The Control of Nonpoint Pollution when Damages are Heterogeneous

Abstract
The expansion of intensive agriculture in Spain during recent decades has created substantial ambient pollution loads of nutrients and pesticides in streams and river courses. This pollution degrades water quality and damages aquatic ecosystems. Because the pollution emissions from agriculture are nonpoint, it is almost impossible (or very costly) to identify the responsible agent, the location of sources, and the amount of emissions. This paper analyzes the problem of saline percolation from farms into water bodies using an approach that takes into account the heterogeneity of biophysical processes and farm soils. A common assumption in the nonpoint pollution literature is that the function of marginal damages from pollution is unique across farms and soils. This implies a unique optimal tax rate (or a unique optimal pollution threshold) for all agents. The heterogeneity between farms implies that the pollution damage functions depend on biophysical characteristics, a very likely situation in nonpoint pollution where transport and fate processes are involved. Therefore, the implementation of a unique tax rate (or pollution threshold) for all agents generates significant welfare losses. This study highlights the importance of taking into consideration the heterogeneity among farms in order to design better pollution policies. Results show that no regulation could be a preferred option over regulation with a unique pollution tax (or threshold) when agents are heterogeneous.

Keywords: nonpoint pollution, heterogeneous farms, pollution damage functions, uniform and non-uniform pollution taxes and thresholds.

Introduction

Protecting water resources is an important objective of environmental policies in all countries, especially in arid and semiarid regions of the world. The quality of water resources is a significant issue in European environmental policies.

Agriculture is an important source of nonpoint pollution, with nutrient and pesticide emission loads as major components of water quality degradation. Nonpoint pollution from agriculture is a negative externality resulting in damages to natural ecosystems that reduce the services from the environment and consequently social welfare. The main problem in addressing nonpoint pollution is the lack of information and knowledge about the responsible agents, their precise location, and the amount of pollutants at the source. Ambient pollution is easily measurable, but the transport and fate processes linking source pollution and ambient pollution are mostly unknown in all countries. The emissions at the source cannot be observed accurately because the costs of measuring individual plots are prohibitive. Other features of agricultural nonpoint pollution are the high number of pollutants, the complex mechanisms of transport and fate, the asymmetric information among the agents involved, as well as the stochastic and unknown elements, such as climate and other biophysical characteristics of basins. Consequently, the design and implementation of nonpoint pollution control measures is a very complicated task.

A type of agricultural pollution is salinity coming from irrigated crop production activities. Salinization of cultivation fields occurs when salts increase in the root zone, because soils are affected by salinity and cropland is not well managed and improper irrigation elements are used (e.g. irrigation with saline water). Salinity is an important problem, particularly widespread in arid or semiarid areas where crop production requires irrigation schemes (Tedeschi et al. 2001, Tanji 1990). At least 20 percent of all irrigated land is salt-affected, with some estimates being as high as 50 percent (Pitman et al. 2002). The use of large quantities of water in irrigated agriculture generates percolation and runoff which drag salinity from salt deposits. This salinity pollutes water courses and other lands and creates considerable damages to the natural environment. Additionally, high levels of salinity are a limiting factor in the production of several crops. Most crops are sensitive to high soil salinity concentrations, reducing crops yield or even making production infeasible.

This study focus on the problem of water quality degradation from salinity emission loads in a watershed located in the Ebro basin (Spain). A substantial acreage of land in the Ebro basin is affected by salinity, estimated at around 310,000 ha (Alberto et al. 1986). The Ebro basin is a semiarid area with low precipitations (400 mm/year) and high evapotranspiration during the warm season. Because of the significant salinity in the area and the semiarid weather, saline leaching is an important environmental problem in the Ebro basin (Navas et al. 1995). The development of irrigated agriculture in the basin has vastly expanded the irrigation return flows and the drag of salts, which degrade water quality in the Ebro basin water courses and damage aquatic ecosystems.

The study develops a model with heterogeneous farms dedicated to irrigated agriculture. Farms are different depending on the irrigation technology, crops, and soils. The main consequence of the heterogeneity between farm lands is the existence of different pollution damage functions by farm. Because farms have different types of soils containing diverse salinity levels, water percolation from irrigation drags different amounts of salts depending on the type of soil washed. Therefore percolation is responsible for the ambient salinity pollution in downstream water bodies.

In this study, three pollution emission functions are defined for each of the three types of soils identified by salinity (saline, moderate, and non saline), with the map of soils showing their spatial distribution. Because of the existence of three pollution damage functions, different ambient-differentiated pollution taxes (or pollution standards) have to be implemented to abate pollution and achieve efficiency. The results from the analysis show that a uniform pollution tax produces an important loss in the social welfare. Forcing a unique tax could be even worse than doing nothing, because our results show that the welfare outcome form a uniform tax could be below the welfare under no regulation. The purpose of the study is to highlight the inefficiencies of applying uniform pollution instruments when different damage functions are identified.

The paper is organized as follows: section 2 extends a theoretical nonpoint pollution model common in the literature, and highlights the importance of taking into consideration non-uniform tax rates in a context of different damage pollution functions. Section 3 describes the empirical model, presenting the study area and the bioeconomic model. Section 4 presents the results of the analysis under alternative policy scenarios. Finally, section 5 concludes with the main findings and implications.

The control of nonpoint pollution: theoretical model

Following the methodological approach on nonpoint pollution by Segerson and Wu (2006), the present study analyzes how pollution policies change when there are different pollution damage functions instead of a unique damage function. Different pollution damage functions arise because the underlying biophysical processes make farms heterogeneous, with each class of farm having their own damage function. Under different pollution damage functions for heterogeneous farms, the optimal pollution level and shadow price of pollution is different for each class of farm. However, the usual proposition in the literature calls for a unique tax rate, which may lead to substantial welfare losses when multiple damage functions are ignored.

Segerson and Wu propose that the regulator makes a threat of imposing in the future an ambient tax as a mechanism to enforce a pollution threshold in the current period. If the threshold is exceeded in any past period, then the ambient tax is implemented forever. Their results highlight how this combination of voluntary compliance in the current period, and the threat of an ambient tax in the future is more effective than a pure ambient-tax.

The model considers n farmers generating pollution in a water body. Each farmer i can use abatement practices $a_i = (a_{i1}, a_{i2}, \dots, a_{in})$. Each farmer has different characteristics (soil, costs, skills, etc) which are denoted by the parameter θ_i. Expected ambient pollution is defined as x and depends on the abatement practices and farmers' characteristics $x = x(a_1, a_2, \dots, a_n; \theta_1, \theta_2, \dots \theta_n)$. The cost of abatement to farmers depends on abatement practices and farm characteristics $C_i = (a_i, \theta_i)$.

The social planner decides the threshold of pollution that cannot be exceeded, which is x^s (with $x^s < x(0, \dots, 0;\ \theta_1, \dots, \theta_n)$). The optimization problem is given by the expression:

$$Min \quad \sum_{i=1}^{n} C(a_i,\ \theta_i)$$

$$s.t. \quad x(a_1, \dots, a_n;\ \theta_1, \dots, \theta_n) \le x^s \quad and \quad a_{ij} \ge 0 \quad i = 1, \dots, n;\ j = 1, \dots, m \qquad (1)$$

The first order condition of this problem is given by:

$$\frac{\partial C}{\partial a_{ij}} + \lambda^*(x^s, \theta) \cdot \frac{\partial x}{\partial a_{ij}} \ge 0 \qquad (2)$$

where $\lambda^*(x^s, \theta)$ is the optimal value of the lagrangian. Therefore $C^* = C(a_i^*(\theta_1, \dots, \theta_n, x^s), \theta_i)$.

With this information, the regulator wants farmers to achieve the threshold voluntarily. If the threshold is not meet, the regulator imposes a mandatory policy using a linear tax on ambient pollution. The tax payment TP_i is given by the expression:

$$TP_i \begin{cases} 0 & if\ x(a^v,\theta) \leq x^s \\ \tau_i \cdot [x(a^t,\theta) - \bar{x}] & if\ x(a^v,\theta) > x^s \end{cases} \quad (3)$$

where a^v represents the abatement practices vector when farmers choose voluntarily not to exceed the threshold ($x(a^v,\theta) \leq x^s$), and a^t is the abatement vector when farmers do not meet the threshold ($x(a^t,\theta) > x^s$). The tax is imposed in all subsequent, where parameter τ_i is the ambient tax rate on farmer i, and $\bar{x}$ is a "cuttoff level" of pollution ($\bar{x} \leq x^s$).

If $\tau_i = \lambda^*(x^s,\theta) \equiv \tau^*$, then $a^t = (a_1^*, \dots, a_n^*)$ is the unique Nash equilibrium for the tax subgame. Therefore, the regulator can induce cost-minimizing abatement decisions by threatening with imposing an ambient tax on each farmer equal to τ^*. The optimal tax is uniform for all farmers, even though the abatement levels and contributions of farmers can differ. This is because the tax rate is equal to the shadow price of pollution.

Segerson and Wu analyze the social benefits of a single farmer meeting the threshold voluntarily and not paying the tax in the future, and then with multiple polluters. In the case of a single polluter, results show that when $\bar{x} \leq x^s - \frac{rC^*}{\tau^*}$ the regulator can induce voluntary compliance in all periods.[1] When there are multiple polluters, free-riding behavior can emerge because the costs of abatement are different (C_i^*). The pollution threshold can be meet voluntarily but not at minimum cost, because C_i^* varies by farmer and free-riding behaviour appears.

Even with this free-riding effect, all farmers would prefer to meet the threshold voluntarily but with an inefficient abatement allocation. Zero abatement is also a Nash equilibrium but dominated by voluntary compliance. The above results correspond to the case of a non retroactive tax, where farmers pay forever starting in the year after the threshold is exceeded. Imposing a retroactive tax, where farmers pay also for the year they have exceeded the threshold, eliminates free-riding and zero abatement. The advantage of a voluntary and threat instrument is that the regulator does not have to incur in information costs associated with the tax, in order to gather information on the characteristics of farmers θ_i. The main conclusion of this analysis is that the regulator

[1] Parameter r is the interest rate.

can induce cost-minimizing abatement without incurring in farm specific information costs.

The optimal cost of abatement is different by farm in the case of multiple polluters, because costs depend on the individual abatement vector and on farm characteristics, $C_i^* = (a_i, \theta_i)$. But even for multiple farmers, a key assumption is that there is only one pollution damage function. When the pollution damage function is unique, the shadow price of pollution (or the tax rate) is the same for all farmers, $\tau_i = \lambda^*(x_s, \theta) \equiv \tau^*$. With this unique tax rate, farmers achieve the Nash equilibrium which is the optimal abatement level, $a^t = (a_1^*, \ldots, a_n^*)$. The assumption of a unique pollution damage function is a key hypothesis made by Segerson and Wu in the demonstrations supporting their findings.

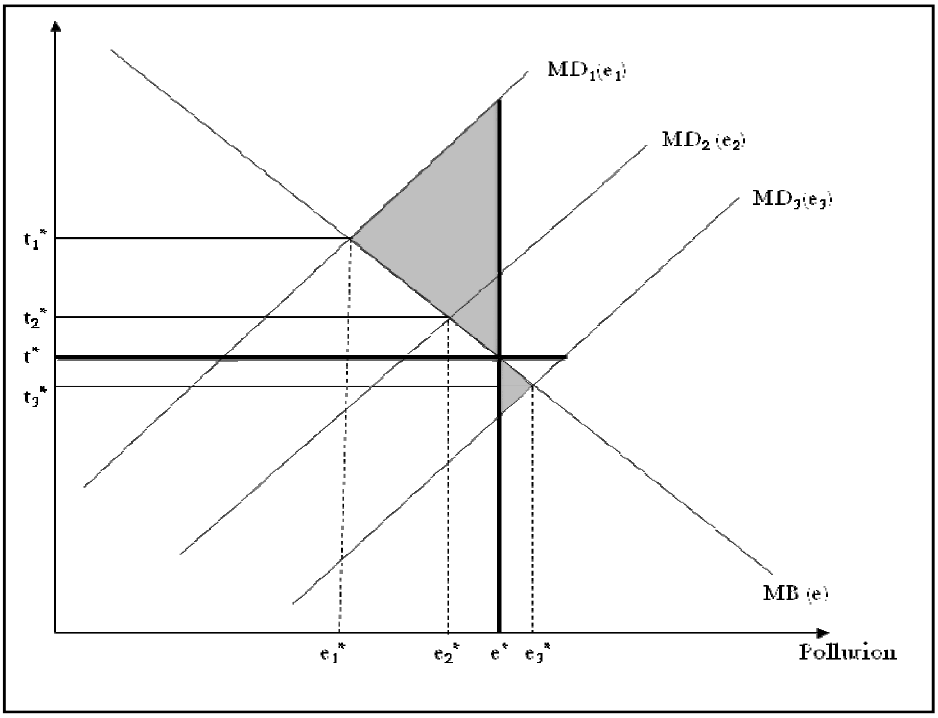
The purpose of this study is to analyze the case of different pollution damage functions, with their corresponding shadow prices of pollution which are the tax rates. A common assumption in the literature is that pollution damage functions are unique for all agents. This implies a single optimal pollution level where marginal benefits and damages from pollution are equal, and there is a single optimal shadow price of pollution for all farms.

The underlying biophysical processes are quite likely to make farms heterogeneous with respect to damages caused by their pollution loads. These damages from pollution are different because of the heterogeneity of farms related to soils, technologies and other spatial features (Kolstad 2000).[2] Figure 1 shows the welfare losses of using a uniform tax rate, when in fact there are different pollution damage functions by class of heterogeneous farm, and different shadow prices of pollution. The figure shows for every class of heterogeneous farm the optimal pollution emissions (e_1^*, e_2^* and e_3^*), and the optimal shadow prices of pollution (t_1^*, t_2^* and t_3^*) which are the Pigouvian tax rates. The implementation of a unique tax rate t^* for all farms implies losses in social welfare, measured by the shared areas of figure 1.[3]

The analysis presented here introduces specific damage functions for each class of farm. Farms are heterogeneous because of the type of soil which can be saline, moderate saline, or non saline. Percolation from each farm is the polluting variable. Percolation

[2] See chapter 9 "Emissions fees and marketable permits".
[3] Kolstald (2000) states in page 160: "The loss from a uniform fee depends on the nature of the marginal cost and damage functions. The steeper the marginal cost functions and the flatter the marginal damage, the smaller the deadweight loss".

Figure 1. Welfare losses of ignoring the different pollution damage functions.



Note: MD_1, MD_2 and MD_3 are the pollution marginal damages from farms of class 1, 2 and 3. MB is the marginal benefit of pollution. t_1^*, t_2^* and t_3^* are the optimal shadow prices of pollution to be used as tax rates for farms of class 1, 2 and 3. t^* is the uniform pollution tax when heterogeneity of damages is ignored. e_1^*, e_2^* and e_3^* are optimal pollution levels for farms of class 1, 2 and 3, while e^* is the uniform pollution level when heterogeneity is ignored.

goes through saline soils driving the transport and fate processes of salinity towards water courses, causing damages to ecosystems and to other human activities. The damage function from percolation of each class of farm is different and depends on the type of soil.

The objective function is given by equation 1, where different pollution functions give rise to different pollution thresholds. The minimization problem becomes:

$$Min \sum_{si=1}^{n1} C_s(a_{si}, \theta_{si}) + \sum_{mi=1}^{n2} C_m(a_{mi}, \theta_{mi}) + \sum_{ni=1}^{n3} C_n(a_{ni}, \theta_{ni})$$

$$\begin{aligned} s.t. \quad & x_s(a_{s1}, \dots, a_{sn1};\ \theta_{s1}, \dots, \theta_{sn1}) \le x_s^s \\ & x_m(a_{m1}, \dots, a_{mn2};\ \theta_{m1}, \dots, \theta_{mn2}) \le x_m^s \\ & x_n(a_{n1}, \dots, a_{nn3};\ \theta_{n1}, \dots, \theta_{nn3}) \le x_n^s \\ & and \quad a_{si}, a_{mi}, a_{ni} \ge 0 \qquad n = n_1 + n_2 + n_3 \end{aligned} \tag{4}$$

where n is the total number of farmers in the model. The sub-indexes s, m, and n represent the type of soils: saline, moderate saline, and non saline respectively. $C_s(a_{si}, \theta_{si})$, is the abatement vector of farms with saline soil, $C_m(a_{mi}, \theta_{mi})$ is the abatement vector of farms with moderate saline soil, and $C_n(a_{ni}, \theta_{ni})$ is the abatement vector of farms with non saline soil. $x_s\left(a_{s1}, \dots, a_{sn_1};\ \theta_{s1}, \dots, \theta_{sn_1}\right)$ is the total pollution from farms in saline soils, $x_m(a_{m1}, \dots, a_{mn_2};\ \theta_{m1}, \dots, \theta_{mn_2})$ is the total pollution from farms in moderate saline soils, and $x_n(a_{n1}, \dots, a_{nn_3};\ \theta_{n1}, \dots, \theta_{nn_3})$ is the total pollution from farms in non saline soils. x_s^s is the pollution threshold for farms in saline soils, x_m^s is the pollution threshold for farms in moderate saline soils, and x_n^s is the pollution threshold for farms in non saline soils.

There are three separate threshold restrictions because the pollution (percolation) from each group of farms is different; so the optimal quantities of pollution are also different. The first order conditions of equation 4 yield three Lagrangian multipliers, which are the three pollution tax rates sought by the regulator. These tax rates correspond to each type of soil (saline, moderate and non-saline).

The first order conditions of problem 4 are given by:

$$1. \frac{\partial C(a_{si}, \theta_{si})}{\partial a_{si}} + \lambda_s^*(x_s^s, \theta) \cdot \left(\frac{\partial x}{\partial a_{si}}\right) \geq 0 \tag{5}$$

$$2. \frac{\partial C(a_{mi}, \theta_{mi})}{\partial a_{mi}} + \lambda_m^*(x_m^s, \theta) \cdot \left(\frac{\partial x}{\partial a_{mi}}\right) \geq 0 \tag{6}$$

$$3. \frac{\partial C(a_{ni}, \theta_{ni})}{\partial a_{ni}} + \lambda_n^*(x_n^s, \theta) \cdot \left(\frac{\partial x}{\partial a_{ni}}\right) \geq 0 \tag{7}$$

The Lagrangian multipliers of equations 5, 6 and 7 are the shadow prices of pollution for farms in each type of soil: ($\lambda_s^*(x_s^s, \theta)$ saline, $\lambda_m^*(x_m^s, \theta)$ moderate saline, and $\lambda_n^*(x_n^s, \theta)$ non saline. These Lagrangian multipliers are the optimal tax rates for the class of farms by type of soil. Compared with the model by Segerson and Wu, there are three first order conditions, instead of one condition (equation 2), with three multipliers.

Methodologically, the model of Segerson and Wu minimizes the costs of abatement undertaken by farms. Kampas and White (2004) show that to minimize the abatment costs is equivalent to maximize the social welfare. The abatement costs of farms are the difference between the unrestricted profit of farms and the restricted profit of farms under pollution regulation:

$$\sum_{i=1}^{n} C_i^e = \sum_{i=1}^{n} \pi_i(q_i, e_i) - \sum_{i=1}^{n} \pi_i^e(q_i, \widetilde{e_i}) \tag{8}$$

where $\pi_i(q_i, e_i)$ is the unrestricted profit of the i^{th} farm as a function of output q_i and pollution e_i, while $\pi_i^e(q_i, \tilde{e_i})$ is the restricted profit of the i^{th} farm with a pollution constraint $\tilde{e_i}$. The restricted profits are the solution of the following problem:

$$\underset{q,e}{Max} \sum_{i=1}^{n} \pi_i(q_i, e_i)$$

$$s.t.\ G\left(\sum_{i=1}^{n} \tilde{e_i}, \sum_{i=1}^{n} \sigma_i, \alpha\right) \leq \tilde{E} \qquad (9)$$

Solving problem 9 is equivalent to minimizing the total costs of abatement (problem 1). The formulation of Kampas and White is the dual of the Segerson and Wu problem.

The control of nonpoint pollution: empirical model

Study area

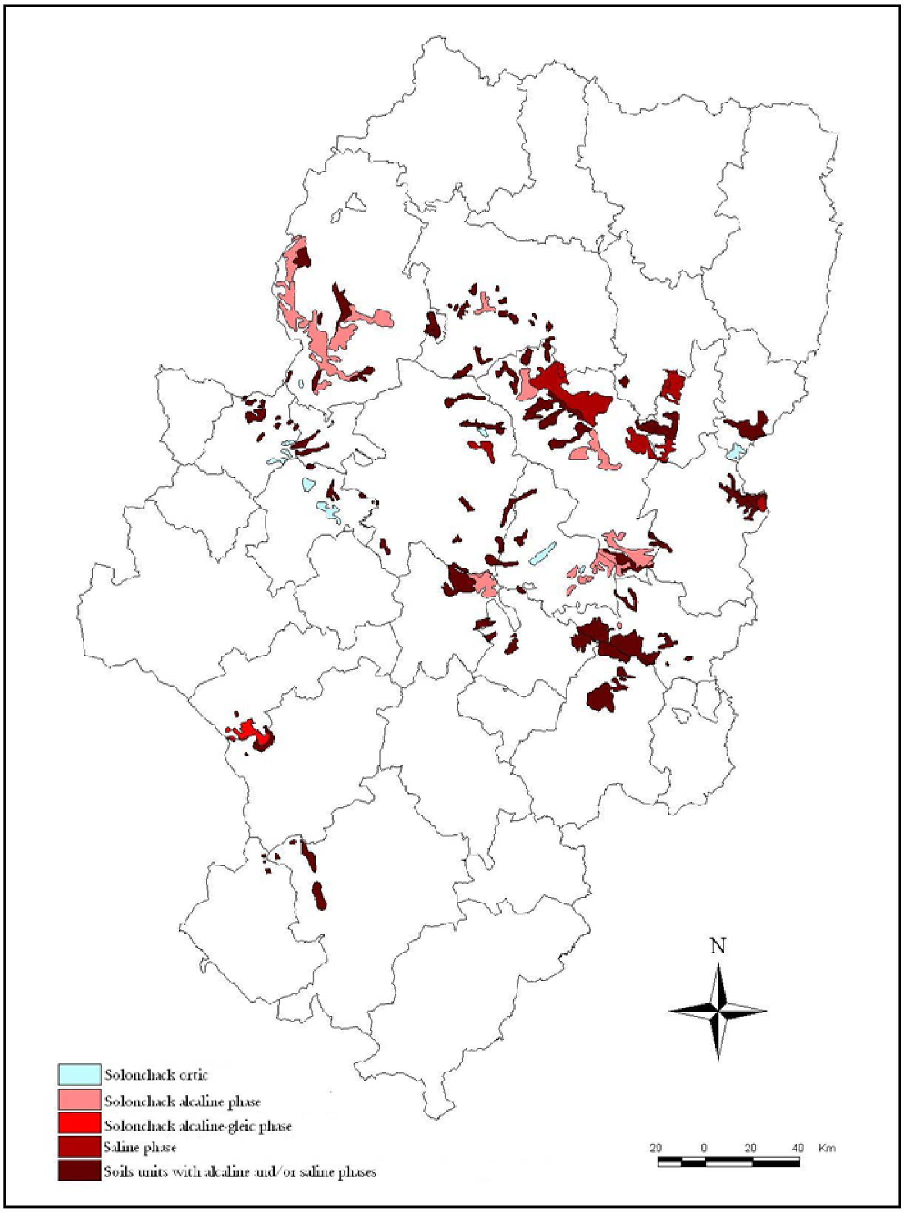
The empirical analysis is tested on the Flumen-Monegros area, which is a sub-basin of the Ebro river basin in Spain. The Flumen basin includes a total of 32 municipal districts. The basin covers 77,800 ha, part located in the Monegros irrigation district (35,300 ha) and part located in the Flumen irrigation district (32,500). The total acreage dedicated to irrigated agriculture is around 47,000 ha.

The area is characterized by a semi-arid climate with scarcity in precipitations, and irrigation is required for agricultural production. The most common irrigation technology in Flumen is flood covering around 30,000 ha, whereas sprinkler technology is used in around 17,000 ha.[4] Water resources in this area include the river Gállego, the Sotonera dam, and the Flumen and Monegros canals. The main crops are corn, alfalfa, wheat, and barley.[5] The acreage of corn is 13,000 ha, alfalfa covers 10,500 ha, wheat 7,000 ha, and barley 5,600 ha.

An important feature of the Flumen basin is the existence of salinity because of the geological formation of soils of the area. Mema (2005) has classified soils by their salinity levels. Figure 1 shows the distribution of salinity in the Flumen basin.[6] Approximately 13,800 ha of soils have serious problems of salinity, 13,000 ha have moderate saline soils, and 11,300 ha are non saline soils. The definition of each category of soils is given in Table 1.

[4] Drip irrigation is not considered because the use of this technology is marginal in the study area.
[5] Statistical data about crop acreage are available in Gobierno de Aragón (2007).
[6] Using information from Nogués et al. (1999) and Nogués (2000).

Figure 1. Salinity map of Aragon.



Source: Mema 2005.

Bioeconomic model

The heterogeneous farms are defined by combining the type of crop (corn, wheat, alfalfa, and barley), the irrigation system (flood and sprinkler), and the type of soil (saline, moderate, and non saline). Crop production functions are specified with different functional forms in the literature. The main functional forms are polynomial, Von Liebig, and Mitscherlich-Baule (Frank et al. 1990). The Von Liebig specification is consistent with the idea that crops respond linearly to the most limiting input, and this specification displays a zero elasticity of substitution among inputs and also a growth plateau beyond the application threshold. Under the Mitscherlich-Baule specification,

Table 1. Types of soil by saline level

Soil type	Electrical conductivity (CEe, dS/m)	Soil depth (ps, cm)
Saline soil	>8	120-80
Moderate saline soil	2-6	80-60
Non-saline soil	<2	60-40

there are substitution among inputs and a growth plateau beyond the input threshold. The problem with this specification is that there are problems of convergence in the estimation of parameters.

The polynomial functional form displays substitution among inputs and a maximum yield level, but does not have the property of a growth plateau. The properties and easy of estimation of the polynomial specification explain that it is the usual choice for crop production functions, in particular the quadratic specification. In this study, the crop production function is defined with a quadratic specification:

$$f_{cs}(x_i) = \alpha_{cs} + \beta_{cs} \cdot x_i + \delta_{cs} \cdot x_i^2 \quad (10)$$

where x_i is the water used by each farm i (where $i = 1, \dots, n$), the sub-indexes c and s indicate that the crop production parameters depend on the type of crop and irrigation system respectively. Table 2 shows the estimated parameters for the different crops.

The parameters of production functions have been calculated from previous estimations by Uku (2003). These estimation have been calculated with EPIC (Environment Policy Integrated Climate) a crop growth simulation package. EPIC simulates the relationships between crop growth and variables such as soil, weather, water use, nutrients and crop management. The model has been calibrated to represent

Table 2. Production functions by crop and irrigation technology

Flood				
Coefficient	Corn	Alfalfa	Wheat	Barley
α_{ci}	-5.64	-2.36	-1.42	-2.36
β_{ci}	$3.06 \cdot 10^{-3}$	$2.90 \cdot 10^{-3}$	$3.02 \cdot 10^{-3}$	$3.23 \cdot 10^{-3}$
δ_{ci}	$-1.42 \cdot 10^{-7}$	$-1.29 \cdot 10^{-7}$	$-3.20 \cdot 10^{-7}$	$-4.02 \cdot 10^{-7}$
Adjusted R^2	0,92	0,93	0,89	0,85
Sprinkler				
Coefficient	Corn	Alfalfa	Wheat	Barley
α_{ci}	-8	-0.52	1.9	0.31
β_{ci}	$5.14 \cdot 10^{-3}$	$4.09 \cdot 10^{-3}$	$2.73 \cdot 10^{-3}$	$2.97 \cdot 10^{-3}$
δ_{ci}	$-3.03 \cdot 10^{-7}$	$-2.56 \cdot 10^{-7}$	$-3.57 \cdot 10^{-7}$	$-4.61 \cdot 10^{-7}$
Adjusted R^2	0,97	0,90	0,81	0,80

the crop production functions in the study area. Additionally, the results of the estimations have been tested with surveys distributed to farmers and also by checking these results with field experiments. The production functions depend on the inputs water use and nitrogen. The parameters of the production functions have been re-estimated taking into account the results by Uku.

For each crop, the production functions are concave and depend only on the irrigation water input in a deterministic manner. Farmers are price takers, and their crop production activities generate an individual pollution at the source which is not observable. Therefore, control measures can only be based on the observable ambient pollution, which is the sum of the individual pollution loads. Farmers behave rationally between them, adapting their individual production in response to measures taken by the regulatory agency. The negative externality generated by the production activities of farmers is damaging the environment, but has no direct impact on farmers.

Salinity arises in water bodies because the leaching of saline substances from the soil and sub-soil; this leaching of salts is driven mostly by water returns from irrigated agriculture. Percolation is the filtering of water through the soil since part of the irrigation water is not taken by the plant and returns to the environment. This percolation goes through the salinity in the soils and is responsible of salinity into water bodies.

Percolation is defined as the product of irrigation water by one minus irrigation efficiency:

$$pe(x_i) = (1 - ef) \cdot x_i \qquad (11)$$

where x_i is the input water and ef is the efficiency of the irrigation system: 0.75 in sprinkle irrigation, and 0.55 in flood irrigation.

Under no regulation, farmers maximize their private profits without taking into account that their activities generate environmental damages, so farmers do not internalize the social costs of their activity. The problem for each individual crop in the farm without regulation can be stated as: $Max \;\; \pi_i = p_c \cdot (\alpha_{cs} + \beta_{cs} \cdot x_i + \delta_{cs} \cdot x_i^2) - p_x \cdot x_i + s_c - F_c$. The municipal district is considered the decision unit, and therefore the optimization problem is run for each municipal district. The results obtained from each municipal district are aggregated for the entire Flumen basin. The optimization problem without regulation is given:

$$Max \quad \Pi = \sum_{i=1}^{n}\sum_{c=1}^{k}\sum_{s=1}^{v}(p_c \cdot (\alpha_{cs} + \beta_{cs} \cdot x_i + \delta_{cs} \cdot x_i^2) - p_x \cdot x_i + s_c - F_c) \qquad (12)$$

where the index c indicates crop (with $c = 1, \dots, 4$) and the index s indicates irrigation system (with $s = 1, 2$). p_c is the price of the crop, p_x is the water price, s_c is the amount of subsidy, and F_c are fixed costs of production that depends on the type of crop.

The 'first-best' scenario is obtained when farmers internalize the environmental damage of their activity. Methodologically, the formulation of this problem consists in the maximization of farmers' private profits subject to not exceeding a threshold of percolation. Percolation is the polluting variable and the threshold is established by the regulator.

The optimization problem under regulation is given by:

$$\begin{aligned} Max \quad \Pi^{\mathrm{R}} = & \sum_{i=1}^{n_1}\sum_{c=1}^{k}\sum_{s=1}^{v}(p_c \cdot (\alpha_{cs} + \beta_{cs} \cdot x_i + \delta_{cs} \cdot x_i^2) - p_x \cdot x_i + s_c - F_c) \\ & + \sum_{j=1}^{n_2}\sum_{c=1}^{k}\sum_{s=1}^{v}(p_c \cdot \left(\alpha_{cs} + \beta_{cs} \cdot x_j + \delta_{cs} \cdot x_j^2\right) - p_x \cdot x_j + s_c - F_c) \\ & + \sum_{h=1}^{n_3}\sum_{c=1}^{k}\sum_{s=1}^{v}(p_c \cdot (\alpha_{cs} + \beta_{cs} \cdot x_h + \delta_{cs} \cdot x_h^2) - p_x \cdot x_h + s_c - F_c) \end{aligned}$$

$$\begin{aligned} s.t. \qquad & \sum_{i=1}^{n_1}(1 - ef) \cdot x_i \leq \overline{pe}_s \\ & \sum_{j=1}^{n_2}(1 - ef) \cdot x_j \leq \overline{pe}_m \\ & \sum_{h=1}^{n_3}(1 - ef) \cdot x_h \leq \overline{pe}_n \end{aligned} \qquad (13)$$

where ef_s is efficiency of sprinkler irrigation and ef_f is the efficiency of flood irrigation. $\overline{pe}_s$, $\overline{pe}_m$, and $\overline{pe}_n$ are the thresholds of percolation for saline, moderate saline and non saline soils respectively.[7] The sub-index i indicates farms with saline soil (where $i = 1, \dots, n_1$), the sub-index j shows farms with moderate saline soil (where

[7] These values of percolation are the total percolation for each type of soil (saline, moderate, and non saline). As indicated the optimization problem is run for every municipal district, which is considered the decision unit. The number of municipal districts in the Flumen basin that have been considered is 24. Thereafter, the solutions obtained by municipal districts are aggregated at basin level.

$j = 1, \dots, n_2$), and h are farms with non saline soils (with $h = 1, \dots, n_3$). n is the total number of farms considered, where $n = n_1 + n_2 + n_3$.

To decrease environmental damages, the amount of percolation over saline soils has been reduced by 35 percent with respect to the current situation without regulation (baseline). In the case of moderate saline soils with lower concentration of salts, the percolation has been reduced by 25 percent of the baseline. For non saline soils having low salt contents, the reduction in percolation is just 5 percent of the baseline. These reductions in percolation imply that the thresholds for the entire Flumen basin are: $\overline{pe}_s = 23.1$ Mm^3, $\overline{pe}_m = 25.8$ Mm^3, and $\overline{pe}_n = 28.1$ Mm^3. The shadow prices of percolation are the values of the Lagrangian multipliers from the first order conditions of problem 13. These shadow prices are $\lambda_s^* = 0.390$ €/m^3, $\lambda_m^* = 0.283$ €/m^3, and $\lambda_n^* = 0.057$€/m^3.

The thresholds for percolation have been defined based on information on salinity loads. Salinity loads are calculated using the Hoffman (1986) formula, modified by Quílez (1998). Quílez equation relates initial salinity in the soil with final salinity: $s = \left\{CE\left[CE \cdot \frac{cl}{\frac{(1-ef)\cdot x}{ps}+cl}\right]\right\} \cdot 640 \cdot 10^{-6} \cdot [(1-ef)\cdot x]$. Where s is salinity load, CE is final salt concentration in the soil, CE_0 is initial salt concentration in the soil, cl is leaching fraction, pr is percolation, and ps is soil depth. This equation is used to generate data on salinity loads from percolation. The cost of the environmental damages from salinity loads are approximated by the costs of extracting the salts from water. The costs of extracting salts from water are estimated at 0.05 €/kg.[8] This information is used to figure out the salinity load reductions in each type of soil. These percentages of reductions in percolation (35%, 25% and 5%) attain the desired reductions of salinity loads.[9] The percentages of reduction in percolation are used to define the thresholds of percolation by type of soil ($\overline{pe}_s, \overline{pe}_m$, and $\overline{pe}_n$), which are used in the optimization problem 13.

Following Kampas and White (2004), the costs of abatement are given by $C = \Pi - \Pi^R$. The social welfare is defined by the private profit of farm production activities

[8] Information provided by CIRCE (Center of Energy Research) that estimates this cost at around 0.036 €/kg, based on a cost of desalination of 0.030 €/m^3 and on salinity loads of 1.2 kg/m^3. This value of 0.036 €/kg has been increased to 0.050 €/kg as a result of increases in energy prices during recent years.

[9] Because percolation drives salinity, the percentages of reduction in percolation will achieve the desired reductions in salinity loads.

minus the environmental damage, $SW = \Pi - \lambda^* \cdot e$, where λ^* is the shadow price of pollution and e is pollution.

The parameters of output and input prices are: corn price 193 €/t, wheat price 223 €/t, alfalfa price 92 €/t, barley price 185 €/t, and water price 0.03 €/m^3 (Government of Aragon 2007). The fix costs are: corn 1,259 €/ha, wheat 930 €/ha, alfalfa 1,122 €/ha, and barley 900 €/ha. The subsidies are 100 €/ha corn, 60 €/ha wheat, 10 €/ha alfalfa, and 60 €/ha barley (MARM 2007).

Analysis of results

Several scenarios are run to compare the current situation or baseline, with regulatory scenarios to control pollution. The regulation scenarios are examined under two alternatives, considering or not considering the heterogeneity of farm soils. The scenarios present the results on private profits, water use, percolation and social welfare.

Under regulation considering the heterogeneous soils, the regulator sets three pollution thresholds, one for each type of soil, and the control measure is a different pollution tax for every soil. This non uniform pollution tax is the ‘first-best’ measure. Under regulation without considering the heterogeneous soils, the regulator sets up a unique pollution threshold disregarding soil types, and the control measure is a uniform pollution tax which is a ‘second-best’ measure. The baseline and regulation scenarios have been run with the GAMS optimization package, using the CONOPT solver.

The results are presented for the whole Flumen basin. The optimization problem is run for every municipal district, and the results are aggregated at basin level. The production activities include the four main crops in the area, the two irrigation technologies, and the three soil types.

Table 3 compares the results between the baseline scenario and the regulation under heterogeneity, which involve the ‘first-best’ pollution control measure. Under the baseline scenario, there is no regulation and farmers do not internalize the pollution damages of their production activities. Under the regulation with heterogeneity, farmers internalize the negative externality of their production activities and reduce their percolation to abide by the three pollution thresholds.[10]

[10] The reduction in percolation is 35 percent in farms with saline soils, 25 percent in farms with moderate saline soils, and 5 percent in farms with non saline soils.

Table 3. Results under no regulation and regulation with heterogeneous soils.

Baseline	
Water use (Mm^3)	502.6
Percolation (Mm^3)	99.5
Farmers private profits (million €)	31.9
Social welfare (million €)	24.5
Regulation with heterogeneity	
Water use (Mm^3)	411.7
Percolation (Mm^3)	77.0
Farmers private profits (million €)	28.2
Social welfare (million €)	27.7

Water use, percolation, and crop production are higher under no regulation, because farmers are not internalizing the pollution damages of their activities. The reduction in the water use between the baseline and the 'first-best' control policy is 91 Mm^3, with a fall of 22.5 Mm^3 in percolation. Private profits under the baseline are 31.90 million euros and they fall to 27.71 million euros under the 'first-best'. The increase in social welfare in the 'first-best' compared with the baseline is 3.09 million euros. This increase in the social welfare seems to justify the intervention of the basin authority in order to induce farmers to abate pollution.

The next step is to find if welfare differences between considering or not heterogeneity are large enough to justify the use of non-uniform instruments, instead of a uniform one. Table 4 presents the aggregated results for the whole Flumen basin when a unique threshold is implemented for all types of soils. The level of this unique threshold has been set first at 35 percent pollution reduction, and then at 25 and at 5 percent.[11] Table 4 shows the welfare impacts of choosing the particular unique pollution threshold. The better option is choosing a threshold that reduces percolation by 25 percent, because welfare is not too far from the first best welfare outcome of table 3.

The comparison of the three homogeneous thresholds shows that the worst option is the threshold reducing percolation by 35 percent, both in terms of social welfare and private profit of farmers. The reduction of 35 percent corresponds to farmers with saline soils and very high pollution emissions. If this high reduction is applied to every other type of soil, the inefficiencies of the policy measure become very important with significant welfare losses. The losses in welfare are not so high if the homogeneous threshold is a reduction of 5 percent, which corresponds to non saline soils.

[11] This exercise is a sensitivity analysis that shows the impact of choosing the unique threshold level.

Table 4. Results under regulation with homogeneity (3 uniform thresholds).

Threshold with 35 percent reduction for all farms	
Water use (hm^3)	358.6
Percolation (hm^3)	64.7
Farmers private profits (million €)	25.0
Social welfare (million €)	23.5
Threshold with 25 percent reduction for all farms	
Water use (hm^3)	401.1
Percolation (hm^3)	74.7
Farmers private profits (million €)	28.3
Social welfare (million €)	26.6
Threshold with 5 percent reduction for all farms.	
Water use (hm^3)	483.4
Percolation (hm^3)	94.6
Farmers private profits (million €)	31.7
Social welfare (million €)	25.6

These results demonstrate that when there are different damage pollution functions, and the authority ignores this heterogeneity and considers only a unique tax or threshold, the loss in social welfare can be very significant. Simplifying multiple damage pollution functions to only one function implies choosing a unique pollution tax rate or pollution threshold, and selection of this threshold by the regulation authority has important consequences in welfare terms.

There are considerable variation of social welfare by comparing the results of tables 3 and 4. A unique tax rate (or unique threshold policy) reduces quite significantly social welfare. By using the pollution tax rate of saline soils in the whole basin ($\lambda_s = 0.390$ or $\overline{pe}_s = 35$ %), social welfare decreases by 17 percent with respect to the 'first-best'. But comparing this with the social welfare under the baseline scenario, the results demonstrate that regulation in this case is worse than no regulation. When the unique tax rate chosen is the moderate saline soil rate ($\lambda_m = 0.283$ or $\overline{pe}_m = 25$ %), the loss of social welfare compared with the 'first-best' is 6 percent. In this case, the social welfare improves with respect to the baseline scenario of no regulation. By choosing the unique rate equal to that of non saline soils ($\lambda_n = 0.0057$ or $\overline{pe}_n = 5$ %), the loss in the social welfare with respect to the 'first-best' is 10 percent. Again, there is an improvement in the social welfare with respect to no regulation.

The tax payments under the different scenarios are shown in table 5. Under regulation with heterogeneity, farmers are interested in reducing pollution because their profits by abiding the pollution thresholds (28.2 million €) are above their profits by not

Table 5. Tax payments and farmers profits under the regulation scenarios (10^6 €).

Type of regulation	Complying	Not complying	
	Farmers Profits	Tax payments	Farmers profits
Heterogeneous with three thresholds	28.2	8.1	23.8
Homogeneous with 35% reduction	25.0	13.6	18.3
Homogeneous with 25% reduction	28.3	7.0	24.9
Homogeneous with 5% reduction	31.7	0.3	31.6

abiding the pollution thresholds (23.8).[12] Under regulation with homogeneity, farmers are also interested in reducing pollution because their profits by abiding the threshold (25.0 million € for 35%, 28.3 million € for 25%, 31,7 million € for 5%) are above their profits by not abiding the threshold (18.3 million € for 35%, 24.9 million € for 25%, 31.6 million € for 5%).[13] However, some farmers with highly profitable crops may have higher profits by not complying than by complying, and therefore they have incentives to have a 'free-rider' behavior than those farmers with less profitable crops. This question deserves further inquiry by using game theory.

The presence of high transaction and administrative costs, and also the information problem are factors that hinder the implementation of non-uniform instruments. But even though these factors call for uniform instruments, the social planner needs to weight carefully the tradeoff between getting accurate biophysical knowledge and designing simple policy instruments. The instrument can be simple, but policy failure is especially worrying when policy designers misunderstand the biophysical features, and choose any simple but wrong measure that is politically palatable for decision makers.

Conclusions

Nonpoint pollution from agriculture is a negative externality resulting into damages to natural ecosystems. These damages degrade the services provided by the environment and consequently reduce social welfare. An important objective of environmental policies is to correct and control the pollution problems by forcing agents to internalize the social damages they generate.

[12] Under regulation with heterogeneity, the tax payments of not complying are equal to the sum of the shadow price of percolation multiplied by the amount of percolation for each type of soil: $0.390 \cdot 12.45+0.283 \cdot 8.59+0.05 \cdot 1.48=8.13$.

[13] Under regulation with homogeneity, the tax payments of not complying are equal to the shadow price of percolation multiplied by the amount of percolation. For a 35% reduction the tax payments are $0.390 \cdot 34.83= 13.58$. For a 25% reduction the tax payments are $0.283 \cdot 24.88=7.04$. For a 5% reduction the tax payments are $0.057 \cdot 4.97=0.28$.

Agriculture is an important source of nonpoint pollution because of the large emission loads of nutrients and pesticides that are causing water quality degradation. The subsequent damages to natural ecosystems reduce environmental services and generate welfare losses. The main problem in addressing nonpoint pollution is the lack of information and knowledge about the responsible agents, the precise location of sources, and the amount of pollutants at the source. Ambient pollution is easily measurable, but the transport and fate processes linking source pollution and ambient pollution are mostly unknown.

This lack of information and knowledge leads to situations of asymmetric information where farmers can act strategically. The challenge for policy makers is to design appropriate measures that are able to elicit cooperation among farmers. The question of designing the appropriate incentives to achieve collective action by farmers is crucial, since farmers are the agents responsible for taking care of water resources.

Excessive irrigation levels in areas with salinity problems causes large salinity loads into rivers, which causes damages in aquatic ecosystems and other agents. The theoretical approach is tested in the Flumen basin (Northeastern Spain), using an empirical model that combines heterogeneous farms, with different soils, crops, and irrigation technologies.

The main contribution of the paper is that when there are different pollution damage functions, heterogeneous pollution thresholds or pollution tax rates have to be implemented in order to avoid welfare losses. The optimal percolation level is not the same for all farms, and depends on the location, since pollution damages are quite different by soil class.

The finding is illustrated empirically by defining three pollution thresholds for three types of soils: saline, moderate saline, and non saline. Different scenarios are run analyzing the cases of no regulation, regulation with heterogeneous measures, and regulation with homogeneous measures. The empirical results confirm that under different pollution damage functions, the implementation of a uniform threshold or tax rate to all farms generates policy inefficiencies. The model shows that in some situations, and depending on the uniform threshold or tax rate chosen, the inefficiencies can be so large that the absence of regulation would be preferable to a homogeneous policy that ignores biophysical processes.

The presence of high transaction costs or information problems are factors that hinder the implementation of non-uniform instruments. But even though these factors call for uniform instruments, the social planner needs to weight carefully the tradeoff between getting accurate biophysical knowledge and designing simple policy instruments. The instrument can be simple, but policy cannot ignore the existence of heterogeneity between agents in order to design efficient measures.

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