and Kling, 1996). The NPS literature focuses on two basic options that we will briefly review in turn.

The first one is to base the regulation on a collective performance variable, namely the ambient concentration of pollutants in environmental media. Following the pioneering work of Segerson (1988), the set of polluters can be considered like a team whose joint product is the level of pollution observed in the environmental media. The regulatory agency only monitors ambient pollution concentrations and firms' tax payments. Taxes (subsidies) are charged (paid) to the firms when the ambient pollution concentration rises above (falls below) an exogenously determined target. This is a classic problem in the literature on moral hazard in teams (Holmström, 1982). The implementation of the tax yields the first-best outcome as a Nash equilibrium given that the profit, nonpoint emissions and fate and transport functions (and other essential informations) are common knowledge. The seminal model has been widely refined (Cabe and Herriges, 1992, Horan *et al.*, 1998, Horan *et al.*, 2002). Weersink *et al.* (1998) suggest that ambient taxes may be best suited to managing environmental problems in small watersheds, in which agriculture is the only source, farms are relatively homogeneous, water quality is readily monitored and there are short time lags between polluting activities and their water quality impact.

The second option bases the regulation on individual variables related with pollution flows, that are more or less easy to monitor such as inputs, productions or agricultural practices. This point received much attention from a long time (Holterman, 1976). The challenge is to design input-based incentives that achieve environmental goals at reasonable cost (Shortle and Horan, 2001). Griffin and Bromley (1982) demonstrate that taxing inputs that increase a nonpoint externality and subsidizing inputs that reduce it, could replicate the outcome reached with a tax on the externality. Shortle and Dunn (1986) describe a nonlinear input tax/subsidy scheme that reaches the first-best solution under asymmetric information about profit types in the limiting case of a single nonpoint polluter and zero transaction costs. Smith and Tomasi (1995) demonstrate that only second-best solutions are obtainable with direct revelation mechanisms when there are transaction costs related to the collection of tax revenues. Wu and Babcock (1996) develop a mechanism design approach to induce land-based nonpoint polluters to choose second-best input vectors depending on their land type. Wu and Babcock consider farmers who are heterogeneous along one dimensional index of soil quality. These farmers exploit the same surface. The regulator has information on the distribution of the soil quality index ; he proposes to the farmer a contract menu on this input and an associated transfer. Last, Shortle *et al.* (1998) extend Griffin and Bromley's work to the design of input tax/subsidy schemes with stochastic and imperfectly estimated emissions.

The model developed in this paper is related to this second set of the literature. We focus on the management of NPS pollution problems in large watersheds, where the farms are heterogenous with regards to the available area for crops and when they have more information on their skills and farming techniques than the regulator. In this case, ambient instruments are not appropriate and the design of output or input-based incentives that achieve environmental goals at a reasonable cost has not been analyzed in the literature when the regulated farmers may exploit different areas.

More precisely, we consider the regulation of NPS water pollution through non linear taxation/subsidization of agricultural production for a population of farmers. Farmers are heterogenous along two dimensions, their ability to transform inputs into final production and the available area they possess. Productive ability is private information to the farmers while available area and final production are observable characteristics which may be part of the regulatory scheme. Asymmetric information put constraints on the optimal policy that must induce self-selection. We first show that when farmers cannot escape the regulation, which however does not allow the agency to impose net losses on farmers, then the range of less efficient farmers that are induced to quit the sector is larger than under complete information. Also, due to incentives costs, the level of production induced is lower whatever the type of farmers, compared to the complete information situation. Moreover, the total level of pollution is reduced first because the less efficient and most polluting farms are shut down and second because the remaining active farms are required to produce less intensively and therefore pollute less. It is worth noting that the optimal policy toward any farm not only depends on its ability to produce but also on its land capacity. In particular, two farms with the same ability parameter but with different land capacity may not be induced to produce at the same level per acre. Indeed, the downward distortion due to adverse selection may be or not exacerbated when surface increases. In particular, if there is a positive relationship between size of land and ability, then adverse selection effects are exacerbated.

We calibrate the model using data on a French watershed (the Don watershed) and we simulate the optimal policy. With our data, the loss of welfare related to private information is lower than the cost of information required to implement the first best production levels. We finally characterize the allocation of the abatement effort among the farmers.

The paper is organized as follows. Section 2 is devoted to assumptions and notations and analysis of regulation under complete information. Regulation under asymmetric information is analyzed in section 3. The empirical application to the Don watershed is exposed in section 4 whereas section 5 concludes. Most proofs are relegated into appendixes.

2 The model

2.1 The farmer's behavior

Consider a farmer whose final product y (say milk) is produced from a quantity s of land devoted to feed crops and a polluting input such as fertilizers that costs $c(y,\theta)$ per unit of land. The parameter θ belongs to the set $\Theta = \left[\underline{\theta}, \bar{\theta}\right]$ and represents the farmer's ability to transform feed crops into the production of milk. Parameter θ can be understood as a function of several on-farm characteristics (management skills, soil quality, genetic value of the herd...).[1]

We make the following assumptions: $c_y > 0$, $c_{yy} \geq 0$, $c_\theta < 0$ and $c_{y\theta} < 0$. The two latter assumptions mean that we normalize the set of types by assuming that the variable cost is decreasing in the ability parameter and that the marginal cost of producing milk is also decreasing with the ability (the so-called single-crossing conditions). In other words, a more efficient farmer is also associated with lower optimal rates of input use.[2]

Total land available for the production we consider is denoted by S that belongs to the set $\mathcal{S} = \left[\underline{S}, \bar{S}\right]$. For each land capacity S, there is a continuum of farmers characterized by their ability, with mass unity. Farmers are distributed along this line segment according to ability density function $f(\theta; S)$ with cumulative function $F(\theta; S)$. We assume that $f(\theta; S) > 0$ for every θ and S. Note that we also assume that the set Θ does not depend on S.[3] This assumption does not presume that θ and S are independent. Moreover, the risk ratio $\frac{1-F(\theta;S)}{f(\theta;S)}$ is assumed to be strictly increasing in θ.[4] Finally, land capacity S is distributed according to land density function $h(S)$ with cumulative $H(S)$. We also normalize the total land devoted to agriculture to unity.

Agricultural land also differs in environmental consequences of production. We assume that pollution is represented by a pollution production function per hectare, denoted $g(y,\theta)$, that estimates well emissions using simulation models, where $g(.,.)$ is increasing with y and depends on θ. We do not impose assumptions on the sign of g_θ that may vary: this is indeed the case on our empirical application. As a consequence, a more efficient farmer may or may not pollutes less at the margin *ceteris paribus*.

Let us describe the private optimum of the profit-maximising farmer with ability θ and available land S, assuming there is no intervention by the environmental agency. It is given by solving the

[1] See section 4 for a method of constructing such an ability index in our empirical application.

[2] In addition, we make the following technical assumptions: $c_{\theta yy} < 0$, $c_{\theta\theta y} > 0$. These assumptions will help us in obtaining optimal policies that effectively separate the different farmers.

[3] This assumption can be relaxed but at a much higher cost of complexity for the analysis. In that case, it is possible to diminish incentives costs because private information is partially verifiable by the regulator (see Green and Laffont, 1986).

[4] This regularity condition is made in order to prevent the incidence of "pooling" in the optimal policy resulting from the probability function, that is policy in which the same allocation is selected for different values of θ.

following program :

$$\max_{s,y} \; \pi(s,y,\theta) \equiv (py - c(y,\theta))s$$
$$\text{s.t. } s \leq S$$

where p is the (exogenous) product price.

We assume that in the status quo situation, all the farms are active. Then, obviously, the constraint $s \leq S$ is binding[5]. At the optimum, the farmer chooses to produce $y^\circ(\theta)$ defined by the equality between the price and the marginal cost ($p = c_y$). Given our assumptions on $c(.,.)$, the optimal production level $y^\circ(\theta)$ is increasing with the farmer's ability θ. The farmer's profit absent any regulation is then $\pi(\theta) = (py(\theta) - c(y(\theta),\theta))S$, which increases in θ. Obviously, at the optimum, $\pi^\circ(\theta)$ is greater than income obtained from available outside opportunities (we normalize to zero the profit gained outside of the agricultural sector without loss of generality).

2.2 The Environmental Agency objective

Consider now the problem of the regulatory (utilitarian) agency. She seeks to maximize a social welfare function, written as the sum of taxpayers surplus weighted by the social cost of public funds $(1+\lambda)$, the farmers total surplus and the environmental damage D. We assume that the social cost of pollution D depends on total pollution emitted E :

$$D(E) \equiv D\left(\int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} sg(y,\theta)f(\theta;S)d\theta h(S)dS\right)$$

where $D(.)$ is increasing, convex in total pollution.

Note that we do not include any consideration to the consumer surplus in the welfare function. As the regulation is implemented on a small watershed, we expect that any variation in the agricultural production following the regulation will have negligible impacts on total production sold on the market. The parameter $\lambda > 0$ represents the marginal cost of public funds which is assumed to be positive.

As emphasized in the introduction, both the land effectively used and the level of production are observable and verifiable by anybody. However, information asymmetry arises from the impossibility for the regulator to identify each farmer's ability. Alternatively, one may assume that ability

[5] Alternatively, we could have considered that the optimal cropped area s is interior, simply by adding a fixed cost $k(s)$ for land in the profit function: $\pi(s,y,\theta) \equiv (py - c(y,\theta))s - k(s)$. This extension is straightforward but does not modify drastically the features of the optimal policy derived in the paper.

is observable but that institutional or political constraints prevent the regulator from perfectly discriminating farmers on that basis. Thus, a self-selecting policy remains the only option available to the regulatory agency.

Applying the Revelation Principle, we can restrict our attention to the set of direct revelation mechanisms. The regulator seeks to determine the optimal second-best allocation $s(\theta), y(\theta)$ and a transfer $t(\theta)$ offered to any θ-type farmer with a given land capacity S.[6]

The regulator's objective is written as follows:

$$\begin{aligned}\mathcal{W} \quad \equiv \quad & \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} [\pi(\theta) - (1+\lambda)t(\theta)] f(\theta; S) d\theta h(S) dS \\ & - D\left(\int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s(\theta) g(y(\theta), \theta) f(\theta; S) d\theta h(S) dS \right)\end{aligned}$$

where $\pi(\theta) = (py(\theta) - c(y(\theta), \theta))s(\theta) + t(\theta)$. Finding the optimal policy amounts to find the land $s(.)$, the production level $y(.)$ and the net gain $\pi(.)$ (or equivalently the transfer $t(.)$) that are feasible in a sense to be precised below and that maximize the welfare function. Eliminating the transfer $t(.)$ we obtain:

$$\begin{aligned}\mathcal{W} = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} [(1+\lambda)(py(\theta) - c(y(\theta), \theta))s(\theta) - \lambda\pi(\theta)] f(\theta; S) d\theta h(S) dS \\ - D\left(\int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s(\theta) g(y(\theta), \theta) f(\theta; S) d\theta h(S) dS \right)\end{aligned}$$

Note that if at the optimum $s(\theta) < S$ then set-aside is part of the contract for a θ-type farmer with land capacity S. In particular, the regulator may find optimal to shut down some farmers by assigning them $s(\theta) = 0$.

Feasible allocations are constrained first by the information set of the regulator, assuming that true ability θ is not observable. The farmer sends a message $\hat{\theta}$ to the regulator about his private information parameter or equivalently chooses a contract among all offered contracts (by choosing a production level $y(\hat{\theta})$, a forage area $s(\hat{\theta})$ in exchange of a tax/subsidy $t(\hat{\theta})$, the farmer implicitly reveals his type).

The contract scheme has to satisfy incentive compatibility constraints described by:

$$\pi(\theta) \geq \pi(\theta, \hat{\theta}), \quad \forall \theta, \forall \hat{\theta} \tag{IC}$$

where $\pi(\theta, \hat{\theta}) = ps(\hat{\theta})y(\hat{\theta}) - s(\hat{\theta})c(y(\hat{\theta}), \theta) + t(\hat{\theta})$ and $\pi(\theta) \equiv \pi(\theta, \theta)$. This ensures that any farmer correctly reveals his true type.

[6] For the purpose of clarity, we omit to condition the allocation $\{s(\theta), y(\theta), t(\theta)\}$ on the land capacity S.

Moreover, the participation of any θ-type farmer is effective if and only if it is individually rational. Assuming that the best outside option for any type of farmer yields a constant (not type dependant) profit, we normalize this reservation profit to 0 and we obtain the following individual rationality constraints:

$$\pi(\theta) \geq 0, \quad \forall\theta \tag{IR}$$

In this setting, the regulator is thus able to enforce its policy as long as it does not entail any net loss for farmers. Hence, the regulator's commitment and enforcement power is relatively strong because the policy enforced does not take into account the profits that farmers may have before its implementation. We will discuss the issue of the regulator's enforcement power in the conclusion.

2.3 Regulation under complete information

Before analyzing the optimal self-selecting policy, we characterize here the optimal policy under complete information, ignoring incentive compatibility constraints (IC). The program to be solved is:

$$\max_{s(.),y(.),\pi(.)} \mathcal{W} \quad \text{s.t. (IR)}, \ s(\theta) \leq S \quad \forall\theta, \forall S.$$

The following proposition states the main features of the optimal policy under complete information that we denote $(y^{PI}(\theta), s^{PI}(\theta), \pi^{PI}(\theta))$, resulting in the emission level E^{PI} given by

$$E^{PI} = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s^{PI}(\theta) g(y^{PI}(\theta), \theta) f(\theta; S) d\theta h(S) dS.$$

For that purpose, it is useful to define the social net marginal surplus of land as:

$$\Omega(\theta, y, E) = (1+\lambda)(py - c(y,\theta)) - D'(E)\, g(y,\theta), \tag{1}$$

which we assume to be increasing in θ.[7]

Proposition 1 *Assume that* $\Omega(\overline{\theta}, y^{PI}(\overline{\theta}), E^{PI}) > 0$*. The optimal policy* $(y^{PI}(\theta), s^{PI}(\theta), \pi^{PI}(\theta))$ *is such that, for any* S*,*

(i) *any active* θ*-type farmer produces* $y^{PI}(\theta)$ *using their land capacity* S *such that*

$$(1+\lambda)(p - c_y(y^{PI}(\theta), \theta)) = D'\left(E^{PI}\right) g_y((y^{PI}(\theta), \theta)), \tag{2}$$

[7] Given that $c_\theta < 0$, a sufficient condition is that $g_\theta < 0$ or non too positive. This assumption is actually valid on our empirical application.

(ii) *if* $\Omega(\underline{\theta}, y^{PI}(\underline{\theta}), E^{PI}) < 0$*, for any* θ *such that* $\underline{\theta} \leq \theta < \theta^{PI}(S)$*, production is not allowed and the threshold type* $\theta^{PI}(S)$ *is given by*

$$\Omega(\theta^{PI}(S), y^{PI}(\theta^{PI}(S)), E^{PI}) = 0.$$

(iii) *Finally, for any* $\theta \in \Theta$*, we have* $\pi^{PI}(\theta) = 0$*.*

Proof. see Appendix A. ■

The optimal production level $y^{PI}(\theta)$ is determined by the standard rule consisting in equalizing social marginal benefit and social marginal damage. Moreover, the optimal regulation entails a decrease in production per hectare compared to the private optimum ($y^{PI}(\theta) < y^{\circ}(\theta)$), in particular drastically for the set of excluded farmers if any. Those low θ-type farmers are excluded as their social marginal surplus of land net of pollution damage is non positive. This in turn implies that total pollution is also reduced compared to the *laissez-faire* level. Finally, because leaving rents to the farmer is socially costly, the regulator extracts all the farmers' rents without any cost.

3 Optimal policy under incomplete information

Back to the incomplete information setting, standard arguments (see Guesnerie and Laffont, 1984) indicate that incentive constraints can be replaced by the following set of constraints:

$$\pi'(\theta) = -c_\theta(y(\theta), \theta)s(\theta)$$

$$-s'(\theta)c_\theta(y(\theta), \theta) - s(\theta)c_{\theta y}(y(\theta), \theta)y'(\theta) \geq 0$$

Because the rate of growth of rents is positive ($\pi'(\theta) > 0$), then participation constraints reduce to $\pi(\underline{\theta}) \geq 0$.

The regulator has hence to solve the following program:

$$\max_{s(.), y(.), \pi(.)} \mathcal{W}$$

$$\begin{aligned} \text{s.t.} \quad & \pi'(\theta) = -c_\theta(y(\theta), \theta)s(\theta) && \text{(IC1)} \\ & 0 \geq s'(\theta)c_\theta(y(\theta), \theta) + s(\theta)c_{\theta y}(y(\theta), \theta)y'(\theta) && \text{(IC2)} \\ & \pi(\underline{\theta}) \geq 0 && \text{(IR)} \\ & s(\theta) \leq S \quad \forall\theta, \forall S && (3) \end{aligned}$$

We first neglect the second order conditions (IC2) and we will check later that the optimal solution meets them. Then integrating (IC1), we get : $\pi(\theta) = \pi(\underline{\theta}) - \int_{\underline{\theta}}^{\theta} c_\theta(y(u), u)s(u)du$. Replacing in the objective $\mathcal{W}$, we obtain :

$$\mathcal{W} = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} [(1+\lambda)s(\theta)(py(\theta) - c(y(\theta), \theta)) - \lambda\pi(\underline{\theta})] f(\theta; S)d\theta h(S)dS$$
$$+ \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} \lambda \int_{\underline{\theta}}^{\theta} [c_\theta(y(u), u)s(u)du] f(\theta; S)d\theta h(S)dS$$
$$- D\left(\int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s(\theta)g(y(\theta), \theta)f(\theta; S)d\theta h(S)dS\right)$$

and, integrating by parts, we finally get :

$$\mathcal{W} = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} [(1+\lambda)s(\theta)(py(\theta) - c(y(\theta), \theta))$$
$$+ \lambda s(\theta)c_\theta(y(\theta), \theta)\frac{1 - F(\theta; S)}{f(\theta; S)}] f(\theta; S)d\theta h(S)dS$$
$$- \lambda\pi(\underline{\theta}) - D\left(\int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s(\theta)g(y(\theta), \theta)f(\theta; S)d\theta h(S)dS\right)$$

Note that at the optimum, (IR) is necessarily binding so that $\pi(\underline{\theta}) = 0$. We will first derive the optimal production level denoted $y^*(\theta)$ and secondly the optimal forage area level denoted $s^*(\theta)$ together with the subset of active farmers. We also denote E^* as the corresponding total emissions level

$$E^* = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s^*(\theta)g(y^*(\theta), \theta)f(\theta; S)d\theta h(S)dS.$$

Derivating with respect to $y(\theta)$ and rearranging, we get for all active producers (with $s^*(\theta) > 0$) the following necessary condition:

$$(1+\lambda)(p - c_y(y^*(\theta), \theta)) = D'\left(E^*\right) g_y(y^*(\theta), \theta) - \lambda c_{\theta y}(y^*(\theta), \theta)\frac{1 - F(\theta; S)}{f(\theta; S)} \qquad (4)$$

This equation has a straightforward interpretation: compared to its complete information counterpart (see equation (2)) a positive distortion is added to the marginal damage (the term $D'g_y$) when equalizing with the marginal social surplus of production (which is equal to $(1+\lambda)(p - c_y)$). This distortion is due to incentive compatibility and it amounts to reduce the production level for a given land use compared to the situation of complete information.[8]

[8] Note that if we had assumed that $c_{\theta y} > 0$ (i.e. marginal productivity of input is decreasing with ability) then we would have increased production (for a given land use) in order to diminish the informational rent. However, this would not mean that pollution increases because in the meantime total land use would still decrease.

Derivating $\mathcal{W}$ with respect to $s(.)$, we obtain the following expression for the social marginal surplus of land:

$$\frac{\partial \mathcal{W}}{\partial s(\theta)} = (1+\lambda)(py^*(\theta) - c(y^*(\theta),\theta))f(\theta;S) + \lambda c_\theta(y^*(\theta),\theta)(1-F(\theta;S)) - D'(E^*)\,g(y^*(\theta),\theta)f(\theta;S)$$

Comparing this expression with its counterpart under complete information (see (1)), we find that the marginal social net surplus of land now includes a negative distortion $\lambda c_\theta(y^*(\theta),\theta)(1-F(\theta;S))$ due to incentive compatibility constraints. Indeed, for every S, a decrease in the land assigned to a θ-type farmer yields to reduce the incentives of all higher types (with a weight $1-F(\theta;S)$) to mimic him.

The following proposition states that the optimal solution for $s(\theta)$ is bang-bang under additional technical assumptions. It also indicates the other properties of the optimal policy.

Proposition 2 *Assuming an optimal separating policy for any S,*[9]

(i) *the set of active farmers that are allowed to produce using their land capacity S is an interval $\left[\theta^*(S),\bar{\theta}\right] \subset \Theta$ where $\theta^*(S)$ is a threshold type defined by*

$$\Omega(\theta^*(S), y^*(\theta^*(S)), E^*) = -\lambda c_\theta(y^*(\theta^*(S)),\theta^*(S))\frac{1-F(\theta^*(S);S)}{f(\theta^*(S);S)}.$$

Moreover, the threshold type $\theta^*(S)$ increases in S if and only if the hazard rate $\frac{1-F(\theta^*(S);S)}{f(\theta^*(S);S)}$ increases in S,

(ii) *the optimal level of production for any active farmer is given by:*

$$p - c_y(y^*(\theta),\theta) = \frac{1}{1+\lambda}D'(E^*)\,g_y(y^*(\theta),\theta) - \frac{\lambda}{1+\lambda}c_{y\theta}(y^*(\theta),\theta)\frac{1-F(\theta;S)}{f(\theta;S)} \qquad (5)$$

(iii) *for any θ such that $\underline{\theta} \leq \theta < \theta^*(S)$, production is not allowed and $\pi(\theta) = 0$.*

Proof. see Appendix B. ■

As indicated by Proposition (2), the threshold type is determined by equating the marginal surplus net of damage $(\Omega(\theta^*(S), y^*(\theta^*(S)), E^*)f(\theta^*(S);S))$ of keeping active the θ-type$^*(S)$ farmer with the corresponding incentive cost $(-\lambda c_\theta(y^*(\theta^*(S)),\theta^*(S)))$ for all higher type farmers (in proportion $1-F(\theta^*(S);S)$). Indeed, if the $\theta^*(S)$-type farmer is allowed to produce, then the regulator has to increase the informational rents left to more efficient farmers in order to deter them from mimicking less efficient types. Finally, note that θ^* depends on S if and only if $f(\theta;S)$ depends on S.[10]

[9] In appendix C, we indicate sufficient assumptions for the second order conditions (IC2) to be satisfied.

[10] Otherwise, when θ and S are independently distributed, the threshold type is constant whatever the land capacity S.

If it is the case that the hazard rate increases in S then the threshold type increases when land capacity S grows and so the range of excluded farmers at the optimum, and conversely. To illustrate, let us consider a special case of Beta density functions, that is a linear density $f(\theta; S) = v(S) + w(S)\theta$ with $\theta \in [0, 1]$ for simplicity. Using $F(\overline{\theta}; S) = 1$, we get $f(\theta; S) = 1 + w(S)(\theta - \frac{1}{2})$. It is then easy to check that the hazard rate $\frac{1-F(\theta;S)}{f(\theta;S)}$ is strictly decreasing in θ and non decreasing in S if and only if $w(S)$ is non decreasing. This means that when S increases, the slope of the density function increases and there are more and more farmers with ability higher than 1/2. Such an assumption could reflect the fact that there is a positive relationship between the size of land and the ability of farmer and consequently the greater S is the larger the range of excluded farmers is.

As indicated by point (ii), at the optimum, we obtain the equalization of the output price with the *adjusted* marginal cost, which is composed of the private marginal cost of production, the positive marginal damage weighted by the social cost of publics funds and the positive marginal cost of incentives, as indicated by (5). As a consequence, the optimal level of production assigned to any type (θ, S) farmer is reduced compared to the laissez-faire situation $(y^*(\theta) < y^\circ(\theta))$. Moreover, the total level of pollution E^* is reduced because first the less efficient and most polluting farms are shut down and second because the remaining active farms are required to produce less intensively and therefore pollute less. Furthermore, the introduction of this environmental regulation entails a profit loss for any farmer ($\forall\theta$, $\pi^*(\theta) \leq \pi^\circ(\theta)$, as indicated in appendix D).

Note that the optimal policy towards any farm not only depends on its ability to produce but also on its land capacity. Indeed, from (5), it is clear that the downward distortion due to adverse selection is exacerbated when the hazard rate increases in S, and conversely. In particular, two farms with the same ability parameter but with different land capacity may not be induced to produce at the same level per acre. Let us consider two farmers with the same θ parameter and cropping different forage areas, S_1 and S_2, $S_1 > S_2$. Suppose that the hazard rate $\frac{1-F(\theta;S)}{f(\theta;S)}$ increases with S, then Proposition 2 indicates that the larger farm (with area S_1 here) will be induced to produce less per hectare than the smaller farm $(y_1 < y_2)$. This is because the marginal cost of incentives becomes larger when S increases and consequently the downward distortion on production level compared to the complete information outcome is greater.

4 Empirical application to the Don watershed

For this application, we used data collected on Don Watershed (Loire Atlantique, France) during winter 2000-2001. The whole population (820 farms) has been stratified with production system criteria, and a sample of 68 farms has been randomly drawn among these strata (with samples size proportional to each stratum size). Data collected for this survey dealt with productions, breeding management and current fertilizing practices and cropping and forage areas. We used the data collected for year 2000 only, in order to avoid distortions related with price change.

We restrict our analysis to dairy production, the main production on the watershed. Thus for the sampled farms, the area devoted to forage crops for milk herd was isolated. Note that if we restrict our analysis to dairy production, and to the forage area devoted to the milking herd, the dairy quotas which actually apply to the farms have only consequences on the choice of the initial area devoted to milk, and not on the initial milk production per hectare: the farmers choose to produce y° defined by $p = c_y$ and bind their constraint $a \leq S$, with S being the area devoted to milk production under quotas' policy application (and not the whole farm area).

4.1 Modelling

4.1.1 Definition and estimation of ability

In the relationship between production and pollution, there are many parameters that can be costly to observe or even unobservable to the regulator. The critical point in the application is to define a unidimensional measure (θ) which allows to reduce the dimensionality of the set of acute parameters. This index is the basis of our policy design which aims at differentiating farmers. In practice, there are two ways to consider the implementation of the policy. First, the farmer may be asked to fill a form on a computer that will give him his index and immediately the contract terms he is offered (subsidy, production and forage area). Hence, he would be able to test the consequences of any set of characteristics he might declare. Alternatively, the farmer chooses his preferred contract among the menu of contracts offered by the regulator.

This parameter θ represents in our framework the ability for a given farmer to transform his forage area into dairy production. We proceed in two steps to determine θ and its empirical distribution on our dataset. Firstly, some experts in local extension services build a relative (one-dimensional) classification of the surveyed farms. Secondly we combine the variables used to recover the classification proposed by the experts, and thus we determine a function linking these variables to the one-dimensional parameter θ.

In our approach, farmers' ability to transform forage crops into milk is estimated by combining the following technical variables that capture differences across farms (see appendix E):

- the amount of dry matter produced by grasslands : this variable is a clue for herbage availability and grazing management, which both affect nutrient supply in grazing cows (Kuusela and Khalili, 2002).

- the amount of milk produced per cow : high yielded dairy cows are more sensitive to feeding management than lowed yielded ones (Peyraud and Astigarraga, 1998).

- the balance in forage feed between proteins and energy : recent whole-animal models of N utilization in dairy cow show that the availability of energy is crucial to the efficiency of N utilization by the animals (Kebreab *et al.*, 2002).

- the amount of required concentrates, estimated as a difference of a theoretical food intake (calculated with high quality forages) and what is observed on each farm. Increased levels of concentrates supplementation is reported to have a substantial impact on the profitability and nutrient balance for grazing dairy farms (Soder and Rotz, 2001).

Soils have their importance in milk production, but authors do not agree on their exact influence, so we deliberately omitted them in the explicative variables[11]. A farmer who manages to obtain high grass yields, who breeds high productive cows, who gives them good quality forages and who needs low rates of concentrates to produce milk is considered to possess a good ability to transform his forage crops into milk, and thus his θ-parameter is high.

For our sample, the estimation of parameter θ suggests that high θ-type produces more milk with less inorganic N than low ones (see Figure 1). Note that because the more efficient farmers tend to produce with higher yields, there is no homothetic relationship between the θ-type parameter and either the production cost or the individual emissions. Moreover, on the Don watershed, the ratio profit/emissions is not monotonous in θ for the laissez-faire situation (see Figure 7).

4.1.2 Population description

We first estimate the distribution $h(S)$. It appears from the sample that this distribution is not symmetric. Consequently, a beta function has been preferred, and the parameters have been estimated using the Kolmogorov-Smirnov test (see Figure 2).

Second, we have to estimate a distribution function for θ. The distribution function $f(\theta; S)$ has been estimated on the whole population taking into account the information gathered on the sample[12], depending on the class of forage area (see Figure 3). A Kolmogorov-Smirnov test confirmed that the observed densities $f(\theta; S)$ are not the same for the different surface classes that we built. The parameters for these densities are described in appendix F.

[11] In fact, soil effects are already included in the parameters entering in the definition of our θ-type: fertile and easy-to-manage soils allow high yields for grasslands, provide high quality forages and thus allow high production cows and low levels of concentrates.

[12] We use two datasets : for the whole population, only the production system is described, while for the sample we collected very precise data on farming practices.

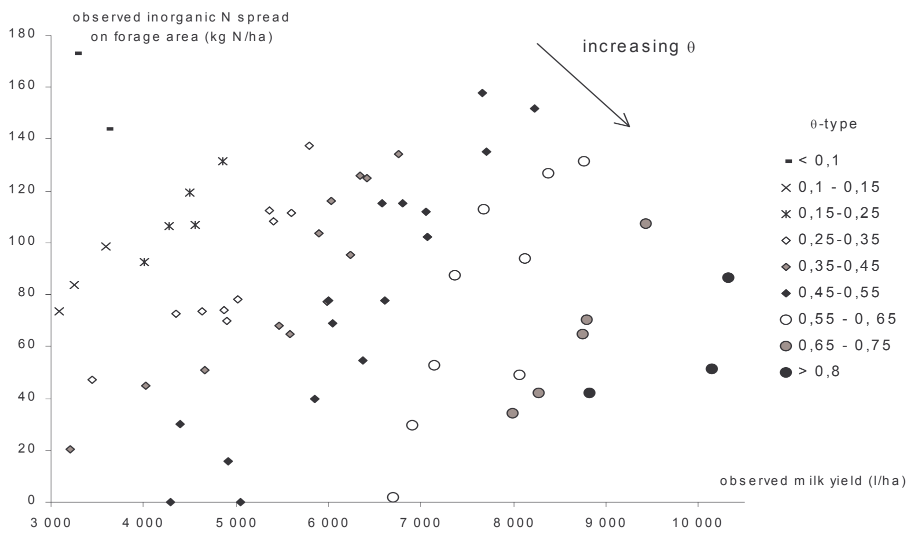

Figure 1: Observed milk yield and inorganic N spread on the forage area for the surveyed farms on the Don waterteshed.

Note that with our data, the hazard rate variations are not monotonous on S (see Figure 4). Thus, the downward distortion on the production level compared to the complete information outcome will be exacerbated for some range of forage areas S and more compensated for others.

4.1.3 Cost estimation

Following Yiridoe *et al.* (1997), the amount x of N fertilizer used is expressed as a quadratic function of production y :

$$x(y, \theta) = \alpha(\theta)y^2 + \beta(\theta)y + \delta(\theta)$$

The parameters of this function have been estimated from the data collected on the sample. Unfortunately, not all of these surveys include a complete description of costs associated with milk production. Thus we assume that production costs can be decomposed in two parts :

- costs associated with forage production, assumed to be proportional to the amount of fertilizers used,
- and other costs, more related with breeding operations.

Consequently the cost function is written as follows :

$$c(y, \theta) = w\vartheta(\theta)x(y, \theta) + \omega(\theta)y + \varrho$$

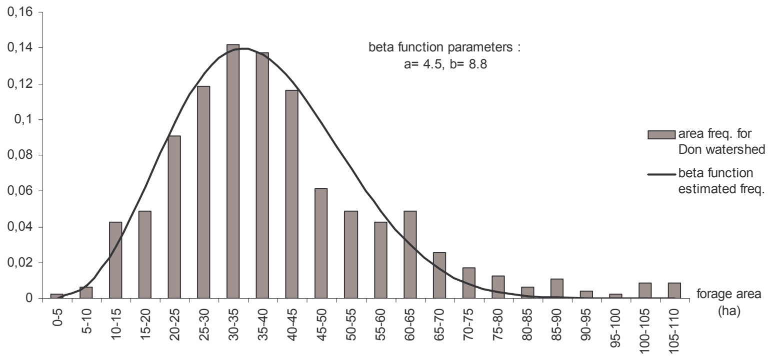

Figure 2: Observed and estimated forage area frequency on Don watershed.

where :

$c(y, \theta)$: milk production cost,

w: inorganic N price,

$\vartheta(\theta)$: proportionality factor of fertilizers in forage operation costs,

$x(y, \theta)$: amount of N fertilizer used,

$\omega(\theta)y + \varrho$: cost related to breeding operations.

Coefficient $\alpha(\theta)$ is estimated using the following functional form: $\alpha(\theta) = \alpha_1\theta^2 + \alpha_2\theta + \alpha_3$ and parameters α_1, α_2 and α_3 are estimated with a maximum likelihood method. A similar method is applied for $\beta(\theta)$ and $\delta(\theta)$ (see Table 1).

parameters for $\alpha(\theta)$		parameters for $\beta(\theta)$		parameters for $\delta(\theta)$	
α_1	$2.47\ 10^{-6}$ *	β_1	-0.00237 *	δ_1	215.0 *
α_2	$-9.12\ 10^{-6}$ *	β_2	0.00796 *	δ_2	293.8 *
α_3	$7.91\ 10^{-6}$ *	β_3	-0.0206 *	δ_3	121.1 *

* significant at 0.05 level.

Table 1: Estimated parameters for the cost function

The other parameters (ϑ, ω and ϱ) have been calibrated so that $p = c_y$ in the laissez-faire (i.e. observed) situation.

4.1.4 Emission parameters and damage estimations

Individual emissions have been estimated using a local hydrological model (Turpin *et al.*, 2001) from data collected on the surveyed farms and other data concerning soils, hydrology and local climate on

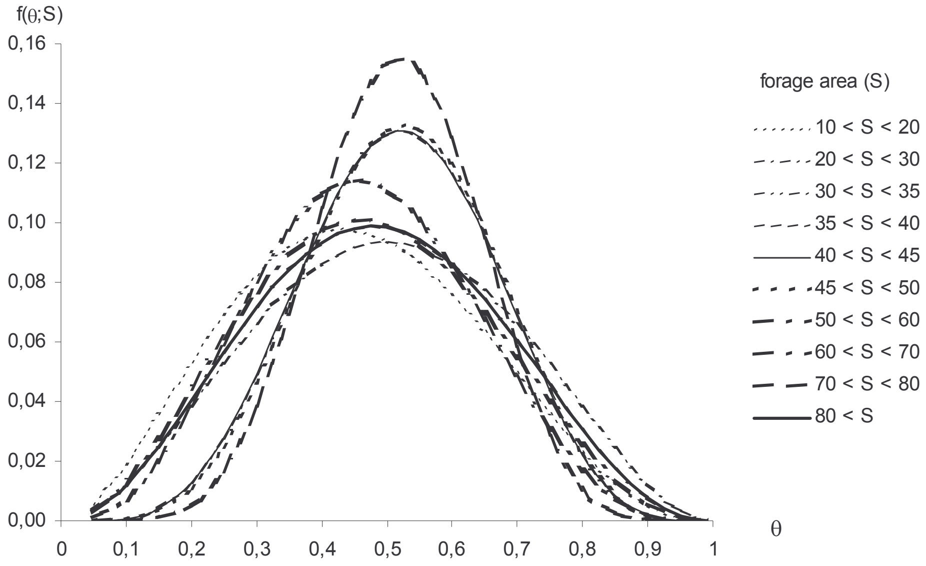

Figure 3: Estimated θ density depending on the forage area on the Don watershed.

the Don watershed. Type-dependent emissions have been determined from these estimations, using a quadratic function and a constrained maximum likelihood method (Gouriéroux and Montfort, 1995).

parameters for the estimation of the emission function : $g(y,\theta) = \left(\zeta_1\theta^2 + \zeta_2\theta + \zeta_3\right) y^2 + \left(\xi_1\theta^2 + \xi_2\theta + \xi_3\right) y + \left(\varkappa_1\theta^2 + \varkappa_2\theta + \varkappa_3\right)$					
parameters for $\zeta(\theta)$		parameters for $\xi(\theta)$		parameters for $\varkappa(\theta)$	
ζ_1	$7.668\ 10^{-5}$ °	ξ_1	0.0120 °	$\varkappa_1$	29.379 *
ζ_2	-1 10^{-5} *	ξ_2	-0.0524 *	$\varkappa_2$	-12.98 *
ζ_3	$7.668\ 10^{-5}$ °	ξ_3	0.0139 *	$\varkappa_3$	17.28 *

° constrained value (to have non negative emissions).
* significant at 0.05 level.

Table 2: parameters estimation for emission function

Moreover, social damage is valued as being the cost of water treatment aimed at transforming untreated water into drinking water (Falala, *et al.,* 2002). Obviously, a complete evaluation of damage should include the consequences of lack of biodiversity, eutrophication, decrease in recreation activities, and so on. This task is out of the scope of the paper. Thus our valuation will be an underestimation of total social damage.

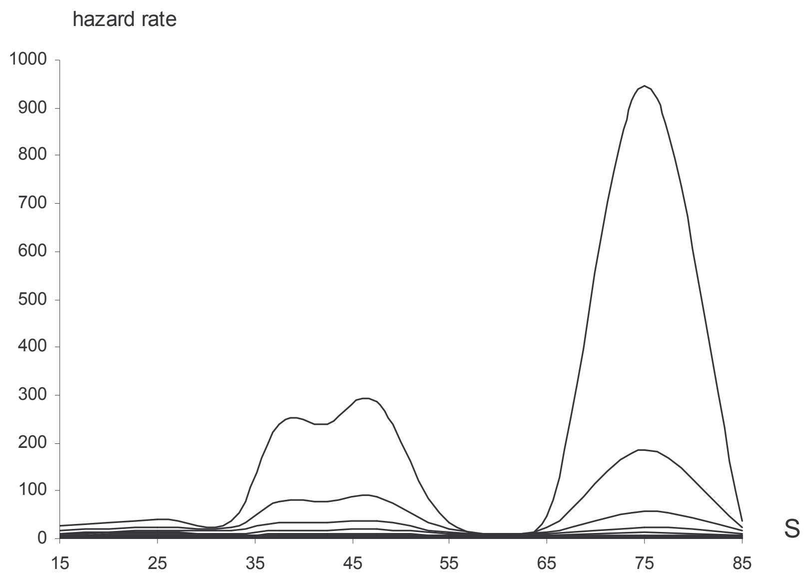

Figure 4: Hazard rate $\frac{1-F(\theta;S)}{f(\theta;S)}$ for some specific values of θ on the Don watershed.

4.2 Analysis

Instead of exploiting the first order conditions exhibited in the theoretical part of this paper, the optimal policies for the mandatory and the political regulation cases have been more easily determined by solving the regulator maximization program directly. For this purpose we used the Gams software (Brooke et al., 1998) and the Conopt optimization procedure (Drud, 1994).[13]

Figure 5 depicts optimal production levels for each class of forage area, compared to the laissez-faire situation and the complete information scheme. Mitigating the NPS pollution under a complete information situation implies a slight decrease in the production level, except for the higher θ-type farms. The greater the value of the θ-type, the higher the decrease of production level. For the high types, we note a decrease in the required level of production: this is due to the fact that there the emission level strongly increases in θ for given production level, that is $g_{\theta y}$ is strongly positive for high θ (see Table 2). This implies that $y^{PI}(\theta)$ should decrease for high types as their contribution to pollution is large.

The regulation under the imcomplete information scheme leads to a completely different pattern of production levels. The range of farms excluded from production is larger : production is allowed for farmers with a type greater than 0.19 to 0.28 depending of the forage area, which represents a

[13] Computing directly the value of the analytical first order conditions derived in section 3 would lead to code functions with discontinuous derivatives, and the model would be far more difficult to solve.

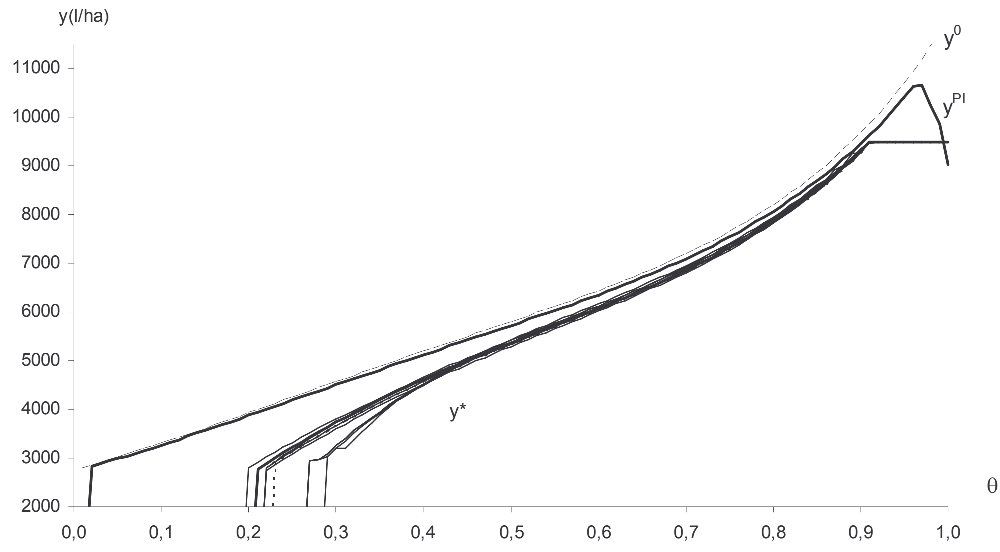

Figure 5: Optimal production level for the laissez-faire situation (y^0), the perfect information scheme (y^{PI}) and the optimal differentiated policy (y^*) depending on the forage area S.

range of excluded population from 3.0 to 8.1 % of each class of forage area. Overall, 5.5 % of the farmers are put out of production. For the highest types, a pooling phenomenon appears because the second order conditions (IC2) which imply the monotony of y are binding: as seen for the complete information case, the regulator would want to decrease the production level of the high types but this contradicts incentive compatibility constraints. The regulator cannot do better than inducing those types to produce a constant level of production (see Guesnerie and Laffont, 1984). More important, the decrease in the production level induced by the regulation is greater for the higher θ-type farms than for the smaller ones, up to a type threshold of 0.9 which corresponds to the binding of the second order conditions.

The tax pattern appears to be completely different in the complete and incomplete information schemes (see Figure 6): whilst in the complete information regulation the tax raises rapidly and continuously with the θ-type, this tax increases far more smoothly for the optimal policy.

The two regulation schemes are far different from each other. Assuming a complete information leads the regulation to induce a slight variation in the production level (and thus in the damage) but to tax as much as possible the farmers. This results in a slight decrease of the damage and a dramatic drop in the farmers' profit. Under an incomplete information pattern, the regulation excludes more farms from the production, induces a greater modification in the production levels but taxes less the farmers : the resulting damage is slower and the farmers' profit higher. Moreover,

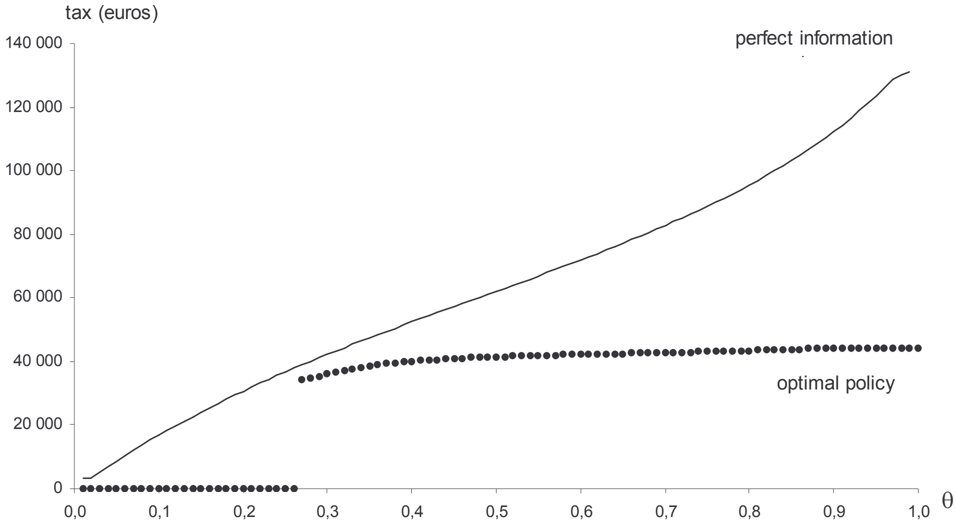

Figure 6: Tax level depending on the θ-type : example for farms cropping 42.5 hectars.

the efficient farmers are induced to reduce less their production level but are more taxed than the inefficient ones : their profit is much decreased and they bear the cost of the reform.

Most regulators believe that an efficient way to mitigate NPS agricultural pollution is to regulate first the farms with the less favorable ratio profit/emissions. Our application suggests that the balance between the farmers' and the tax-payers' surplus in the regulator's objective and the incentive compatibility constraints lead to split the population of farmers into three parts (see Figure 7). The first subset corresponds to farmers having high θ-type values who are induced to reduce all the more their emissions since their ratio profit/emissions is low. The second subset groups together farmers with low θ-type values who are also induced to reduce their emissions depending on their initial ration profit/emissions, but the induced reduction is lower than for the farmers belonging to the first subset, given the same ratio. Ultimately, it is in the regulator's interest to exclude from the production the farmers who have the lowest ratio profit/emissions.

5 Conclusion

Compensating farmers who adopt costly but pollution-decreasing practices is an idea that is supported by an increasing number of both farmers and environmentalists, and has already been tested in many areas in Europe. But stewardship compensation programs must overcome many difficulties, the most important being enforcements problems when the practices are not easily observed. In this case, the regulation of pollution can be designed on the basis of a small set of variables that

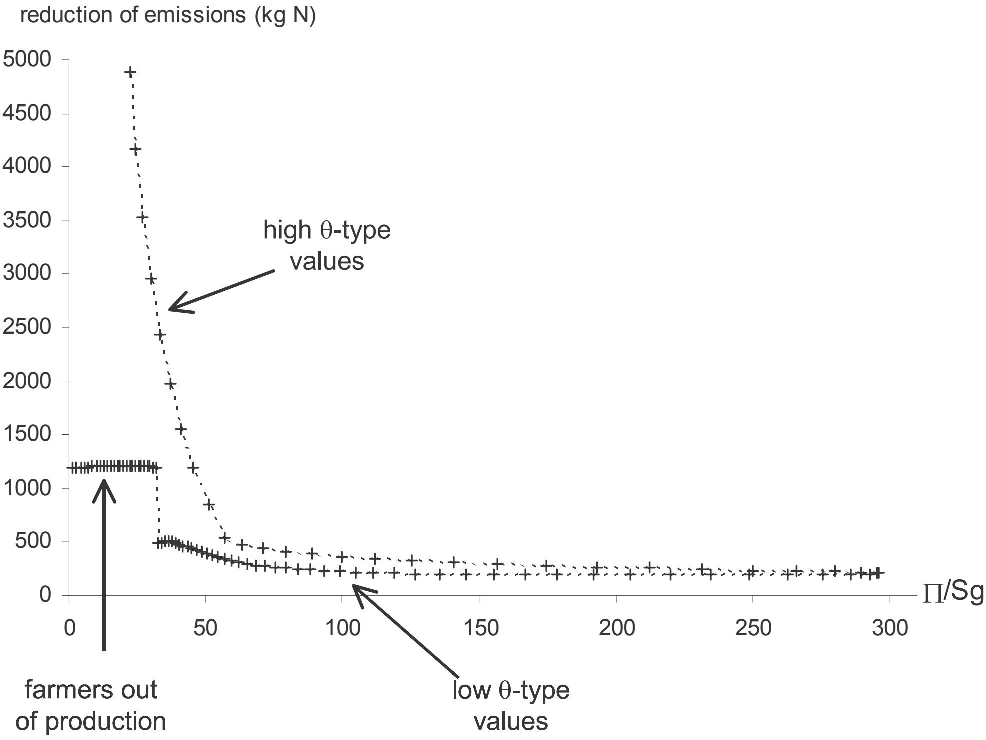

Figure 7: Reduction of total emissions induced by the optimal regulation for farmers cropping 42.5 hectars, depending on their initial ratio $\frac{\pi^{\circ}}{Sg}$ and their θ-type.

are common knowledge. This paper presents the regulation of NPS pollution from a population of farmers when the level of production is easily observed. We assume that the farmers have more information about their own resource setting than the regulator but that this information can be summarized into a one-dimensional parameter, the farmer's type, which is not observed. Private information makes self-selection necessary. We assume that the relationship between pollution, profits production level and farmer's type is known, which allows the design of a payment scheme. The program requires the farmer to declare both the level of production and the area he chooses and then receive the associated subsidy (or pay the associated tax). Adjusting subsidies or taxes depending on the farmer's type has not yet been widely developed by policy makers, with an exception for adjustments according to the size of the farm. But because within the Water Framework Directive (2000/60/EC, hereafter WFD) EU Member States have to ensure a programme of measures to mitigate water pollution, they need to select the most cost-effective measures among the set of potential ones. In our application case, the loss of welfare related to private information is lower than the cost of information required to implement the first best production levels and obviously such a program with adjusted subsidies is cost-effective to implement the WFD.

The design of policies to mitigate NPS pollution from farms with a differentiated framework induces a better allocation of the abatement effort between farms: the empirical application on the Don watershed suggests that this abatement effort is mostly borne by the farms having the lower ratio profit/emissions, and, given this ratio, by the more efficient farmers.

The model that we described here can be widely refined. The farm model can be fitted to farms with multiple productions because the farmers can switch one production with another when the relative profitability changes. Parametrizing such a model with data from the European Farm Accountancy Data Network (FADN) could provide a European wide farm model which captures the type of farming, the size and location of the farms and the density in each class of farmer's ability. European wide hydrological model are still not available but should be provided within a few years and thus a Decision Support System for implementing the WFD could be designed. Last, we have only considered here nitrate pollution but phosphorus, sediments, metals or bacteria emission should be taken into consideration too. Regulating water quality through production may hence provide multiple environmental benefits.

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Appendix

A Proof of Proposition 1

First, differentiating the objective w.r.t. $y(\theta)$, we obtain the following necessary conditions:

$$(1+\lambda)(p - c_y(y^{PI}(\theta), \theta)) = D'\left(E^{PI}\right) g_y((y^{PI}(\theta), \theta)) \tag{6}$$

where PI denotes complete information and $E^{PI} = \int_{\underline{S}}^{\overline{S}} \int_{\underline{\theta}}^{\overline{\theta}} s^{PI}(\theta) g(y^{PI}(\theta), \theta) f(\theta; S) d\theta h(S) dS$. Then, differentiating the objective w.r.t. $s(\theta)$, we obtain:

$$\frac{\partial \mathcal{W}}{\partial s(\theta)} = \left[(1+\lambda)(py^{PI}(\theta) - c(y^{PI}(\theta), \theta)) - D'\left(E^{PI}\right) g(y^{PI}(\theta), \theta)\right] f(\theta; S) = \Omega(\theta) f(\theta; S).$$

Differentiating $\Omega(\theta, y(\theta), E)$ w.r.t. θ and using (6) leads to

$$-(1+\lambda)c_\theta(y^{PI}(\theta), \theta) - D'\left(E^{PI}\right) g_\theta(y^{PI}(\theta), \theta)$$

which is positive under our assumptions. We assume that $\Omega(\overline{\theta}, y^{PI}(\overline{\theta}), E^{PI}) > 0$ otherwise every farmer should be shut down. When $\Omega(\underline{\theta}, y^{PI}(\underline{\theta}), E^{PI}) < 0$, there exists a unique threshold type $\theta^{PI}(S)$ such that for any S, whenever $\theta \leq \theta^{PI}$, the farmer is not allowed to produce ($\forall S$, $s^{PI}(\theta) = 0$, $\forall \theta \leq \theta^{PI}(S)$). On the contrary, the more efficient farmers produce using their total land capacity ($\forall S$, $s^{PI}(\theta) = S$, $\forall \theta > \theta^{PI}(S)$). When $\Omega(\underline{\theta}, y^{PI}(\underline{\theta}), E^{PI}) > 0$, then all farmers are allowed to produce at the optimum involving complete information.

Finally, as the objective is decreasing in the rent $\pi(\theta)$ left to any agent, participation constraints are clearly binding at the optimum ($\pi(\theta) = 0$, $\forall \theta, \forall S$).

B Proof of Proposition 2

Part (i): note that

$$sign(\partial \mathcal{W} / \partial s(\theta)) = sign(A(\theta))$$

where

$$\begin{aligned} A(\theta) &= (1+\lambda)\left[py^*(\theta) - c(y^*(\theta), \theta)\right] + \lambda c_\theta(y^*(\theta), \theta) \frac{1 - F(\theta; S)}{f(\theta; S)} \\ &\quad - D'(E)\, g(y^*(\theta), \theta) \end{aligned}$$

Using (4) and dropping any argument, we get by derivating:

$$A'(\theta) = -(1+\lambda)c_\theta + \lambda c_{\theta\theta} \frac{1-F}{f} + \lambda c_\theta \frac{d}{d\theta}\left(\frac{1-F}{f}\right) - D'(E) g_\theta > 0$$

when $c_{\theta\theta} > 0$ (or at least not too negative). Note that $A(\overline{\theta})$ does not depend on S so that $A(\overline{\theta}) > 0$ for any land capacity S. Indeed, $A(\overline{\theta}) = (1+\lambda)(py^*(\overline{\theta}) - c(y^*(\overline{\theta}), \overline{\theta}) - D'(E)\, g(y^*(\overline{\theta}), \overline{\theta})$ where $y^*(\overline{\theta})$ is given by $(1+\lambda)(p - c_y(y^*(\overline{\theta}), \overline{\theta})) = D'(E)\, g_y(y^*(\overline{\theta}), \overline{\theta})$. Thus, considering only interior solutions, with the additional technical assumption $A(\underline{\theta}) < 0$, there exists a unique threshold type $\theta^*(S)$ such that for every $\theta < \theta^*(S)$, $\partial\mathcal{W}/\partial s(\theta) < 0$ and consequently $s^*(\theta) = 0$ so that all sufficiently inefficient farmers are shut down. Moreover, for any $\theta > \theta^*(S)$, $\partial\mathcal{W}/\partial s(\theta) > 0$ and consequently $s^*(\theta) = S$. Note that the threshold type is given by:

$$\begin{aligned}(1+\lambda)&(py^*(\theta^*(S)) - c(y^*(\theta^*(S)), \theta^*(S)))f(\theta^*(S); S)\\ &- D'\left(\int_{\underline{S}}^{\overline{S}} \int_{\theta^*(S)}^{\overline{\theta}} Sg(y^*(\theta), \theta) f(\theta; S) d\theta h(S) dS\right) g(y^*(\theta^*(S)), \theta^*(S)) f(\theta^*(S); S)\\ &\qquad = -\lambda c_\theta(y^*(\theta^*(S)), \theta^*(S))(1 - F(\theta^*(S); S))\end{aligned}$$

or equivalently

$$\Omega(\theta^*(S), y^*(\theta^*(S)), E^*) = -\lambda c_\theta(y^*(\theta^*(S)), \theta^*(S)) \frac{1 - F(\theta^*(S); S)}{f(\theta^*(S); S)}.$$

Moreover, derivating totally this expression w.r.t. S, we obtain:

$$\theta^{*\prime}(S) = -\frac{\lambda c_\theta(y^*(\theta^*(S)), \theta^*(S))}{A'(\theta^*(S))} \delta(\theta^*(S); S)$$

where $\delta(\theta; S) = \frac{d}{dS}\left(\frac{1-F(\theta;S)}{f(\theta;S)}\right)$. As $c_\theta < 0$ and $A' > 0$, the sign of $\theta^{*\prime}(S)$ is completely determined by the sign of $\delta(\theta^*(S); S)$.

Parts (ii) and (iii): comes easily from derivation in the text above (see (4)).

C Second order conditions

We now check that equation IC2 is satisfied. For any type-(θ, S) farmer who is allowed to produce, equation IC2 can be written as:

$$-Sc_{\theta y}(y^*(\theta), \theta) y'(\theta) \geq 0$$

Derivating equation (4) with respect to θ, and dropping any argument, we have:

$$\begin{aligned}&-(1+\lambda)(c_{yy}y' + c_{\theta y}) - D'(E) g_{yy} y' - D'(E) g_{\theta y}\\ &\qquad + \lambda\left(\frac{1-F}{f}\right)(c_{\theta yy}y' + c_{\theta\theta y}) + \lambda c_{\theta y}\frac{d}{d\theta}\left(\frac{1-F}{f}\right) = 0\end{aligned}$$

This equation can be written as:

$$y' = \frac{(1+\lambda)c_{\theta y} + D'(E) g_{\theta y} - \lambda\left(\frac{1-F}{f}\right) c_{\theta\theta y} - \lambda c_{\theta y}\frac{d}{d\theta}\left(\frac{1-F}{f}\right)}{-(1+\lambda)c_{yy} - D'(E) g_{yy} + \lambda\left(\frac{1-F}{f}\right) c_{\theta yy}}$$

We have already made the following technical assumptions: $c_{\theta y} < 0$, $c_{\theta yy} < 0$, $c_{\theta\theta y} > 0$ and $\frac{d}{d\theta}\left(\frac{1-F}{f}\right) < 0$. Thus, if in addition $g_{\theta y} < 0$ or not too positive and furthermore $g_{yy} > 0$, then we have $y'(\theta) > 0$, $\forall\theta$ and the second order conditions are fulfilled. Note than on our empirical application, those conditions will not be fulfilled everywhere (in particular for the high types) so that a pooling phenomenon will appear (see section 4).

D Proof that $\pi^*(\theta) \leq \pi^\circ(\theta)$

First, recall that by (IC1), $\pi^*(\theta)$ can be written as follows:

$$\pi^*(\theta) = \int_{\theta^*(S)}^{\theta} -c_\theta(y^*(u), u)Sd\theta.$$

Moreover, using the envelop theorem, we have before any regulation $\pi^{\circ\prime}(\theta) = -Sc_\theta(y^\circ(\theta), \theta)$. Integrating, we obtain:

$$\pi^\circ(\theta) = \pi^\circ(\theta^*(S)) + \int_{\theta^*(S)}^{\theta} -c_\theta(y^\circ(u), u)Sd\theta$$

where $\pi^\circ(\theta^*(S)) > 0$. As $c_{\theta y} < 0$ and $y^*(\theta) < y^\circ(\theta)$, we also have:

$$0 < -c_\theta(y^*(\theta), \theta) < -c_\theta(y^\circ(\theta), \theta)$$

and thus $\int_{\theta^*(S)}^{\theta} -c_\theta(y^\circ(u), u)Sd\theta > \int_{\theta^*(S)}^{\theta} -c_\theta(y^*(u), u)Sd\theta$. Therefore, $\pi^*(\theta) \leq \pi^\circ(\theta)$.

E A technical definition for θ

The θ parameter is estimated by combining the technical variables that capture differences across farms and describe 43% of the whole variability among the farms.

$$\theta = \frac{TMS_{prairies}}{10} - cor_{prod} - cor_{conc} - cor_{eq} - cor_{qual}$$

with:

$TMS_{prairies}$ the amount of estimated dry matter produced by the grassland area;

cor_{prod} a corrective coefficient relating the amount of milk produced per cow, $\mu etable$ to the mean on the watershed:

$$cor_{prod} = -\frac{\mu etable - 6000}{10000}$$

cor_{conc} a corrective coefficient comparing the amount of milk production per hectar in the laissez-faire situation, y°, and the amount of milk that would have been produced if the cows eat rough forages only, $milk_{ration}$:

$$cor_{conc} = \begin{cases} \text{if} \quad y^\circ > milk_{ration} & \frac{y^\circ - milk_{ration}}{10000} \\ \text{if} \quad y^\circ > milk_{ration} & 0 \end{cases}$$

cor_{eq} a corrective coefficient which describes the difference of milk production permitted by the energy in the cows feed intake, $milk_{UFL}$, and of milk production permitted by the proteins in the cows feed intake, $milk_{PDIN}$:

$$cor_{eq} = -\left(\left|\frac{milk_{UFL} - milk_{PDIN}}{milk_{UFL}}\right| - 10\right)/200$$

cor_{qual} a corrective coefficient which compares the amount of milk produced per hectar, y°, and the theoretical production that would be observed if the forages where of medium-high quality, $milk_{good}$:

$$cor_{qual} = \begin{cases} \text{if} \quad y^{\circ} > milk_{good} \begin{cases} \text{if } |y^{\circ} - milk_{good}| < 0,02.milk_{good} & \frac{5}{|y^{\circ} - milk_{good}|} \\ \text{otherwise} & 0 \end{cases} \\ \text{if} \quad y^{\circ} < milk_{good} \qquad\qquad\qquad\qquad \frac{y^{\circ} - milk_{good}}{40000} \end{cases}$$

All these coefficient have been determined using the surveyed data on the Don watershed and using the cow feed intake softwares used by the local extension services.

F Density $f(\theta; S)$ parameters on the Don watershed

Beta function parameters for the densities $f(\theta; S)$ are given in the following Table:

Area classes	10<S<20	20<S<30	30<S<35	35<S<40	40<S<45	45<S<50	50<S<60	60<S<70	70<S<80	80<S
parameter a	2,9	3,0	3,2	5,8	5,8	6,0	3,2	4,0	8,0	3,2
parameter b	3,5	3,0	3,4	5,4	5,4	5,5	3,6	4,6	7,5	3,4

Table 3: Beta function parameters describing the densities f.

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