Policy for the Adoption of New Environmental Monitoring Technologies to Manage Stock Externalities*

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Abstract

With the development of modern information technologies, relying on nanotechnologies and remote sensing, a number of systems can be envisaged that allow for monitoring of the negative externalities generated by producers, consumers or travelers – road pricing schemes or individual emission meters for automobiles are two examples. In the paper, we analyze a dynamic model of stock pollution when the regulator has incomplete information on emissions generated by heterogeneous agents. The paper's contribution is to explicitly study a decentralized policy for adoption of monitoring equipment over time. We determine the second-best tax rates, the pattern of monitoring technology adoption, and identify conditions for the voluntary diffusion of monitoring technologies over time. Simulations show the welfare gains compared to alternative policies.

Keywords: externalities, environmental taxation, monitoring technology adoption, diffusion, nanotechnologies, stock pollution

JEL codes: D62, H23, L51, O33, Q58

1. Introduction

Some of the major environmental problems of our time are stock externality problems, including contamination of water bodies by accumulating salt and chemicals, climate change, other air pollution problems where accumulating pollutants damage health or property, deforestation and loss of biodiversity. Frequently, the activities contributing to these problems cannot easily be attributed to individual agents, which is a challenge to policy making. However, applications of new technologies including computers and the internet, wireless telephony, remote sensing, and geographic information systems, enable the introduction of increased numbers of monitoring systems to identify externality sources. In some cases, e.g., road pricing in Singapore, we already see instantaneous monitoring of road use that generate negative externalities (congestion and air pollution). The new technologies may require large investment in infrastructure, as well as in individual units of equipment. While in some cases, individual agents may need to invest in new technologies, in others they may rent environmental monitoring equipment,[1] and in other situations polluters may subscribe to third-party monitoring services.

The paper aims to analyze policies leading to the adoption of new monitoring technologies over time to control stock externalities. The analysis centers on individual agents' incentives to adopt monitoring technology, their changing behavior over time, and the trade-off between a decentralized policy and a policy consisting of mandatory monitoring. The paper's contribution is to identify an optimal decentralized policy for inducing the adoption of pollution monitoring technology and to analyze the time paths of the adoption process and of key economic and environmental variables. The principle behind this optimal policy when monitoring is feasible but costly is that each agent is assumed "Guilty until Proven Innocent"

[1] For example, companies such as Enviro-Equipment, Inc (http://www.enviroequipment.com/), Ashtead technology (http://www.ashtead-technology.com/us/), Satellite Imaging Corporation (http://www.satimagingcorp.com/services.html) and Fondriest Environmental (http://www.fondriest.com) rent either environmental monitoring equipment or monitoring services for various applications.

as proposed by Swierzbinski (1994). Specifically agents are required to pay the maximum pollution fee, and it is up to them to prove that they are entitled to a refund. Several existing or proposed regulations of pollution or damages are based on this principle. For example, the California Department of Pesticide Regulation establishes default inhalation rates for children and adults for assessing the exposure rates to chemicals and those are imposed in cases when the applicator cannot provide her own assessments. The regulation order for the California Low Carbon Fuel Standard Regulation states that the carbon content of fuels will be verified at the user's expense for every fuel category, otherwise a "conservative" default value is assumed.[2]

The scheme that we propose for delegation of monitoring adoption has potentially important applications since it results in diffusion of monitoring technology over time through voluntary adoption of the new technology. One potentially relevant application is the use of smart dust in monitoring and tracing pollution to its source (Warneke et al., 2001; Sailor and Link, 2005). Identity preservation is becoming part of current food safety policies that rely on the tracing of a faulty product towards its origin (source), and identity preservation through the tagging of molecules of dirty inputs can now be envisaged using nanotechnologies. Identity preservation applied to polluting inputs such as pesticides and chemical fertilizers would enable the regulator to trace the source of pollution in case of environmental degradation and will have interesting applications for water quality policy.

The paper relates to several bodies of literature: the literature on threshold models of technology adoption, the literature on stock externalities and the literature on pollution regulation with costly information. The threshold model of technology adoption was first introduced by David (1969) to provide a stronger micro-economic foundation to the Griliches (1957) model; it assumes that agents are heterogeneous (for example in size) and that profit

[2] The California Low Carbon Fuel Standard Program, Section 95486, accessed at http://www.arb.ca.gov/regact/2009/lcfs09/lcfscombofinal.pdf.

maximization implies a threshold in the quality parameter, after which it becomes profitable for the individual agent to adopt. Technology diffusion over time will then depend on the distribution and dynamics of the characteristic that determines heterogeneity among adopters (Stoneman, 1983; Sunding and Zilberman, 2001). Here we use a threshold model to study the diffusion of new monitoring technology for stock externalities. Major environmental problems, such as climate change, water pollution, soil erosion and buildup of pesticides resistance are frequently stock externality problems (Farzin, 1996), and moreover they are usually caused by heterogeneous sources (Hoel and Karp, 2002; Xepapadeas, 1992). Thus, for an efficient design of policies to control stock externalities both time and heterogeneity dimensions of these problems should be considered (Xabadia, Goetz and Zilberman, 2006). The buildup of the pollution stock can be modified through changes in production practices, by reducing input use, by decreasing the number of agents that operate in the economy, and through adoption of modern conservation or precision technologies that enhance input use efficiency (Khanna and Zilberman, 1997).

The last body of research that we contribute to is the literature on pollution regulation with costly information. Many of today's most important pollution problems are plagued by costly information on individual emissions. Examples include traffic emissions and agricultural runoff into water, such as nitrogen or pesticide leaching from fields. Carbon emissions from stoves and burners are another example. The diffuse pollution from many small sources whose individual emissions are unobservable constitutes a nonpoint source pollution problem. Following Holmstrom (1982), the first-best solution is a tax equal to the full social marginal cost on each polluter (Segerson, 1988; Xepapadeas, 1991; Herriges, Govindasamy and Shogren, 1994; Laffont, 1994; Hansen, 1998). In some cases, it can be difficult to do so, in particular when polluters do not realize their impact on the aggregate measure of pollution (Cabe and Herriges, 1992), or when the regulator cannot be certain about the level of cooperation within the group (Millock and Salanié, 2005). Investing resources in improving the monitoring of individual emissions may thus be worthwhile. Xepapadeas (1995) showed how risk-averse polluters may prefer to pay an emissions tax rather than a variable ambient tax. Millock, Sunding and Zilberman (2002) proposed discriminatory treatment for agents who invest in monitoring equipment and pay a tax proportional to the pollution they generate, while others will pay a fixed tax. Thus, the definition of nonpoint source pollution is not fixed but will evolve as the social cost of pollution changes.

The first papers to study the dynamics of investment in monitoring have focused on the regulator's centralized decision of investment in her stock of knowledge about the pollution process (Xepapadeas, 1995; Dinar and Xepapadeas, 1998, 2002; Farzin and Kaplan, 2004). Dinar and Xepapadeas (2002) develop a model of the regulator's information acquisition for regulating groundwater in irrigated agriculture. Monitoring is treated as the regulator's stock of knowledge (information), which can be added to by investments in geographical information systems (GIS), or study of the soil conditions in the region and other factors that affect transport and fate. There is thus no individual decision to adopt a monitoring technology at each individual source. The model shows theoretically and empirically (Dinar and Xepapadeas, 1998) that it is more efficient to direct resources to investment in knowledge capital about the emissions process than try to monitor input use in order to levy input taxes as a proxy to pollution taxes. Farzin and Kaplan (2004) also model monitoring as an effort on behalf of the regulator to improve a stock of knowledge capital, including knowledge of pollution transport and fate. They analyze the problem of a private or public manager that must target abatement resources in a National Park area with a fixed budget, and where the sediment load (pollution) is a function of unknown site-characteristics. Their simulations confirm that information acquisition improves the budget allocation of the National Park Manager and hence reduces expected damage compared with the case of an ex ante, uniform prior distribution of abatement effort. While these papers study monitoring as a public investment problem, we model monitoring in a micro adoption model. This paper thus adds a crucial element by recognizing that polluters are participants in the monitoring effort.

The basic model is presented in Section 2 below. Section 3 presents the policy benchmarks of no monitoring or mandatory monitoring. In Section 4 we analyze the proposed decentralized policy for monitoring diffusion over time, and give conditions for monitoring diffusion over time. Section 5 presents simulation results on the welfare gains from decentralized monitoring compared to alternative policies. The last Section concludes.

2. The Model

We model a large number of agents that are heterogeneous with regard to a quality parameter θ. The parameter θ should be interpreted as a characteristic that affects profitability, but is unobservable to the regulator, such as managerial ability, site-specific ecological conditions or properties of physical capital (good insulation). To keep the model simple, we assume that quality is fixed and does not change over time. The regulator knows the overall distribution of quality, which is defined on a support $\left[\underline{\theta},\overline{\theta}\right]$, with a known continuous probability density function *g(θ)* and distribution function *G(θ)*. The quality parameter θ combined with input use determines output of each agent. Profits are represented by a reduced form notation where pollution (*z*) is viewed as an input to production, and profits net of input costs are denoted by $\pi(z,\theta)$. The profit function $\pi(z,\theta)$ is assumed twice differentiable, increasing and concave in pollution and the efficiency parameter.[3] There are 2 different cases for $\frac{\partial^2 \pi}{\partial z \partial \theta}$. Either quality increases the marginal profitability of the polluting input

[3] We assume agents share a common production function (as well as pollution function) and that output differs only because of differences in quality and use of inputs. Later on, we will introduce an index *i* to indicate the difference in pollution when a firm is monitored or not.

and $\frac{\partial^2 \pi}{\partial z \partial \theta} > 0$, or increased quality implies reduced marginal profitability of the polluting input and $\frac{\partial^2 \pi}{\partial z \partial \theta} < 0$. We will assume that high quality agents utilize pollution efficiently and that small amounts of pollution yield them most of the profits. This may be a result of precision in input use and higher accuracy or better conservation efforts. We assume that at low levels of pollution $\frac{\partial^2 \pi}{\partial z \partial \theta} > 0$ and that the marginal profitability of pollution increases with quality. But, at a certain level of pollution, z_c, the marginal profitability of low quality agents is equal to that of high quality agents, and from that point onwards $\frac{\partial^2 \pi}{\partial z \partial \theta} < 0$. Figure 1 illustrates this assumption. One implication is that when $\frac{\partial \pi}{\partial z} = 0$, lower quality agents use more pollution. In Figure 1 it is assumed that the equilibrium occurs at $z > z_c$, implying that $\frac{\partial^2 \pi}{\partial z \partial \theta} < 0$. This applies for example when the quality parameter measures input use efficiency and pollution is created from unused residues from production; this is the case of modern irrigation technologies that imply less water run-off and hence pollution from the field, or energy efficient technologies that reduce airborne pollutants from energy use.

FIGURE 1 ABOUT HERE

Pollution is a function of quality: $z = z(\theta)$. Let $\delta_1(\theta, t)$ denote the share of agents who at time *t* are in business and adopt the monitoring technology, and $\delta_0(\theta, t)$ the share of agents that at time *t* operate but do not adopt monitoring. We assume that $0 \le \delta_i(\theta, t) \le 1$ for $i = 0,1$, i.e., the share of agents who operate and are not being monitored and the ones who operate and are being monitored must be between zero and one. Moreover, the following condition has to hold at each time t:

$$\sum_{1=0,1} \delta_i(\theta,t) \le 1 \quad \forall t . \tag{1}$$

These definitions also suggest that the share of agents of quality θ that are not producing at time t is $1-\delta_0(\theta,t)-\delta_1(\theta,t)$.

We can now define pollution at time t as a function of quality and whether an agent is monitored or not: $z_i=z_i(\theta,t)$. Using the preceding definitions, gross aggregate profits (excluding monitoring costs) and aggregate pollution at time t are defined as:

$$\Pi(t) = \int_{\underline{\theta}}^{\overline{\theta}} \left(\sum_{i=0,1} \delta_i(\theta,t)\pi(z_i(\theta,t),\theta) \right) g(\theta)d\theta \tag{2}$$

$$Z(t) = \int_{\underline{\theta}}^{\overline{\theta}} \left(\sum_{i=0,1} \delta_i(\theta,t)z_i(\theta,t) \right) g(\theta)d\theta \tag{3}$$

The linearity in δ of the optimization problems analyzed in this paper leads to corner solutions for almost all θ. That is, there is a range of θs where no one will operate ($\delta_i(\theta,t)=0$ for $i=0,1$), another range of operation and complete adoption of monitoring, $\delta_0(\theta,t)=0$ and $\delta_1(\theta,t)=1$, and a third range where agents operate without adopting a monitoring technology, $\delta_0(\theta,t)=1$ and $\delta_1(\theta,t)=0$. We will investigate the properties of θs where there is a switch from one regime to another.

Each agent pays a fixed annual unitary cost for monitoring, denoted v_i, with $v_0=0$ and $v_1=v$. It is assumed equal for all monitored agents, since it represents a cost connected with the technology of tagging the pollution and not the individual agent. One example is transponder technology in road traffic control. The annualized cost can also be interpreted as a fee for a certification agency.[4] The aggregate monitoring technology cost borne by the agents is:

$$V(t) = \int_{\underline{\theta}}^{\overline{\theta}} \left(\sum_{i=0,1} \delta_i(\theta,t) v_i \right) g(\theta) d\theta \tag{4}$$

The pollutant accumulates over time with emissions *Z(t)*, less the natural rate of decay, *α*, here assumed to be a simple linear function of the stock, *S(t)*:

$$\dot{S}(t) = Z(t) - \alpha S(t) = \int_{\underline{\theta}}^{\overline{\theta}} \left(\sum_{i=0,1} \delta_i(\theta,t) z_i(\theta,t) \right) g(\theta) d\theta - \alpha S(t) \tag{5}$$

Finally, the social cost of the stock of pollution at time *t* is an increasing convex function *C(S(t))*. Although the regulator cannot observe individual emissions, we make the standard assumption of the nonpoint source literature that she can observe aggregate emissions without cost and measure social damage costs.

3. Policy Options

Since monitoring each firm in every time period is costly ($v > 0$), it may not be optimal to monitor all sources of pollution. Let us present the two benchmarks that we use to represent the two extreme cases of assumptions. When agents can be monitored, the regulator can levy a charge on each unit of pollution; but when monitoring is not available only fixed fees are possible that do not depend on the agent's pollution, nor type.

3.1. The case of a franchise fee

[4] Third-party disclosure is one alternative to individual disclosure or mandatory disclosure as discussed in the review by Dranove and Jin (2010).

In the case when monitoring technologies are not available or their cost is prohibitive, it is not possible to observe the agent's emissions and only fixed fees are possible.[5] When an agent of quality θ faces a fixed fee (franchise fee), he solves the following problem:

$$\underset{z_0}{Max} \quad \pi(z_0(\theta,t),\theta) - F(t) \text{ s.t. } z_0 \geq 0 .$$

For every θ, either $z_0^*(\theta,t)$ solves $\dfrac{\partial \pi\left(z_0(\theta,t),\theta\right)}{\partial z} = 0$ or $z_0^*(\theta,t) = 0$.[6] This equation reflects the behavior of agents that cannot be observed individually. In this case, agents will produce at the private profit maximizing level as long as profits are positive.

The solution of the private problem leads to a level of quality $\theta_0(F)$ such that agents with $\theta \geq \theta_0(F)$ will operate, while all the agents with $\theta < \theta_0(F)$ do not operate, since profits increase with quality. The pollution level of an agent varies with quality, and we can derive the following result on the impact of θ on pollution:

$$\frac{dz^*}{d\theta} = \frac{-\dfrac{\partial^2 \pi}{\partial z \partial \theta}}{\dfrac{\partial^2 \pi}{\partial z^2}} < 0 \ (> 0) \qquad \text{iff} \qquad \frac{\partial^2 \pi}{\partial z \partial \theta} < 0 \ (> 0).$$

The condition for a negative relation between pollution and quality holds when pollution originates from residues of production, and when quality is an indicator of input-use efficiency. In the opposite case, agents with low production efficiency also have low pollution, whereas agents with high production efficiency also have high pollution. Such a case is also feasible; we have analyzed it as well, and the results presented below hold, but the

[5] We study the extreme case when only a fixed fee is possible. Extensions of the model may include alternative regulatory measures depending on the information available to the regulator in the initial situation: input taxes (if input use is observable at no cost) or best management practices (if technology or practices are observable at no cost). In all cases, the policy instrument will be a second-best one, imperfectly correlated with the variable of interest, in this case pollution.

[6] This condition reflects the fact that the agent will choose not to operate if $\pi(z_0(\theta,t),\theta) - F(t) < 0$. For simplicity and to save space we do not explicitly include this profitability constraint but obviously production is only relevant when it is profitable. The problems in section 3.2 and 4 also follow the usual convention on the extensive margin.

adoption pattern is reversed. For space reasons, from now on we focus on the case where pollution and the quality parameter are negatively correlated.

3.2. The mandatory monitoring solution

When monitoring technology is available, the most common policy has been the imposition of monitoring on all sources of pollution and that will be our benchmark here. Then, the social planner has full information on each agent's pollution, and the nonpoint problem converts to a point source pollution problem where Pigouvian taxes can be levied.

Thus, the problem of the agents is given by:

$$\underset{z_1}{Max} \quad \pi(z_1(\theta,t),\theta) - \tau(t)z_1(\theta,t) - v \text{ subject to } z_1 \geq 0 .$$

Therefore, each agent chooses a level of pollution $z_1^*(\theta,t)$ that fulfills $\dfrac{\partial \pi(z_1^*(\theta,t),\theta)}{\partial z} = \tau$, or $z_1^*(\theta,t) = 0$ when $\pi(z_1(\theta,t),\theta) - \tau(t)z_1(\theta,t) - v < 0$. As in the former case, we can compute an exit level of quality $\theta_1(\tau)$ that will determine which agents will operate in the economy. Like in the case of a franchise fee, the net social rents and the pollution of an agent vary with quality. Net social rents, defined as $\pi(z_1(\theta,t),\theta) - v - \tau z_1(\theta,t)$, are non-decreasing in quality:

$$\frac{\partial \pi_i^*}{\partial \theta} = \frac{\partial \pi_i^*}{\partial \theta} + \frac{\partial \pi_i^*}{\partial z_i}\frac{\partial z_i}{\partial \theta} - \tau \frac{\partial z_i}{\partial \theta} = \frac{\partial \pi_i^*}{\partial \theta} > 0$$

Since production profits increase and pollution decreases with quality, social net rents are strictly increasing in quality. It can easily be shown, for an operating agent, that $z_1^*(\theta,t) \leq z_0^*(\theta,t)$, since Pigouvian taxes affect the intensive margin, in addition to the extensive margin.

4. Decentralized Policy for Monitoring Diffusion over Time

This section presents a decentralized policy for adoption of monitoring equipment over time. The aim is to study the diffusion of monitoring technologies once the investment in the infrastructure has taken place. We propose to analyse a simple scheme consisting of a fixed fee F_0 on agents that are not monitored and an emission tax τ for monitored agents combined with a fixed payment F_1, which is a tax when F_1 is positive and a subsidy when F_1 is negative. It is a simple linear taxation scheme as in Millock, Sunding and Zilberman (2002). Polluters are assumed guilty until proven innocent (as in Swierzbinski, 1994), i.e., they pay a fixed fee unless they install monitoring equipment to prove their actual pollution.

In each period, the individual agent takes the regulatory instruments $F_0(t)$, $F_1(t)$ and $\tau(t)$ as given and solves the following problem:

$$Max \quad \{\pi(z_0(\theta,t),\theta) - F_0(t), \pi(z_1(\theta,t),\theta) - \tau(t)z_1(\theta,t) - F_1(t) - v\}.$$

For a given θ, the agent chooses to rent monitoring equipment ($\delta_1(\theta,t) = 1$) iff

$$\pi(z_1(\theta,t),\theta) - \pi(z_0(\theta,t),\theta) - \tau(t)z_1(\theta,t) - F_1(t) + F_0(t) - v \geq 0.$$

Define the critical level θ_c by the level of quality for which an agent is just indifferent between renting monitoring equipment or not:

$$\pi(z_1(\theta_c,t),\theta_c) - \pi(z_0(\theta_c,t),\theta_c) - \tau(t)z_1(\theta_c,t) - F_1(t) + F_0(t) - v = 0 \quad \forall t \tag{6}$$

The following comparative statics describe the impact of the policy instruments on the critical level for adoption of monitoring:

$$\frac{\partial \theta_c}{\partial F_0} = -\frac{1}{\left(\dfrac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c} - \dfrac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c}\right)} < 0 \tag{7}$$

$$\frac{\partial \theta_c}{\partial F_1} = \frac{1}{\left(\dfrac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c} - \dfrac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c}\right)} > 0 \tag{8}$$

$$\frac{\partial \theta_c}{\partial \tau} = \frac{z_1(\theta_c, t)}{\left(\frac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c} - \frac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c}\right)} > 0 \tag{9}$$

iff $\frac{\partial^2 \pi}{\partial z \partial \theta} < 0$. Under this assumption the marginal profitability from pollution decreases with quality, and thus lower quality agents are more likely to gain from extra pollution and less likely to adopt monitoring. In this case, a reduction of the fixed tax for not monitoring (F_0) or an increase in the fixed or variable tax on monitored agents will reduce adoption and thus increase the critical level of quality θ_c that defines the lower bound for agents that adopt monitoring. If the opposite assumption holds, different sets of agents would be monitored or not monitored, since the first adopting agent would be the one with the lowest productive efficiency (that also has the lowest pollution). We stick to the stated assumption here because it has a nice interpretation, and limited space precludes us from presenting the two cases here.[7]

The regulator's problem is:

$$\underset{F_0(t),F_1(t),\tau(t)}{Max} \int_0^{\infty} e^{-rt} \left(\int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} \pi(z_0(\theta,t),\theta)\, dG(\theta) + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} \pi(z_1(\theta,t),\theta)\, dG(\theta) - V - C(S(t)) \right) dt$$

s.t. $\dot{S}(t) = \int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} z_0(\theta,t)\, dG(\theta) + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} z_1(\theta,t)\, dG(\theta) - \alpha S$, $S(0) = S_0$

Following Xabadia, Goetz and Zilberman (2006), we will use a two-stage procedure to solve the problem. First, the regulator will choose the optimal allocation of emissions over quality, θ, given an aggregate level of pollution *Z*. Next, he will optimize the value of *Z* over time.

In the first stage, the regulator's solution is given by the value function *J(Z)* defined as

[7] Xabadia, Goetz and Zilberman (2006) analyze two cases with different splits of agents.

$$J(Z) = \underset{F_0,F_1,\tau}{Max} \int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} \pi(z_0(\theta),\theta)\,dG(\theta) + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} \{\pi(z_1(\theta),\theta) - v\}\,dG(\theta)$$

s.t. $$\int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} z_0(\theta)\,dG(\theta) + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} z_1(\theta)\,dG(\theta) = Z\,.$$

Since Z does not depend on quality (θ) the shadow cost of the pre-specified level of emissions (λ) is constant over θ. Moreover, both the profit function and the constraint are concave in z for each quality. Thus, the necessary conditions are also sufficient, and the value function is concave in Z (see de la Fuente, 2000, p.297). The optimal level of monitoring adoption can be attained by the policy described in the following proposition.

Proposition 1: Given aggregate pollution Z, optimal adoption over quality can be obtained with the combination of the following instruments:

A fixed fee on non-monitored agents: $F_0 = \lambda z_0(\theta_0)$

A fixed fee on monitored agents: $F_1 = \lambda\left(z_0(\theta_0) - z_0(\theta_c)\right)$

A unit emission tax on monitored agents: $\tau = \lambda$.

Proof: In appendix.

This policy scheme can be interpreted as a fixed fee on all agents $F_0 = \lambda z_0(\theta_0)$, and a subsidy $F_1 = -\lambda z_0(\theta_c)$ on agents that decide to adopt monitoring. The monitored agents also pay a unit emission tax which is equal to the shadow cost of emissions. In this way, monitored agents are taxed according to the pollution they generate, but subsidized for part of the overestimate of pollution before the installation of the monitoring system.

In the second stage, the value function *J(Z)* from the first stage is maximized over time:

$$\underset{Z(t)}{Max}\int_0^\infty \{J(Z(t)) - C(S(t))\} e^{-rt} dt$$

s.t. $\dot{S}(t) = Z(t) - \alpha S(t)$, $S(0) = S_0$, $Z(t) \geq 0$.

The parameter denoting aggregate emissions over the entire range of θ now becomes the decision variable in the second stage. The current value Hamiltonian of the second stage is defined as:

$$H = J(Z(t)) - C(S(t)) - \gamma(Z(t) - \alpha S(t))$$

where γ denotes the costate variable. It has been multiplied by minus one to facilitate the interpretations. The first-order conditions for an interior solution are:

$$\frac{\partial H}{\partial Z} \equiv \frac{\partial J}{\partial Z} - \gamma = 0 \tag{10}$$

$$\frac{\partial H}{\partial S} \equiv \gamma\alpha - \frac{\partial C(S(t))}{\partial S} = \dot{\gamma} - r\gamma \tag{11}$$

$$\dot{S} = Z - \alpha S, \; S(0) = S_0 \tag{12}$$

Equation (10) states that the marginal value of aggregate emissions should equal the temporal shadow cost of the pollution stock γ. By the Envelope Theorem, a change in the value function as a result of a change in aggregate pollution *Z* is equal to *λ*. From (10), we then see that the shadow values of aggregate pollution in the first and second stages of the optimization are identical, i.e., $\lambda = \gamma$. Equation (11) explains the variation in the shadow cost of a delayed reduction of a marginal unit of the pollution stock from period *t* to period *t+1*. It establishes that the change is equal to the extra discounting and "decay" forgone paid on the shadow cost, $(\alpha + r)\gamma$, minus the social cost of the extra pollution associated with the delay $\partial C / \partial S$.

The incentives for adoption of monitoring equipment over time can be summarized in the following proposition:

Proposition 2: The steady state equilibrium point of the system of equations (11) and (12) is characterized by a local saddle point, where the stable path leading to the steady state is upward sloping. Therefore, the pollution stock, *S*, and its shadow cost, γ, evolve over time in the same direction. Aggregate pollution (*Z)* varies negatively with respect to the shadow cost. Given that the initial pollution stock, S_0, is greater (smaller) than the steady-state stock of pollution, S^∞, the optimal decentralized policy for monitoring diffusion over time consists of:

a) choosing the unit emissions tax, τ, above (below) its steady-state value and gradually decreasing (increasing) the tax over time till reaching the steady state.

b) choosing the fixed fee, F_0, above (below) its steady-state value and gradually decreasing (increasing) it over time till the steady state is reached.

c) choosing the subsidy $|F_1|$, below (above) its steady-state value and gradually increasing (decreasing) it over time towards the steady state value, i.e., $\frac{\partial F_1}{\partial Z} < 0$, iff

$$1 < \frac{\tau \left| \frac{\partial z_0}{\partial \theta_c} \right|}{\frac{\partial \pi(z_1)}{\partial \theta_c} - \frac{\partial \pi(z_0)}{\partial \theta_c}} < \frac{z_0}{z_1}.$$

Corollary: When $S_0 > S^\infty$, there will be diffusion of monitoring equipment over time, that is, $\dot{\theta}_c < 0$, if $\tau \left| \frac{\partial z_0(\theta_c)}{\partial \theta_c} \right| > \left(\frac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c} - \frac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c} \right)$. When $S_0 < S^\infty$, the opposite inequality should hold for adoption to occur.

Proof: In appendix.

The Corollary determines the dynamics of the critical quality ($\dot{\theta}_c$) that defines the adoption of monitoring over time. Since the decision on monitoring depends on both the evolution of the emission tax and the fixed fees, we define two scenarios:

A) The new externality case, where $S_0 < S^\infty$: $\dot{\tau} > 0$

B) The restoration case, where $S_0 > S^\infty$: $\dot{\tau} < 0$

In Case A, that we label the new externality case, there is early awareness of pollution and as pollution grows towards its steady-state level, the shadow cost of pollution increases over time causing aggregate emissions in each time period to decrease to allow the stock of pollution to reach its steady-state value. Aggregate emissions can be modified either by changing the proportion of monitored agents, as indicated by θ_c, or by changing the external margin, that is, by changing the number of agents that operate. As shown in the appendix, $\frac{\partial F_0}{\partial Z} < 0$, and therefore the optimal fixed fee increases over time causing the number of polluting agents to decrease until the steady state is reached. Moreover, since the shadow cost of pollution grows over time, the unit emissions tax also increases over time. In this way, the intensive and extensive margins can be considered as complementary. The direct effect of the increasing emission tax discourages monitoring adoption. On the other hand, the subsidy given to monitored agents, F_1, may increase or decrease over time and therefore, the diffusion of monitoring depends on the sign of $\tau\left|\frac{\partial z_0(\theta_c)}{\partial \theta_c}\right| - \left(\frac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c} - \frac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c}\right)$. If the marginal gain in profitability from the reduction in pollution brought about by adopting monitoring exceeds the marginal change in the pollution tax payment, then there will be full diffusion of monitoring over time. For the condition of the corollary to hold, the subsidy, F_1, needs to be increasing over time. The reason resides in the fact that both the optimal unit emissions tax and the fixed fee increase over time and therefore, the subsidy must increase to encourage monitoring adoption.

In the restoration case (Case B), when monitoring has not been implemented or was not feasible to start with because of the costs of mandatory monitoring, the regulator may implement the second-best policy defined in Proposition 2. As pollution is reduced towards its optimal steady-state level, the shadow cost of pollution decreases over time, hence initial policy needs to be harsh to reduce sufficiently the aggregate emissions, and it softens till the steady-state is reached. In this case, $\dot{\tau} < 0$ and the reduction of the pollution tax encourages more agents to adopt monitoring equipment over time. The initial fixed fee F_0 needs also to be high to deter the more polluting agents and it decreases over time as the pollution problem diminishes. The final impact on adoption will depend, as before, on the evolution of the subsidy. We know that the evolution of the emission tax encourages monitoring adoption in this case, but that the evolution over time of the fixed fee has a discouraging effect on adoption. In the end, the condition for diffusion, stated in the Corollary of Proposition 2, implies that the marginal gain in the variable tax payment has to exceed the marginal change in profitability from the reduction in pollution caused by adoption of monitoring.

The model relies upon two important assumptions – reversible investment in monitoring and that the regulator cannot exploit information in previous time periods to regulate individual agents in the current time period. The first assumption simplifies the model but it is also justified for cases where firms rent equipment or monitoring services, because of the nature of technologies like remote sensing and the emergence of institutions like third-party certification services. The way we model the monitoring investment decision is that the agents can choose whether to rent monitoring equipment or not in each time period. This implicitly means assuming that the regulator does not retain information on agents' quality. Although representing an extreme case, the assumption is not unreasonable. While it is plausible that government may collect information on agents' past behavior to provide a base for future assessment of their pollution choices, such a prejudicial approach may be constrained legally or very costly. Furthermore our model can apply to the case where the population may change over time, and even individual agents' parameters may change, but the overall distribution of quality may be constant over time. Income taxes, for example, require new reporting every year and rely little on past actions to justify present decisions. We can assume that the regulator has the analytical capacity and good sampling techniques that allow her to calculate sophisticated tax formulas, but that both monitoring and memory of individual behavior are costly.

5. Welfare gains from decentralized monitoring

What are the welfare implications of the proposed policy? Under what conditions does society gain from introducing a policy encouraging voluntary adoption of monitoring? We simulate the decentralized policy in order to compare it with mandatory monitoring or a franchise fee. The benchmark by which we evaluate the policies is the full information solution. Our aim is to illustrate how the parameters of the model affect the comparison between policies, in particular the buildup of the pollution stock over time, the damage cost of pollution and the heterogeneity of agents. We also compare the results of decentralized monitoring of a stock pollutant with a static policy, in order to show the importance of the dynamic analysis.

5.1. Parametric assumptions for the simulations

We do not intend to study a particular problem, but rather to illustrate the potential gains of applying a dynamic decentralized policy in a general setting. Common specifications of production functions and pollution functions, such as the quadratic or power function, lead to reduced forms of profits that are summations of power functions. Let the profit function be specified as $\pi = 5\theta + 5z - z^2 - 2(\theta z)^{0.9} - 5$, with $\left[\underline{\theta}, \overline{\theta}\right] = \left[0.1, 1\right]$. The quality parameter is assumed to be uniformly distributed over the interval [0.1,1], with an average quality of 0.55. Different assumptions on the distribution of heterogeneity are tested in the sensitivity analysis at the end. With this profit function, all derivatives conform to the assumptions of the theoretical model on the support indicated for the quality parameter θ. The lowest range of quality has been chosen to prevent numerical problems since most derivatives go to infinity when θ tend to 0 in this type of functions.

When no policy is implemented, the function gives an optimal value of emissions at the lower end of quality of $z^*(\underline{\theta}) = 2.396$ and $z^*(\overline{\theta}) = 1.643$ at the highest end of quality, which implies that the highest quality agents have 31.43% lower emissions than the agents of the lowest quality. Profits are $\pi\left(z^*(\underline{\theta})\right) = 1.18$ and $\pi\left(z^*(\overline{\theta})\right) = 2.38$, implying a doubling of profits of the agents of the highest quality compared to the agents with the lowest quality.

Monitoring costs are taken to be ν =0.1$ per unit and period,[8] which represents 8.47% of profits for low quality agents and 4.20% for the highest quality agents.

Pollution accumulates over time following $\dot{S}(t) = Z(t) - 0.1294S(t)$. The decay rate of 0.1294 corresponds to a half-life time of 25 years.[9] The social cost of pollution is $C = kS^2$ with k=0.0003. The social discount rate is set equal to 0.04. Production and pollution takes place in 5-year intervals. With this parameter setting, we have a situation where, without intervention, the economic activity does not generate almost any welfare because pollution

[8] Since we assume that monitoring equipment can be rented or subscribed to by paying a fee per period, the agent thus faces a periodic decision and balances the change in profits from adopting monitoring and the change in tax payments with the cost of adoption. In each period, the agent faces the same problem, but since the level of taxes changes according to the dynamics of the stock externality, an agent may adopt in period t and exit in a later period.

[9] Dioxins have a half-life of 25-100 years, for example, whereas persistent organic pollutants have shown half-lives of 3-25 years in rice paddies.

damages outweigh profits. The decentralized monitoring policy transforms it to a situation where the economic activity after intervention generates significant overall social welfare. In order to compute the solution of an infinite optimal control problem it is assumed that the economy reaches a steady state after 150 years.

5.2. Policy simulation results

Figures 2a and 2b show the pattern of exit and adoption of monitoring over the period of simulation, in the new externality case (initial stock of pollution equal to zero) with damage coefficient k=0.0003. Figure 2a depicts the evolution of the exit quality, θ_0, and critical quality, θ_c, and figure 2b illustrates the evolution of the share of agents that are being monitored and the ones that leave the economy. The increase in the shadow cost of aggregate emissions towards the steady state causes the exit quality level θ_0 to increase over time, as can be seen in Figure 2a. Thus, the number of agents that leave the economy increases monotonically until the steady-state is reached (Figure 2b). Moreover, Figure 2b shows that agents of high quality adopt first and by time period 10 all operating agents that are in business have adopted. In that time period, the exit quality level θ_0 and the critical quality θ_c coincide, they are equal to 0.44 (Figure 2a). All agents of lower quality have exited. From that time onwards all producing agents have adopted monitoring technology. The pattern of relatively quick adoption of monitoring that is shown in Figure 2b is a consequence of the high cost of accumulating pollution with a quadratic damage function. When pollution has a shorter half-life and/or a lower damage coefficient agents do not adopt monitoring until later (in order to save space we chose not to present the results of these calculations in graphical form). Fewer agents will also exit from production in that case since pollution in each time period is less costly to society.

FIGURES 2a AND 2b ABOUT HERE

Table I summarizes the welfare implications of the alternative policies compared to the full information solution. It shows the shadow price, the share of adoption of monitoring, the share of exit, aggregate profits and quasirents, collected taxes (a pure transfer in this model), aggregate emissions and pollution stock at the end of the initial time period and at steady state. The policies of mandatory monitoring and decentralized monitoring converge to the same steady state stock of pollution, lower than under the full information solution. The franchise fee policy (which fails to internalize the marginal shadow price of pollution in agents' decisions) converges to a slightly higher steady-state level of pollution than in the full information solution. In terms of aggregate damage, as expected the franchise fee policy does worse than the full information solution, whereas the decentralized monitoring policy and mandatory monitoring yields a lower aggregate damage of pollution than the full information solution. This comes at the cost of restraining agents' quasi-rents (but not by as much as under a franchise fee). The decentralized monitoring solution has the lowest welfare losses compared to the full information solution (7.87%), followed by the mandatory monitoring policy (8.53%) and the franchise fee last (10.78%).

TABLE 1 ABOUT HERE

We have also performed the same simulations for the restoration case, with an initial stock equal to twice the full-information steady-state level of the pollution stock in the new externality case ($S_0 = 1030$). In this case, because of the high initial stock of aggregate pollution, initial policy needs to be harsh and complete adoption starts from the first time period (see Figure 3). If monitoring costs are higher we can observe another pattern in the steady state, where all three cases (adoption, no monitoring, and exit) co-exist. Space limits preclude us from showing graphically the corresponding adoption pattern. The initial damage costs of pollution are so high that total welfare is negative. Note that a negative welfare does not indicate that the industry should be shut down completely (initial damage would not change and the economy would miss all profits). Rather, it implies that the policy must induce a decrease of emissions below the assimilation capacity of the environment such that the system can be recovered. In terms of comparison between the alternative policies, though, the decentralized monitoring policy again has the lowest welfare loss (2.73%) compared to the full information solution, together with the compulsory monitoring policy. With a damage coefficient equal to 0.0003 and a half-life of 25 years the two policies yield completely identical results because of the severity of the pollution buildup over time.

FIGURE 3 ABOUT HERE

To show the importance of the dynamic analysis we calculate an optimal static policy and compare it with the dynamic decentralized monitoring policy. The welfare loss of the static policy compared to the full information benchmark is 12.42%, thus unsurprisingly worse than the alternative dynamic policies. Even a franchise fee policy optimized over time does better in terms of social welfare than a static policy.[10]

5.4. Sensitivity analysis

We test the sensitivity of the results on the welfare losses of alternative policies to four parametric assumptions of the simulations: the level of heterogeneity among agents, the rate

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[10] This optimal static policy maximizes net benefits, but we could also compare the dynamic policies to a static policy equal to the decentralized policy in the first time period (27.11% reduction in welfare compared to the full information solution) or a static policy set equal to the policy in steady state (63.25% reduction in welfare compared to the full information solution).

of buildup of the pollution stock, the damage coefficient and the level of monitoring costs. This should give some indication of which factors are the most important in determining when a policy of decentralized monitoring would be a second-best solution in terms of aggregate welfare. In the graphs below we have also included the optimal static policy described above to show the differences with the dynamic policy of decentralized monitoring.

First we change the variance of the quality distribution of agents (Figure 4). The quality distribution is assumed to follow a beta distribution. Besides the uniform distribution (variance of 0.08), an *n*-shaped distribution (parameters equal to 2.625, variance of 0.04) and a *u*-shaped distribution (parameters equal to 0.281, variance of 0.016) were used. However, each distribution gives rise to a different level of profits in the absence of an environmental policy. In order to allow for comparisons, the number of agents in the economy was slightly changed in each of the distributions, such that the aggregate profits are identical when no policy is implemented. When the level of heterogeneity increases, welfare increases since there are more agents with higher quality that produce and more profits. Since the lowest quality agents exit the economy aggregate emissions are also lower. Thus, welfare losses are lower, but the difference between the decentralized policy and the franchise fee or mandatory monitoring is stable or even increases (in the comparison between decentralized monitoring and mandatory monitoring, given that heterogeneity increases the benefits of decentralized monitoring).

FIGURE 4 ABOUT HERE

The central scenario that we presented assumed a half-life of 25 years. We change this to 15 years ($\alpha = 0.2063$) and 50 years ($\alpha = 0.0669$) to analyze the effects of less or more persistent pollutants. The effects of increasing the half-life of pollutants in environment is to lower welfare, since damages increase over time at a higher rate if the environment has a lower assimilative capacity. Hence, the welfare losses of a fixed fee and a static policy increase compared with the decentralized monitoring policy. When the damage is sufficiently high, the decentralized solution is converging to the mandatory one, as everyone adopts (Figure 5).

FIGURE 5 ABOUT HERE

We also tested the sensitivity of the results with respect to the damage coefficient (k=0.003 in the central simulation), by also computing the welfare losses for k= 0.0002 and k=0.0004. When the damage coefficient increases, total welfare decreases, as expected, and the welfare losses from using a franchise fee or a static policy increase. Since damages are so important, in the limit the decentralized policy will obtain results very close to mandatory monitoring. The resulting figure is qualitatively identical to Figure 5, thus we opt for not presenting it in graphical form to save space.

Finally, increasing monitoring costs favors the decentralized policy, as expected (Figure 6). If the monitoring cost is 0.2, the solution of decentralized policy is almost equal to the franchise fee in terms of welfare losses (for the central scenario with a damage coefficient k=0.0003). If monitoring costs are as low as 0.05, the decentralized policy performs equally well as mandatory monitoring. These conclusions are not very sensitive to the damage coefficient.

FIGURE 6 ABOUT HERE

6. Conclusions

We propose a dynamic model for the management of a stock pollution problem through economic incentives that induce gradual diffusion of monitoring equipment when the regulator has incomplete information on emissions generated by heterogeneous agents. The framework was developed for a stock pollution problem, but can apply to a wide array of externality problems. Amongst others, it applies to many nonpoint source pollution problems. Most analyses of nonpoint source pollution problems assume that the regulator is able to fully observe some variable correlated with individual emissions, such as input use or technology choice. In practice, however, policymakers may not be able to observe individual choices that will allow differentiated incentives to control pollution. For example, the regulator may observe quantity of output but not quality and increases in quality may require use of chemicals or other assets. Thus, the emergence of technologies that will allow monitoring of individual activities may allow the regulator to transform difficult to address nonpoint source pollution problems into point source problems. But these technologies may be expensive to introduce and this paper suggests a mechanism to induce their adoption. In some cases, we observe the emergence of third-party verification organizations that monitor externalities, who may take advantage of new technologies (remote sensing, nanotechnologies) as part of the regulatory process. Alternatively, regulators may require that monitoring technologies are installed (as was the case with Continuous Emissions Monitoring for the US sulfur dioxide emissions market). In both cases, regulators require monitoring with accurate reporting of externalities. The burden of proof is on the polluter who should allow measurements of emissions, or otherwise is taxed at a conservative default level.

The paper analyzed a regulatory strategy consisting of voluntary adoption of monitoring induced by a discriminatory tax scheme. Each agent has to choose between paying a fixed fee, or installing monitoring technology and paying a tax on the actual generation of externalities. The highest quality agents will adopt a monitoring technology if the gain from reduced taxation outweighs the impact on profits and the monitoring costs. Since the taxes will evolve over time as the social shadow price of the externality changes, adoption of monitoring technology will also change accordingly. The dynamics of diffusion of monitoring vary depending on the initial stock of pollution. In some situations, when the initial stock of pollution is very high, intervention may lead to initially stiff penalties that will induce fast adoption of monitoring technology. In other cases, when regulatory intervention starts when the pollution stock is relatively low, the pollution taxes increase over time and monitoring is adopted gradually. The numerical analysis shows that when monitoring costs are within a reasonable range (below 19% of profits), the decentralized policy performs better in terms of welfare than a franchise fee. Moreover, when damages are high and/or monitoring costs are low, it will induce complete adoption. The simulations also show that the dynamic aspect is particularly important when regulating a stock pollution problem, since the optimal decentralized static policy performs even worse than a dynamic franchise fee (even though the last one does not internalize the cost of emissions). Finally, the simulations indicate that the gain from the decentralized policy increases with an increase in heterogeneity and when the assimilative capacity of the environment is reduced.

The analysis in this paper is conducted under some simplifying assumptions. The model is deterministic and it would be useful to address to what extent the results hold when the damage is subject to random shocks. We assume that the price of the monitoring technology is given, but this technology may be provided by a monopoly that will change the price over time, thus affecting adoption of the new technology and the nature of the optimal policy. Other issues that may affect the dynamics of adoption and the optimal policy are learning by doing in the production of the monitoring technology that will affect its price dynamics. All these issues present an agenda for future research.

APPENDIX

Proof of Proposition 1.

Denoting the Lagrange multiplier by λ, the Lagrangian for the problem is:

$$L_1 = \int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} \left(\pi(z_0(\theta),\theta)\right) g(\theta)d\theta + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} \left(\pi(z_1(\theta),\theta) - v\right) g(\theta)d\theta +$$

$$+\lambda\left(Z - \int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} z_0(\theta)g(\theta)d\theta - \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} z_1(\theta)g(\theta)d\theta \right)$$

The solution to the problem has to satisfy the following necessary conditions:

$$\begin{aligned} \frac{\partial L_1}{\partial F_0} &= -\frac{\partial \theta_0}{\partial F_0}\left\{\pi(z_0(\theta_0),\theta_0) - \lambda z_0(\theta_0)\right\} g(\theta_0) + \\ &+ \frac{\partial \theta_c}{\partial F_0}\left\{\pi(z_0(\theta_c),\theta_c) - \pi(z_1(\theta_c),\theta_c) + v - \lambda(z_0(\theta_c) - z_1(\theta_c))\right\} g(\theta_c) = 0 \end{aligned} \tag{A1}$$

$$\frac{\partial L_1}{\partial F_1} = \frac{\partial \theta_c}{\partial F_1}\left\{\pi(z_0(\theta_c),\theta_c) - \pi(z_1(\theta_c),\theta_c) + v - \lambda(z_0(\theta_c) - z_1(\theta_c))\right\} g(\theta_c) = 0 \tag{A2}$$

$$\frac{\partial L_1}{\partial \tau} = \frac{\partial \theta_c}{\partial \tau}\left\{\pi(z_0(\theta_c),\theta_c) - \pi(z_1(\theta_c),\theta_c) + v - \lambda(z_0(\theta_c) - z_1(\theta_c))\right\} g(\theta_c) +$$

$$+\int_{\theta_c}^{\bar{\theta}} \left\{ \frac{\partial \pi(z_1(\theta),\theta)}{\partial z_1} - \lambda \right\} \frac{\partial z_1(\theta)}{\partial \tau} g(\theta)d\theta = 0 \tag{A3}$$

$$\frac{\partial L_1}{\partial \lambda} = Z - \int_{\theta_0(F_0)}^{\theta_c(F_0,F_1,\tau;v)} z_0(\theta)g(\theta)d\theta + \int_{\theta_c(F_0,F_1,\tau;v)}^{\bar{\theta}} z_1(\theta)g(\theta)d\theta = 0 \tag{A4}$$

Equations (7)-(9) in the article show that $\frac{\partial \theta_c}{\partial F_0}$, $\frac{\partial \theta_c}{\partial F_1}$ and $\frac{\partial \theta_c}{\partial \tau}$ are non-zero. Thus, for the necessary condition (A2) to hold we need to have

$\pi(z_0(\theta_c,t),\theta_c) - \pi(z_1(\theta_c,t),\theta_c) + v - \lambda\left(z_0(\theta_c,t) - z_1(\theta_c,t)\right) = 0 \quad \forall t$, and, by substitution in (A1); $\pi(z_0(\theta_0,t),\theta_0) - \lambda z_0(\theta_0,t) = 0$. By definition of the marginal quality, $\pi(z_0(\theta_0,t),\theta_0) - F_0(t) = 0$, and hence $F_0(t) = \lambda z_0(\theta_0,t)$. Given that $\frac{\partial z_1}{\partial \tau} < 0$ in the interval $\theta_c \le \theta < \overline{\theta}$, for (A3) to hold we need to have that $\frac{\partial \pi(z_1^*(\theta,t),\theta)}{\partial z} - \lambda = 0$. Private profit maximization leads to $\frac{\partial \pi(z_1^*(\theta,t),\theta)}{\partial z} = \tau$ and so, $\tau = \lambda$. Private profit-maximizing behavior further has that adoption is given by equation (6):

$$\pi(z_1(\theta_c,t),\theta_c) - \pi(z_0(\theta_c,t),\theta_c) - \tau(t) z_1(\theta_c,t) - F_1(t) + F_0(t) - v = 0 \quad \forall t$$

Comparing equation (6) with equation (A2) it can be observed that the regulator's optimal adoption decision coincides with the private agents iff

$F_0(t) - F_1(t) - \tau(t) z_1(\theta_c,t) - \lambda\left(z_0(\theta_c,t) - z_1(\theta_c,t)\right) = 0 \quad \forall t$. We thus have that

$F_1(t) = \lambda\left(z_0(\theta_0,t) - z_0(\theta_c,t)\right)$. Q.E.D.

Proof of Proposition 2.

First part:

A linearization of the canonical system of differential equations around the steady-state values of γ and S results in:

$$\begin{pmatrix} \dot{\gamma} \\ \dot{S} \end{pmatrix} = \begin{pmatrix} \frac{\partial \dot{\gamma}}{\partial \gamma} & \frac{\partial \dot{\gamma}}{\partial S} \\ \frac{\partial \dot{S}}{\partial \gamma} & \frac{\partial \dot{S}}{\partial S} \end{pmatrix} \begin{pmatrix} \gamma - \gamma^\infty \\ S - S^\infty \end{pmatrix} = \begin{pmatrix} \alpha + r > 0 & -\frac{\partial^2 C}{\partial S^2} < 0 \\ \frac{\partial Z_0}{\partial \gamma} \le 0 & -\alpha < 0 \end{pmatrix} \begin{pmatrix} \gamma - \gamma^\infty \\ S - S^\infty \end{pmatrix}$$

Since the trace of the Jacobian matrix is equal to $r > 0$, employing the fact that it equals the sum of its eigenvalues assures that at least one eigenvalue is positive. Additionally, the determinant of the Jacobian matrix is negative and thus, the eigenvalues have opposite signs and the steady state equilibrium is locally characterized by a saddle point. For any initial value of *S* within the neighborhood of S^{∞}, where the superscript ∞ indicates the steady state equilibrium value, it is possible to find a corresponding value of the shadow cost that assures that the optimal environmental policy leads towards the long-run optimum.

The slopes of the $\dot{\gamma} = 0$ and the $\dot{S} = 0$ isoclines are:

$$\gamma\big|_{\dot{\gamma}=0} = -\frac{-C_{SS}}{\alpha + r} > 0, \qquad \gamma\big|_{\dot{S}=0} = -\frac{-\alpha}{Z_{\gamma}} > 0.$$

A phase diagram of the system might look like the one depicted below.

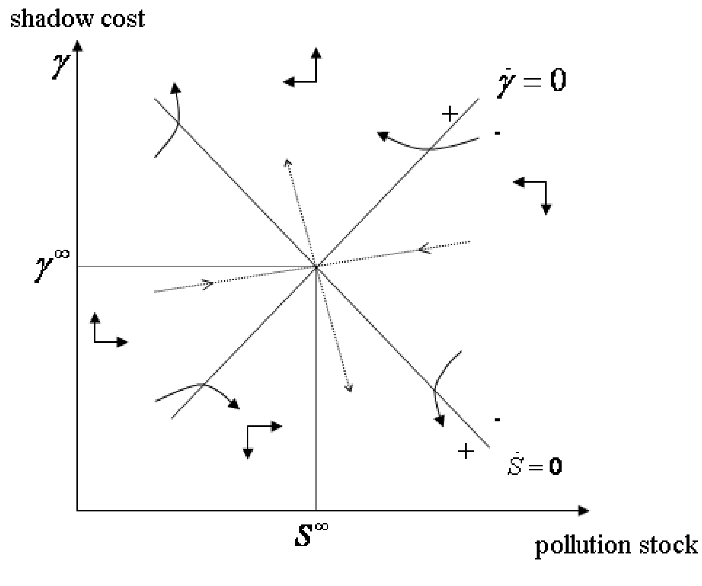

Figure: The phase diagram in the (S, γ) space.

Prop. 2a) follows directly from the fact that $\tau = \lambda = \gamma$ and that γ and *S* evolve over time in the same direction, hence $\dot{\tau} < 0$ iff $S_0 > S^{\infty}$.

Prop. 2b) and 2c): Let us redefine the policy scheme as a fixed fee on all agents $F_0 = \lambda z_0(\theta_0)$, and a subsidy (negative fee) $F_1 = -\lambda z_0(\theta_c)$ on agents that decide to adopt monitoring. In this case, applying the chain rule we obtain:

$$\frac{\partial F_0}{\partial Z} = \frac{\partial \tau}{\partial Z} z_0(\theta_0) + \tau \frac{\partial z_0(\theta_0)}{\partial \theta_0} \frac{\partial \theta_0}{\partial F_0} \frac{\partial F_0}{\partial Z} \text{ and } \frac{\partial F_1}{\partial Z} = -\frac{\partial \tau}{\partial Z} z_0(\theta_c) - \tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \left(\frac{\partial \theta_c}{\partial \tau} \frac{\partial \tau}{\partial Z} + \frac{\partial \theta_c}{\partial F_1} \frac{\partial F_1}{\partial Z} \right)$$

respectively. After some operations it gives:

$$\frac{\partial F_0}{\partial Z} = \frac{\frac{\partial \tau}{\partial Z} z_0(\theta_0)}{\left(1 - \tau \frac{\partial z_0(\theta_0)}{\partial \theta_0} \frac{\partial \theta_0}{\partial F_0}\right)} < 0, \tag{A5}$$

$$\frac{\partial F_1}{\partial Z} = -\frac{\partial \tau}{\partial Z} \frac{\left(z_0(\theta_c) + \tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \frac{\partial \theta_c}{\partial \tau} \right)}{\left(1 + \tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \frac{\partial \theta_c}{\partial F_1} \right)} <> 0. \tag{A6}$$

since $-\frac{\partial \tau}{\partial Z} > 0$, $\frac{\partial F_1}{\partial Z} < 0$ if the nominator and denominator have opposite signs. In the case where $z_0(\theta_c) + \tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \frac{\partial \theta_c}{\partial \tau} > 0$ and $1 + \tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \frac{\partial \theta_c}{\partial F_1} < 0$, substituting the derivatives of θ_c leads, after some transformations, to:

$$\left.\begin{array}{l} \tau \left| \frac{\partial z_0(\theta_c)}{\partial \theta_c} \right| \frac{1}{\left(\frac{\partial \pi(z_1)}{\partial \theta_c} - \frac{\partial \pi(z_0)}{\partial \theta_c} \right)} < \frac{z_0(\theta_c, t)}{z_1(\theta_c, t)} \\ \tau \left| \frac{\partial z_0(\theta_c)}{\partial \theta_c} \right| \frac{1}{\left(\frac{\partial \pi(z_1)}{\partial \theta_c} - \frac{\partial \pi(z_0)}{\partial \theta_c} \right)} > 1 \end{array}\right\}$$

Since $\frac{z_0(\theta_c, t)}{z_1(\theta_c, t)} > 1$, $\frac{\partial F_1}{\partial Z} < 0$ iff $1 < \frac{\tau \left| \frac{\partial z_0(\theta_c)}{\partial \theta_c} \right|}{\left(\frac{\partial \pi(z_1)}{\partial \theta_c} - \frac{\partial \pi(z_0)}{\partial \theta_c} \right)} < \frac{z_0(\theta_c, t)}{z_1(\theta_c, t)}$.[11] Q.E.D.

[11] Note that the case where the numerator is negative and the denominator is positive is not feasible.

Proof of Corollary.

Applying the chain rule, the change in θ_c is given by:

$$\frac{\partial\theta_c}{\partial Z}=\frac{\partial\theta_c}{\partial F_1}\frac{\partial F_1}{\partial Z}+\frac{\partial\theta_c}{\partial\tau}\frac{\partial\tau}{\partial Z} \tag{A7}$$

since F_0 has been redefined as a fixed fee on all agents, and thus $\frac{\partial\theta_c}{\partial F_0}=0$.

The substitution of equation (A6) into (A7) and simplifying the resulting equation leads to

$$\frac{\partial\theta_c}{\partial Z}=\frac{-\frac{\partial\tau}{\partial Z}\left(\frac{\partial\theta_c}{\partial F_1}z_0(\theta_c)-\frac{\partial\theta_c}{\partial\tau}\right)}{\left(1+\tau\frac{\partial z_0(\theta_c)}{\partial\theta_c}\frac{\partial\theta_c}{\partial F_1}\right)} \tag{A8}$$

Substituting in equations (8) and (9) from the text for $\frac{\partial\theta_c}{\partial F_1}$ and $\frac{\partial\theta_c}{\partial\tau}$ gives:

$$\frac{\partial\theta_c}{\partial Z}=\frac{-\frac{\partial\tau}{\partial Z}\left(\frac{z_0(\theta_c,t)}{\left(\frac{\partial\pi(z_1(\theta,t),\theta)}{\partial\theta_c}-\frac{\partial\pi(z_0(\theta,t),\theta)}{\partial\theta_c}\right)}-\frac{z_1(\theta_c,t)}{\left(\frac{\partial\pi(z_1(\theta,t),\theta)}{\partial\theta_c}-\frac{\partial\pi(z_0(\theta,t),\theta)}{\partial\theta_c}\right)}\right)}{\left(1+\tau\frac{\partial z_0(\theta_c)}{\partial\theta_c}\frac{\partial\theta_c}{\partial F_1}\right)} \tag{A9}$$

Given that the numerator in (A9) is positive, for $\frac{\partial \theta_c}{\partial Z}$ to be greater than zero, the denominator needs also to be positive. Substituting the value of $\frac{\partial \theta_c}{\partial F_1}$ into the expression

$\left(1+\tau \frac{\partial z_0(\theta_c)}{\partial \theta_c} \frac{\partial \theta_c}{\partial F_1}\right)$, we obtain that it will be positive iff

$$1+\frac{\tau \frac{\partial z_0(\theta_c)}{\partial \theta_c}}{\left(\frac{\partial \pi(z_1,\theta)}{\partial \theta_c}-\frac{\partial \pi(z_0,\theta)}{\partial \theta_c}\right)}>0\text{, i.e., iff } \tau\left|\frac{\partial z_0(\theta_c)}{\partial \theta_c}\right|<\left(\frac{\partial \pi(z_1(\theta,t),\theta)}{\partial \theta_c}-\frac{\partial \pi(z_0(\theta,t),\theta)}{\partial \theta_c}\right).$$

Q.E.D.

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Figure 1. High quality agents use pollution more efficiently.

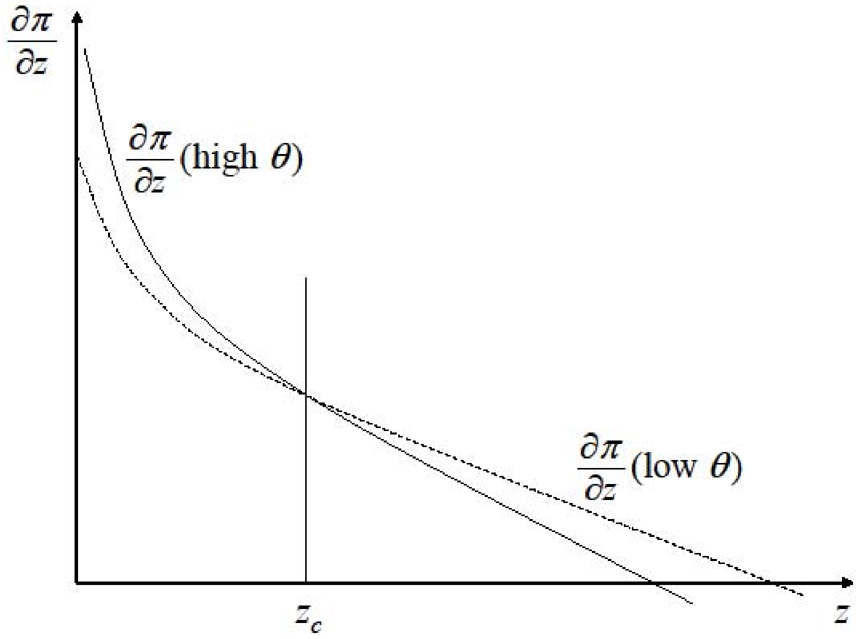
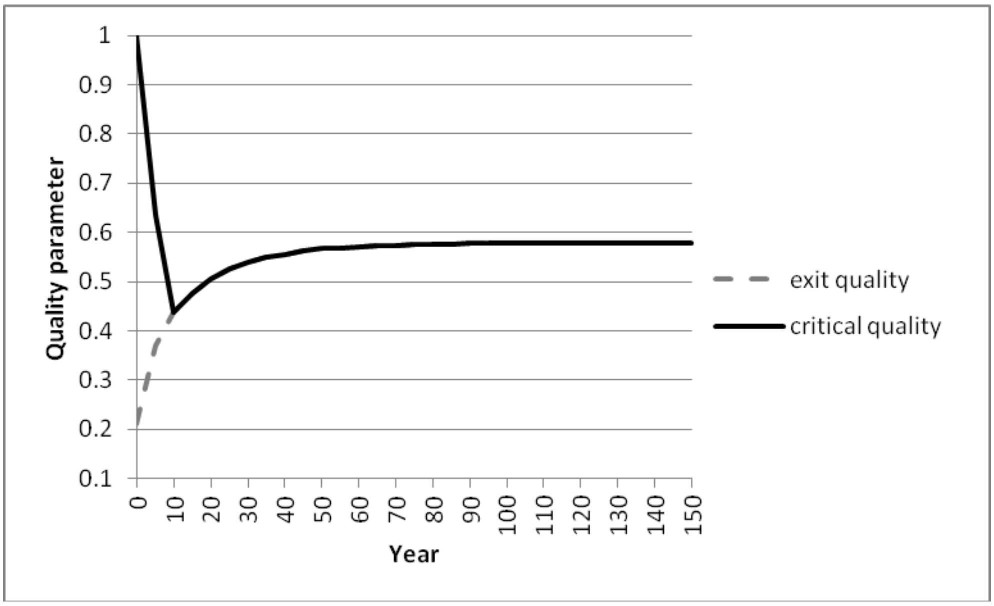


Figure 2. Adoption pattern. New externality case (half-life=25; k=0.0003; $S_0 = 0$).

a) Evolution of the exit quality, θ_0, and critical quality, θ_c.



b) Evolution of the share of adoption of monitoring technology.

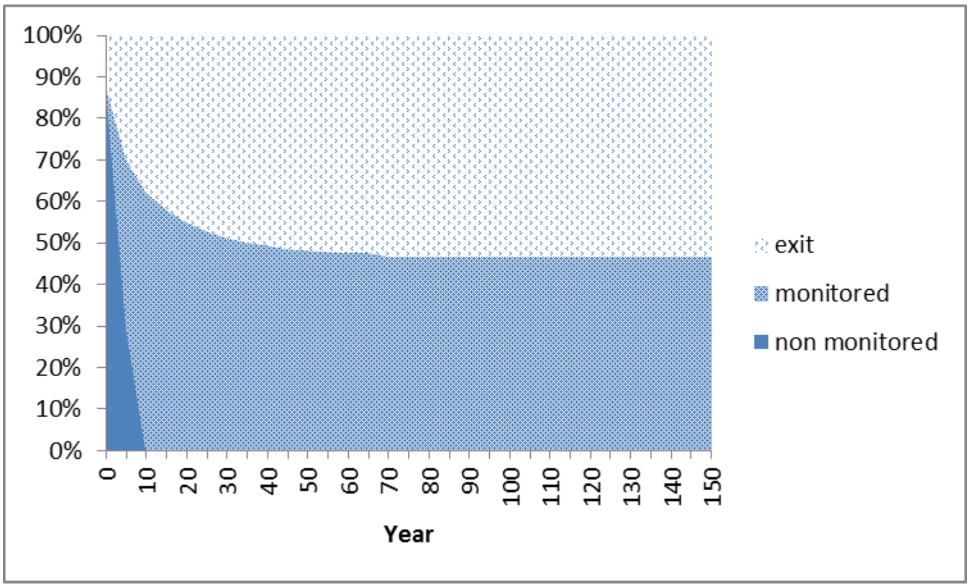


Figure 3. Adoption pattern. Restoration case (half-life=25; *k*=0.0003; $S_0 = 1030$).

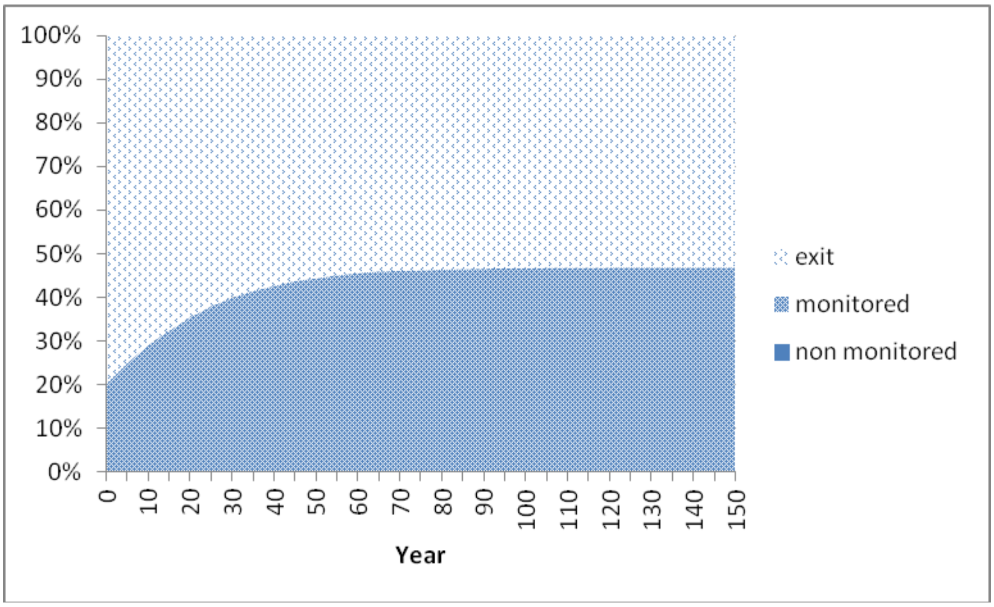


Figure 4. Effects on the welfare comparison of increasing heterogeneity (k = 0.0003 and $S_0 = 0$).

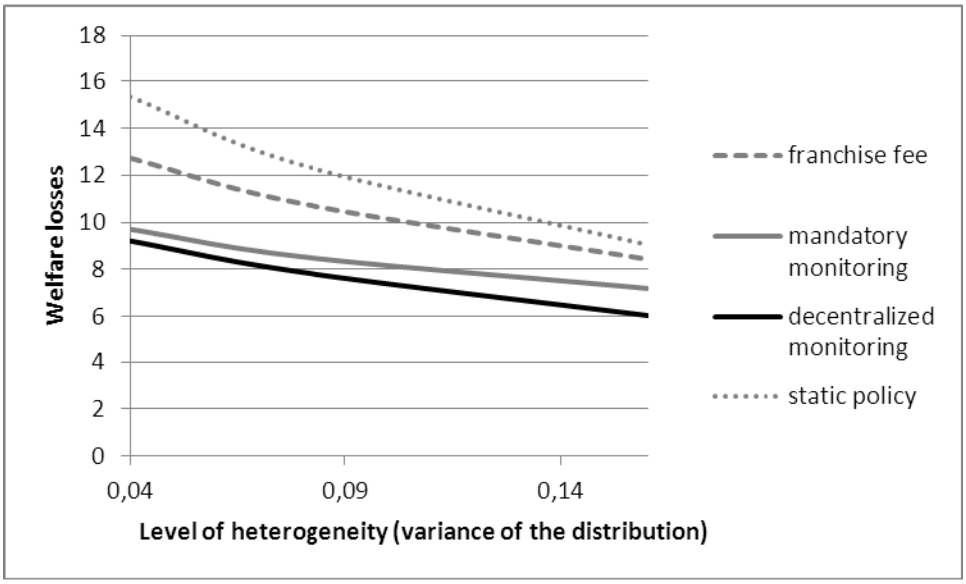


Figure 5. Effects on the welfare comparison of increasing the half-life of pollutants in the environment.

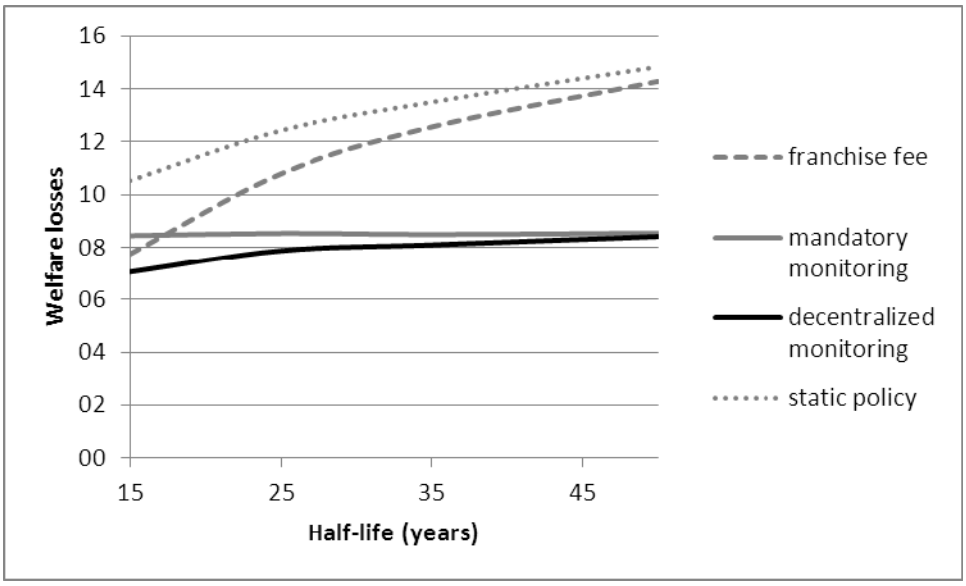


Figure 6. Effects on the welfare comparison of increasing monitoring costs.

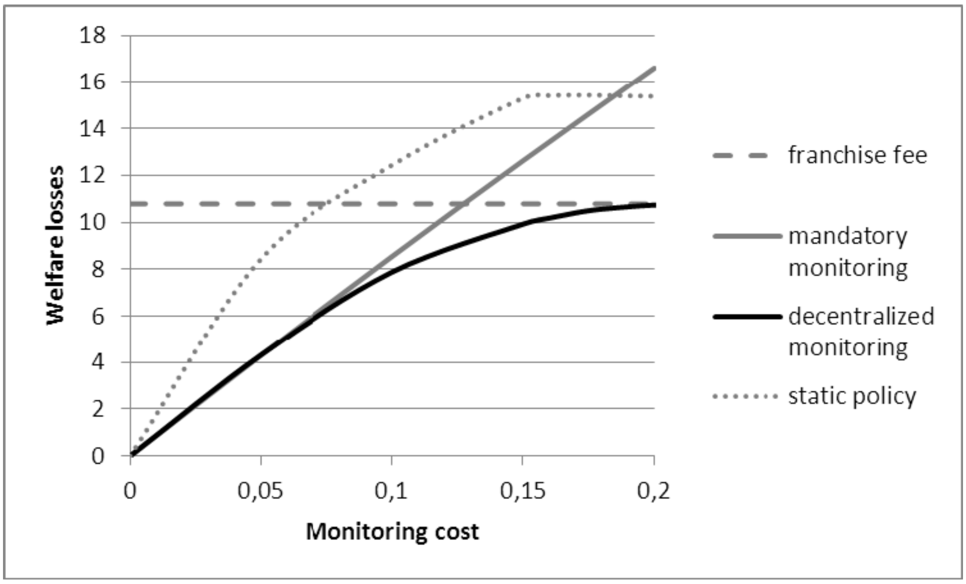


Table I. Comparison of policies in the new externality case ($S_0 = 0$) and half life equal to 25 years.

	Full information solution	Franchise fee	Mandatory monitoring	Decentralized monitoring
Value of variables in the first period				
Initial shadow price	0.53	0.54	0.50	0.53
Share of adoption (%)	100	0	100	0
Share of exit (%)	3.1	15.3	8.6	12.3
Aggregate profits	153	145	139	149
Aggregate quasirents	64	56	59	57
Collected taxes	89	89	80	92
Aggregate emissions	167	165	157	172
Pollution stock	0	0	0	0
Value of variables in the steady state				
Shadow price	0.89	0.91	0.86	0.86
Share of adoption (%)	100	0	100	100
Share of exit (%)	50.9	62.1	53.2	53.2
Aggregate profits	85	77	79	79
Aggregate quasirents	27	16	24	24
Collected taxes	58	61	55	55
Aggregate emissions	66	67	64	64
Pollution stock	515	521	494	494
Discounted sum of economic variables				
Discounted sum of profits	630.34	591.44	576.38	585.88
Discounted sum of quasirents	230.47	176.33	211.90	206.35
Discounted sum of collected taxes	399.86	415.10	364.48	379.52
Discounted sum of damages	199.99	207.50	182.74	189.39
Welfare	430.34	383.93	393.64	396.49
Welfare losses (EL)	0%	10.78%	8.53%	7.87%