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ON OPTIMAL ENVIRONMENTAL TAXATION AND ENFORCEMENT: INFORMATION, MONITORING AND EFFICIENCY

CARLOS MARIO GÓMEZ GÓMEZ
Universidad de Alcalá
Facultad de Ciencias Económicas
Plaza de la Victoria s/n
Alcalá de Henares
2802 Madrid, Spain
E-mail: ehgomez@alcala.es

Current address: Institute of Business & Economic Research
University of California - Berkeley
F502 Haas
Berkeley, CA 94720-1922, U.S.A.
E-mail: ehgomez@uclink.berkeley.edu

ABSTRACT. The purpose of the paper is to contribute to the narrowing of the distance between formal theory and practical environmental policy design. We formulate a general and comprehensive theoretical model in order to take into account the different informational and technological problems which characterize the definition and implementation of environmental taxes in a second best world where there also are distortionary taxes. Having formalized these problems, we present a general model which allows us to discuss the existence of efficient and implementable environmental quality objectives and policy instruments, and to analyze many particular cases.

KEY WORDS: Environmental economics, economics of regulation, asymmetric and private information, optimal taxation, mechanism design.

1. Introduction. One of the main propositions that are part of the core of environmental economics states that the imposition of an emission tax, of the appropriate magnitude, will always lead to a socially optimal decrease in the quantity of an emission that constitutes a detrimental externality. Since Pigou, standard microeconomic theory proves that, when an externality occurs, the solution of the social cost problem requires the producers to face an additional cost identical

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to the marginal damage caused by them at the efficient level of the externality. Pigouvian taxes, and adequately designed property rights are political instruments used to put this theory into practice (see, for example, Baumol and Oates [1998]).

Nowadays, the prospect of using Pigouvian taxes in order to improve the environmental quality is again a matter of controversy (see, for example, Morgenstern [1995], Goulder [1995] and Parry and Oates [1998]). This is largely a consequence of the wide distance existing between abstract theory, from which normative policy recommendations are derived, and concrete markets, where policy prescriptions must be applied. In other words, although Pigouvian taxes may be rational in the context of ideal markets, they could be far from efficient in the context of real markets where, apart from environmental degradation, there are also imperfect and asymmetric information, pre-existing distortionary taxes, high enforcement costs, and so forth.

The purpose of this paper is to help to narrow the gap between abstract theory and practical policy design.[1] In order to do this we take into account the different design and implementation problems defined in the next section of the paper (Section 2). All of these problems have been studied separately in various research fields ranging from optimal taxation and enforcement to information economics and the theory of incentives and optimal contracts. Rather than analyzing each one independently, we will try to incorporate them into a general and comprehensive model.

After presenting the main features of the general model in Section 3, we continue in Section 4 by asking, first, what policy objectives, or pollution programs, are feasible given the design and enforcement constraint, and, second, what are the optimal instruments that would allow the application of any feasible pollution program. A pollution program and the best instruments used to reach it form, when put together, what we call an environmental policy, and its properties are illustrated graphically in a reduced version of the model at the end of Section 4. Section 5 comes back to the general model in order to identify and describe the best environmental policy, both in the general model and in many particular cases, and to clarify the way in which the institutional constraints would affect optimal environmental taxes and pollution levels. The main conclusions are presented in Section 6, and the necessary and sufficient condition for implementability of a given environmental policy is formally proved in the Appendix.

2. The institutional context of the environmental policy. The institutional setting is defined by the different problems or constraints that affect the set of decisions the environmental agency can design and enforce. In general terms, design problems come mainly from the existence of asymmetric information about the private opportunity cost of reducing emissions and also from the fact that there are distortions in the economy other than those resulting from excessive pollution. Enforcement constraints and problems arise mainly from costly and poor monitoring technology.

a. Asymmetric information. In most of the relevant situations, the environmental agency does not have full information about the private opportunity cost of abating pollution. Nevertheless, each firm can easily obtain this information and, consequently, could use it strategically. Apart from providing the incentives to behave efficiently, the environmental policy must also be a mechanism able to reveal the private information that any firm has about its abatement cost.

To cope with this problem, we develop an extension of the basic regulation model with asymmetric information (e.g., Baron and Myerson [1982], Fudenberg and Tirole [1991] and Laffont and Tirole [1992]) which has been applied to the design of environmental policy instruments (e.g., Dasgupta et al. [1980], Spulber [1988] and Laffont [2000]). In this context the environmental agency knows the form of the function relating private cost and emissions but is uncertain about the exact value of one of the parameters of that function (which is perfectly known by the regulated firm).

Another way to formalize information problems, which has been used extensively in analyzing environmental policy design, consists of assuming that the environmental agency is uncertain about the value of some relevant parameter of the marginal cost or damage function and designs and enforces a tax or a pollution permit scheme based exclusively on the expected values of the cost and damage functions. In this context the main concern is to measure and compare the inefficiencies that will result when the environmental agency chooses any particular instrument, like a tax or a market for quotas (see

Weitzmann [1974], Adar and Griffin [1976] and Schöb [1996a]). On the contrary, in our model the environmental policy is always optimal, provided that the environmental agency is able to reveal the private information through the design of adequate incentives.

b. Environmental taxes in a second best world. Apart from coping with asymmetric information, at the design stage we must take into account all the social benefits and costs of environmental taxes. Obviously the primary advantage, or "dividend," of environmental taxes is the familiar welfare gain associated with the net benefit of the environmental improvement. Moreover, in the presence of pre-existing tax distortions, the revenues raised by the environmental tax can be used to cut existing taxes that discourage labor supply or capital formation (as proposed by Pearce [1991], Repetto et al. [1992] and Oates [1993]). This "second dividend" coming from the "revenue recycling effect" means that the benefits of environmental taxation would be substantially higher because of pre-existing factor tax distortions.

But recent research has revealed that the previous analysis was too optimistic. Apart from the fact that costly enforcement would reduce the revenues available for recycling, recent analyses have emphasized that, once the previous distortions in the tax system have been acknowledged, we must take into account the full interactions of the new environmental tax with other distortionary taxes. The new environmental tax increases production costs and, by increasing prices and reducing real wages, will result in a reduction in labor supply. This will obviously reduce the second dividend by the negative impact of the now called "tax interaction effect." In some particular situations the second dividend could be negative (Bovenberg and de Mooij [1994]) and in some extreme cases its negative welfare effect could be big enough to even offset the gains resulting from improving the environment. Although the sign and size of the "second dividend" are still an open question, we assume, in order to ease the exposition of the model, that the "tax interaction effect" is slight or at least not important enough to totally offset the gains obtained from the "revenue recycling effect." Theoretically this hypothesis can be justified in several relevant situations as analyzed by Parry and Bento [2000], Parry [1999] and Schöb [1996b].[2]

To introduce the second dividend in our model we will assume that there is a positive value of each unit of public revenue which we denote as $\gamma > 0$; γ is more properly defined as the marginal welfare cost of public funds, or the efficiency loss from the increase in distortionary taxes necessary to raise an extra dollar on tax revenue. Then $1 + \gamma$ is equivalent to the commonly used marginal cost of public expenses.[3] Empirical estimates of the value of γ vary from a figure between 0.21 and 0.35 obtained by Parry [1999] to values higher than 0.5 calculated by Auten and Carroll [1998], and even a number higher to 1 as the results obtained by Feldstein [1999] show.[4]

c. Costly monitoring. To enforce the environmental policy the Agency must observe the behavior of firms and that requires costly monitoring, which obviously reduces the revenue available to cut down distortionary taxes.

Monitoring technology also poses some puzzling problems for enforcement strategy (see, e.g., Harford [1987], Malik [1993] and Russell [1990]). Having accepted that the tax bill the firm must pay will depend on its total emissions, the Agency realizes the emissions will have to be measured, declared or predicted in some way in order to enforce a policy. Things could be straightforward if emissions were easy to measure as in the case of the Agency observing the behavior of the firm and billing it at the end of the period. But this simple scenario is technically impossible as, up to now, there is not any available filter or end-of-pipe device able to report the quantity and composition of effluents going through it without any ambiguity. The most the Agency can do is to inspect the firm a limited number of times, inspect the abatement equipment and take some samples of the on-going emissions, and this could be rather expensive.

Also, it is now accepted that the tax bill must depend on self-declarations by the firms about their emissions during a certain period. But this solution comes with another problem. In most of the relevant cases pollution is “fugitive” and does not leave any trace about its origin once it is dissolved in the atmosphere or the rivers. Therefore, if the tax bill is calculated from self-declarations of the firms about their emission levels during the previous period, the Agency will find itself unable to verify whether they are telling the truth. The solution proposed in this paper consists in a monitoring strategy where each firm declares how much it has decided to pollute during the next period in advance. Only in that context will the Agency have the opportunity to inspect the firm when emissions are observable. More than measuring all the pollution of the firm during the entire period, the aim of the monitoring strategy will be only to verify if the firm is adjusting its emissions to the level declared in advance.

As said before, the existing monitoring technology is rather primitive. In fact, monitoring must rely on experiments or limited sample techniques, the results of which must be interpreted (and not just read) by the environmental agency, giving rise to well-known statistical errors. In practice, the Agency could engage in two kinds of mistakes when, on the basis of a statistical test with limited information, it reaches the conclusion that a firm which complies must be punished or a non-complying firm is behaving correctly (see, e.g., Russell, Harrington and Vaughan [1986] and Russell [1990]). In our case, inefficiencies coming from technological imperfections will be incorporated by taking explicitly into account the exact measure of the statistical error as suggested in the approach used by Laffont and Tirole [1992, Chapter 10] to study the auditing of the cost padding problem.

Furthermore, with the mentioned restrictions, when inspecting the firm, the Agency is unable to measure the magnitude of the deviations from the reported emission levels accurately, its judgments referring only to compliance or not with the pre-declared emissions. In our model we will assume that the Agency can enforce financial fines to firms inspected with negative result in spite of the fact that, as said above, these fines can sometimes be unfair.

Problems coming from imperfect monitoring technology have been analyzed by, e.g., Martin [1984], Russell, Harrington and Vaughan [1986] and Russell [1990]. Their aim was to design cost minimizing inspection policies for given emissions levels allowed by law or historical property rights. Contrary to that, our purpose is to provide a general theory where design and enforcement problems are linked in a singular framework.

Taking into account the problems of monitoring strategies centered in observing the behavior of firms, Xepapadeas [1991], Govindasamy, et al. [1994] and other authors offer the alternative approach of making enforcement decisions based only on the environmental standards (that is to say, in the quality of the air or the water where multiple agents send their pollution). This context leads to the well-known nonpoint pollution problem where the environment is a collective good degraded by multiple nonobservable individual actions. As the individual behavior of firms is not observable, Xepapadeas [1991] suggests a system of random penalties in order to enforce environmental regulation. Govindasamy, et al. [1994] suggests a tournament where the probability of being fined is reduced depending on the previous behavior of the firm. In this paper we try to avoid these kinds of theoretically interesting but implausible policy instruments and prefer to accept that monitoring firms' compliance, although imperfect, is possible and, as will be shown, leads to efficient pollution levels.

3. The model. The objective of the Agency is to obtain a pollution program $(x(\theta))$ which minimizes the overall social cost of obtaining a certain environmental quality. In general terms, the problem of the Agency can be described by the following objective function, the components of which are described below:

$$\text{(1)} \qquad \underset{x(\theta)}{\text{MIN}}\ \text{EED} + \text{ECC} + (1+\gamma)\text{EMC} - \gamma(\text{ET} + \text{EF}).$$

The objective is to obtain a pollution program $(x(\theta))^v$ defining the emissions (x) of each individual firm (indexed by θ, a positive parameter which represents the private information of the firm) which minimizes the sum of the expected environmental damage (EED) plus the expected private compliance cost of emitting a level of pollution (ECC) plus the expected monitoring cost (EMC) multiplied by the marginal cost of public spending $(1 + \gamma)$ minus the sum of the total expected revenue of the environmental policy coming from taxes (ET) and fines (EF) multiplied by the marginal benefit of public revenue (γ).

We assume that the Agency knows the value of the environmental damage of any pollution level that can be defined, as usual, by the (deterministic) damage function $D(x)$, where the marginal damage is positive and increasing in emissions.

Moreover, the Agency does not have perfect knowledge of the opportunity cost of abating emissions at the level of any firm, as it is private knowledge. To define the compliance cost function we consider the environment as an input for the firm. If emissions were free, firms would pollute until the marginal productivity of the last particle discharged was equal to zero. When there is no environmental policy, emissions will be at their maximum possible and the compliance cost will be zero. If emissions are reduced, compliance cost will increase, so compliance cost is decreasing in emissions.

But the compliance cost is not the same for any firm as its exact value is private information. To allow for that we consider that, apart from emissions, the compliance cost function also depends on a positive parameter θ, which stands for the firm's private information. θ is a measure of the relative effort that the firm must do to decrease its emissions. Low compliance cost firms will have a low value of θ and vice versa. Among the factors that determine the value of θ are input prices, the demand for final products, the opportunity cost of setting up and the maintenance of the abatement equipment and so on.

Summing up, compliance cost can be represented as:[6]

$$\mathrm{CC} = \mathrm{c}(x, \theta) \tag{2}$$

and depends negatively on emissions (x) and positively on a parameter (θ). That is to say:

$$\frac{\partial c}{\partial x} < 0; \qquad \frac{\partial c}{\partial \theta} > 0. \tag{3}$$

Reducing pollution in one unit will increase compliance cost in $\partial c/\partial x$, and then the marginal abatement cost is equal to $-\partial c/\partial x > 0$ (the mirror image of marginal compliance cost). We also share the usual assumption that this marginal abatement cost is increasing in abatement which implies that $\partial c/\partial x^2 > 0$. High compliance cost firms also have higher marginal compliance cost than low cost firms. This last assumption implies that $\partial^2 c/\partial x \partial \theta > 0$. Finally, the environmental agency knows the maximum and minimum values of θ, ($\theta \in (\underline{\theta}, \bar{\theta})$) and the differentiable distribution function $F(\theta)$ with density $f(\theta)$. Nevertheless, the Agency is unable to assign a specific type to the firm.

a. The regulation game. We shall now study the environmental regulation problem in a principal-agent mechanism design framework. For simplicity, we assume that only a single agent (the firm) interacts with the principal (the environmental agency). However, as is well known, all the results can be generalized to a situation with multiple independent agents (see, e.g., Laffont and Tirole [1992] and Fudenberg and Tirole [1991, Chapter 7]).

Under this approach, environmental policy is a Bayesian Nash equilibrium of a revelation game with the following three stages:

1. At first, the Agency designs and presents to the firm a mechanism, or contract menu $(x, T(x), \lambda(x), m(x))$, consisting of:

   a. A decision function, or pollution program, x, defining all the emission levels the firm can choose. The Agency will offer a single pollution level for any type of firm, then the overall emission function is $x(\theta)$ and will also offer the incentives needed for each firm to pick up the pollution level the Agency desires for it according to its private information. These incentives are the next components of the menu.

   b. A total environmental tax,[7] $(T(x))$, which specifies what the firm has to pay in advance according to the declared emission level for the next period;

   c. A function $\lambda(x)$ specifying with what probability (λ) the firm would be monitored depending on its declared emission level.

   d. A monetary sanction, $m(x)$, to be applied when the firm is monitored with unfavorable results.

2. Then the firm decides whether to play or not and, in case it does, declares how much it will pollute during the following period (x') and pays the corresponding tax (T) in advance. (If the firm refuses to play it will neither produce nor pollute and the game is finished.)

3. Finally, the firm produces and pollutes and the Agency inspects it with a known probability $\lambda(x)$ and fines it in case of an unfavorable auditing.

b. Overall private cost and the behavior of the firm. In the institutional setting defined above, the firm must make three kind of decisions: it must decide, first, whether it is going to play or not, then which emission level it will declare for the next period, and finally whether to comply or not with the level declared previously. The objective of the Agency is to provide the proper incentives for these decisions to be taken efficiently. In what follows we analyze the three questions although we do not do it in order for practical reasons.

Firm overall cost can then come from abatement effort, from pollution taxes and from fines. The first two concepts are defined above, and now we need a proper definition for fines. As mentioned above, imperfect-monitoring technology implies that the Agency can incorrectly judge the compliance of an inspected firm with a positive probability z, $0 < z < 1$.[8] In this case a firm that complies and is monitored with probability λ would be fined with a probability λz. Similarly, a noncomplying firm would be punished with a probability $\lambda(1 - z)$.

Then, the expected overall cost (C) of a risk neutral firm which declares and complies with an emission level x' can be defined as:

$$C(x', \theta) = c(x', \theta) + T(x') + m(x')\lambda(x')z. \tag{4}$$

A violation of environmental regulations occurs when the firm declares an emission level (x') and emits a greater one. As compliance effort is a moral hazard variable, once the decision of cheating has been taken, the firm will reduce its compliance cost to zero and will emit in accordance (resulting in a pollution level of, say, $x^M > x'$). Hence, the expected overall cost of a firm that declares and cheats an emission level x', is given by:

$$C(x^M, \theta) = T(x') + m(x')\lambda(x')(1 - z). \tag{5}$$

To be enforceable, the policy instruments chosen by the Agency (taxes, inspection probabilities and fines) must fulfill the following condition (derived from (4) and (5)):

$$\begin{aligned} (6) \quad & c(x', \theta) + T(x') + m(x')\lambda(x')z \\ & \qquad \leq T(x') + m(x')\lambda(x')(1 - z) \qquad \text{Enforceability.} \end{aligned}$$

Apart from that, when the Agency proposes a pollution level for any firm type, it will expect that the firm will choose the emission level designed for it and not any other. So the pollution function $x(\theta)$ must be incentive compatible. If a firm is of type θ, it must solve its cost minimizing problem by choosing the pollution level $x(\theta)$ designed for it by the Agency, and not any other (if a firm is of type θ, then $x' = x(\theta)$). Then the pollution menu ($x(\theta)$) must be such that the firm would not have any incentive to pretend to be of a different type (or to lie about its private information). This is represented by the following necessary condition:

$$c(x(\theta),\theta)+T(x(\theta))+m\lambda(x(\theta))z \;\le\; c(x',\theta)+T(x')+m\lambda(x')z \qquad \forall\, x'\neq x(\theta) \qquad \text{(Incentive Compatibility).} \tag{7}$$

If conditions (6) and (7) hold, the firm could find producing nonprofitable. Assuming that the firm cannot close down as a result of setting up the environmental policy, we will need to define a third condition for the equilibrium of the game. The firm will only decide to participate in the game if the cost burden of the environmental policy is not too high for it. We assume that there is a reservation cost ($\overline{C}$) which, in order to simplify matters, will be the same for any type of firm and that, to guarantee the participation of the firm, the contract set by the Agency must fulfill the following necessary condition:

$$c(x(\theta))+T(x)+m(x)\lambda(x)z \;\le\; \overline{C} \qquad \text{(Participation).} \tag{8}$$

4. Design of the environmental policy. Summing up the results obtained in the previous section, in order to guarantee the application of the environmental policy the Agency must set a menu which will make the firm choose the pollution level designed for the private information it has (condition (7)), and will make it adjust its emissions to the level declared to the Agency (condition (6)). Additionally, if the participation restriction is binding, the cost burden of the optimal decision of the firm must guarantee its participation in the regulation game (condition (8)). According to the revelation principle (see Gibbard [1973], Green and Laffont [1977], Dasgupta et al. [1980]) and Myerson [1979]), these conditions are sufficient to define the environmental policy as an equilibrium of the revelation game.

In this section we are interested in solving the following two questions. First, what kind of pollution programs are incentive compatible (or fulfill condition (7)). Second, what are the optimal instruments (taxes, monitoring probability and fines) which enable us to enforce any incentive compatible pollution program (fulfilling simultaneously conditions (6) and (7), and condition (8) if required). In the next section we will analyze a third and central question: What is the most efficient pollution program?

a. Incentive compatible pollution programs. From the incentive-compatibility condition (equation (7)), we can deduce that a pollution program $(x(\theta))$ is incentive compatible if and only if it is nondecreasing in θ. In other words, high compliance cost firms must be allowed to pollute more than low compliance cost firms. Although this result is intuitively acceptable, a higher effort to reduce pollution must be done where it is less costly, when there is private information it is not self-evident. That is why we offer a formal proof of this in the Appendix. In short, this result comes from the application of Mirrlees's sorting condition to the environmental regulation game (see, for example, Guesnerie and Laffont [1984]). A graphical explanation is also offered below in a reduced version of the model.

b. Optimal instruments for incentive compatible pollution programs. Having said that the environmental agency can enforce any nondecreasing pollution program, the next step is to define the optimal policy instruments that the Agency must use with that purpose. In defining the efficient instruments we will first describe the optimal fines and optimal monitoring policies and then the optimal taxes in the two opposite cases when participation restriction is or is not binding.

Feasible fines and optimal inspection probabilities. First of all, from enforceability (condition (6)) we can deduce that the inspection probability and the noncompliance fine are related as follows:

$$\lambda(\theta) \geq \frac{c(x,\theta)}{m(1-2z)}. \tag{9}$$

Then, for a given fine (m), the monitoring probability has to be at least equal to the relation between the savings in compliance cost and the fine multiplied by the effective probability of it being charged. As monitoring is costly and fining cheap, the Agency will always prefer to keep probability λ at its minimum and, if needed, to set a higher fine to avoid consuming resources in monitoring.

However, this is not realistic. In practice, it is reasonable to assume that there exists a maximal (legal, credible or enforceable) noncompliance fine (m), and the Agency will always prefer to impose such a fine to punish any deviation by the firm (see, for similar situations, Harrington [1988]). Therefore, given the maximal fine allowed by law or credibility, the rational Agency will choose the minimal monitoring probability (λ^*) which guarantees the firm's compliance. Then the optimal monitoring policy is given by:

$$\lambda^*(\theta) \;=\; \frac{c(x,\theta)}{m(1-2z)}. \tag{10}$$

The monitoring policy objective is to guarantee that the emission level is adjusted to what was declared by the firm. However, as monitoring technology is imperfect, even when the firm behaves honestly, it faces a positive probability of being punished. Thus, the monitoring policy implies some unfair penalties. It could be though that these penalties should not be collected. However, the designed mechanism requires credible fines and their elimination would only weaken the incentives for compliance. The solution to this apparent contradiction, firms complying and being punished, consists in admitting that the environmental agency must commit itself to impose some penalties on the firms in order to preserve its reputation. Without such penalties, environmental policy is not possible and the unique alternative is to direct polluting firms to close down. This is a direct consequence of the recurrent character of the monitoring game. If firms comply, then they must not be punished; but if there are no penalties, then firms do not comply. In other words, the inspection sub game does not have a pure strategy solution. This is a consequence for two reasons. First, it is obvious that permanent monitoring is technically and financially impossible and never monitoring is inefficient. Second, when monitoring technology is imperfect, no punishment eliminates the credibility of economic sanctions and reduces the power of the Agency to nothing. The only alternative is to impose sanctions based on the available technology.

The next step is to characterize the optimal tax function which allows for the implementation of a feasible decision function. When the firm declares its emission level it also implicitly reveals its type (or at least the type it pretends to be). Using the procedure proposed by Mirrlees [1971], we first define the total expected cost of the type θ firm which is revealed to be a type θ' as:

$$C(\theta,\theta') \;=\; c(x(\theta'),\theta) + T(\theta') + m\lambda(\theta')z. \tag{11}$$

To be incentive-compatible the pollution program and the tax scheme must be such that the firm chooses its best strategy by declaring its true type. This condition can be represented by the following minimum value function:

$$\varphi(\theta) \,=\, \underset{\theta'}{\mathrm{MIN}}\, c(x(\theta'),\theta) + T(\theta') + m\lambda(\theta')z \,\equiv\, C(\theta,\theta) \,\equiv\, C(\theta). \tag{12}$$

And, according to the envelope theorem,

$$\frac{\partial\varphi(\theta)}{\partial\theta} \,=\, \frac{\partial C(\theta)}{\partial\theta} \tag{13}$$

which implies:

$$C(\theta) \,=\, C(\theta) + \int_{\theta}^{\theta} \frac{\partial C}{\partial\theta}\, d\theta. \tag{14}$$

We can now obtain the tax program by first substituting the optimal monitoring policy (10) into the compliance cost function and solving for the tax function. The result is the following optimal tax program, when the participation constraint is not binding:

$$T(\theta) \,=\, C(\underline{\theta}) - c(x,\theta)\left(\frac{1-z}{1-2z}\right) + \int_{\underline{\theta}}^{\theta} \frac{\partial C}{\partial\theta}\, d\theta. \tag{15}$$

According to this equation, the tax bill for the lower cost firm (with type $\underline{\theta}$) can be established independently from the incentive compatibility. From this starting value, a tax function $T(\theta)$ has to be designed to avoid any other firm type getting positive benefits by pretending to hide its true type. The resulting optimal program, which is analyzed in Section 5, does not introduce distortions at the bottom of the distribution function of θ, but it does at all superior levels.

It can occur, however, that, for some firms, the previous solution imposes a financial burden higher than its reservation cost. In this case, participation constraint (condition (8)) is binding, and, as no firm whatever its type can be run out of the market, we need to redefine the tax profile by introducing this constraint at the top of the distribution function. At this level, tax collection must be the highest value that maintains the more polluting firm in operation. Repeating the previous analysis, we obtain the optimal tax when participation constraint is binding as follows:

$$T(\theta) \,=\, \overline{C} - c(x,\theta)\left(\frac{1-z}{1-2z}\right) - \int_{\theta}^{\bar{\theta}} \frac{\partial C}{\partial\theta}\, d\theta. \tag{16}$$

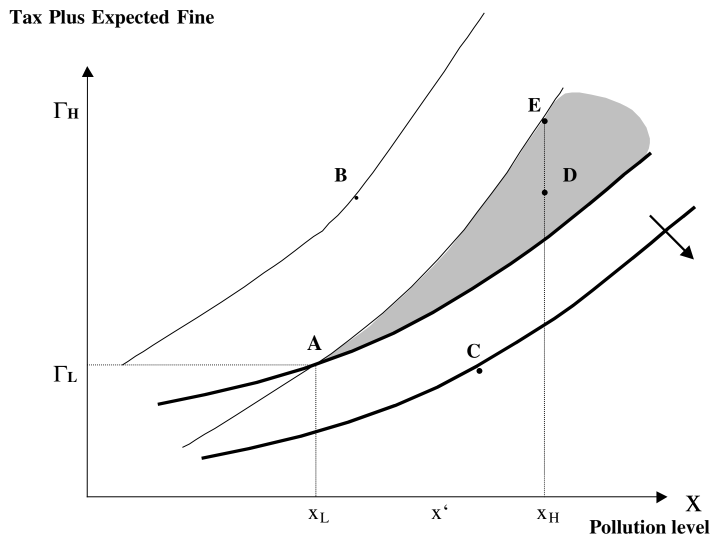

FIGURE 1. Incentive compatible environmental policies.

Summing up: the Agency can enforce any pollution program nondecreasing in the firm type. To enforce that program the Agency must fine firms with negative inspections with the maximum fine and set the inspection probability at the minimum which guarantees full compliance of the firm. Finally, the tax program must be defined in such a way that the firm, whatever its type, will have no incentives to lie about its private information.

c. A graphical illustration of the incentive compatible environmental policies. To obtain a graphical illustration of the incentive compatible programs defined above, we need to simplify our model. This can be done by assuming that the firm could only be one of two types: with a low compliance cost (with $\theta = \theta L$) or with a high compliance cost (with $\theta = \theta_H > \theta_L$). The decision of the firm consists of choosing how much to pollute and, consequently, how much it will pay the Agency in taxes and expected fines. The possible decisions of the firm and the contracts offered by the Agency can all be represented in a single diagram as appears in Figure 1.

The horizontal axis is the pollution level (x) and the vertical axis represents the expected transfer to the Agency (total tax plus expected fine or $\Gamma = \Gamma + \lambda mz$). The firm decision can be analyzed by using the isocost curves derived from equation (4), which are represented by bold lines for the low cost firm and by normal lines otherwise. The firm will always prefer higher pollution and lower taxes and, consequently, the overall cost increases in the southwest direction.

For a certain level of emissions (say x' in the Figure) the high cost firm will also require a higher reduction in the tax bill than the low cost firm in order to be willing to reduce pollution in one unit (as its marginal abatement cost is higher). For that reason the isocost curves are steeper for the high cost firm.[9]

The Agency will propose a menu consisting of a pair of contracts (x_L, Γ_L) and (x_H, Γ_H) and will expect that if the firm is low cost it will choose the first and, otherwise, the second. Now, suppose that the Agency decides to design contract A in Figure 1 for the low cost firm, and let us analyze some alternatives for the contract it can design for the high cost firm.

Contract B, for example, is not incentive compatible. In that case the high cost firm will choose contract A, pretending to be a low cost firm, which will result in less costs than contract B. The same will occur for any contract lying above the isocost curve of the high cost firm passing by point A in the diagram. In all these cases the high cost firm will not have incentives to reveal its true type. Contract C for the high cost firm, for example, is not incentive compatible either. In that case it will be the low cost firm which will prefer C instead of contract A designed for it by the Agency. Then the Agency must not design any contract for the high cost firm lying below the bold curve passing through point A in the diagram. Moreover, any contract lying in between the two isocost curves passing through A, or the shaded area of Figure 1, will be incentive compatible as the firm, whatever its type, will have incentives to take the decision designed for it and will reveal its private information. From that we can also deduce that, provided that the policy instruments are adequate, the Agency can enforce any pollution program that allows the high cost firm to pollute at least the same quantity as the low cost firm.[10]

Suppose now that the Agency wants the emissions of the firm to be x_L if it is low cost and x_H, otherwise. The environmental instruments can be used to give the proper revelation incentives and to enforce this pollution program. The Agency can, for example, present to the firms the pair of contracts A, D, and it will work properly. Nevertheless, as the Agency knows the advantages of a higher revenue, it could do better by increasing the tax bill to point E. That is to say, if the pollution program is (x_L, x_H) the optimal instruments will be (Γ_L, Γ_H). Then for any incentive compatible pollution program it is possible to find the optimal policy instruments.

4. Optimal pollution and optimal taxes. We are now ready to solve the central question of what the optimal pollution program is. For this we first recover the objective function of the Agency defined above and according to which the Agency is committed to minimize the expected social cost of reaching an environmental standard:

$$\text{(1)} \qquad \underset{x(\theta)}{\text{MIN}}\, \text{EED} + \text{ECC} + (1+\gamma)\text{EMC} - \gamma(\text{ET} + \text{EM}).$$

With the above elements we can use equations (2), (10) and (15) to define all the elements of the social welfare function explicitly when the participation constraint is not binding as appears in Table 1.

The first order condition, which characterizes the optimal decision profile, is:

$$\text{(17)} \qquad \frac{\partial D}{\partial x} = -\frac{\partial c}{\partial x}(1+\gamma)\left[\left(\frac{v}{m(1-2z)}+1\right)\right] + \gamma\frac{F(\theta)}{f(\theta)}\,\frac{\partial^2 c}{\partial\theta\partial x}.$$

This expression is the main result of this paper and defines the efficient environmental policy in the general model. Equation (17) defines the best decision for each firm type as a function of the private information it has, the marginal welfare benefit of public revenue (γ), the unitary monitoring cost (v) and the maximum fine ($\bar{m}$). The term in the lefthand side of equation (17) is the marginal environmental damage. The first term in the righthand side is the marginal abatement cost ($-\partial c/\partial c$) multiplied by a factor representing the effects of the different parameters of the problem. The last term represents the monetary incentive that must be given to the firm as an incentive for the honest

TABLE 1.

Components of the Social Welfare Function	
Expected Environmental Damage	$\mathbf{EED} = \int_{\underline{\theta}}^{\bar{\theta}} \mathbf{D}(\mathbf{x}(\theta))\mathbf{f}(\theta)\,\mathbf{d}\theta$
Expected Compliance Cost	$\mathbf{ECC} = \int_{\underline{\theta}}^{\bar{\theta}} \mathbf{c}(\mathbf{x}(\theta),\theta)\mathbf{f}(\theta)\,\mathbf{d}\theta$
Value of Expected Monitoring Cost	$\mathbf{EMC} = (\mathbf{1}+\gamma)\int_{\underline{\theta}}^{\bar{\theta}} \mathbf{v}(\mathbf{c}(\mathbf{x},\theta)/\bar{\mathbf{m}}(\mathbf{1}-\mathbf{2z}))\,\mathbf{f}(\theta)\,\mathbf{d}\theta$
Value of Expected Tax Collection	$\mathbf{ET} = \gamma\int_{\underline{\theta}}^{\bar{\theta}} (\mathbf{c}(\underline{\theta}) - \mathbf{c}(\mathbf{x},\theta)(\mathbf{1}-\mathbf{z})/(\mathbf{1}-\mathbf{2z}) + (\mathbf{1}-\mathbf{F}(\theta))/(\mathbf{f}(\theta))(\partial\mathbf{c}/\partial\theta))\,\mathbf{f}(\theta)\,\mathbf{d}\theta$
Value of Expected Fine Collection	$\mathbf{EF} = \int_{\underline{\theta}}^{\bar{\theta}} \gamma\mathbf{z}(\mathbf{c}(\mathbf{x}(\theta),\theta)/(\mathbf{1}-\mathbf{2z}))\,\mathbf{f}(\theta)\,\mathbf{d}\theta$

v is the nominal cost of a single inspection of the firm.

revelation of its private information. Policy instruments, like the total tax bill and the monitoring probability functions can be derived from equations (15) and (10).

The best way to interpret this result is by comparing it with the theoretical Pigouvian program. In a "perfect world," where incentives to reveal private information are not needed, there is no distortionary taxation ($\gamma = 0$) and monitoring is costless and perfect ($v = 0$ and $z = 0$), the optimal pollution is obtained when the marginal damage is equal to the marginal abatement cost:

$$\frac{\partial D}{\partial x} = -\frac{\partial c}{\partial X} \qquad \text{(Pigou).} \tag{18}$$

All other terms in the general solution denote the inefficiencies coming from the pre-existence of distortionary taxation, from costly and imperfect monitoring and from asymmetric information. We can now obtain several particular cases that appear in the literature.

First, let us assume that monitoring is free ($v = 0$) and there is perfect information (the last term on the righthand side of (17) is zero). In that case we will obtain the Bovenberg and Goulder [1996] solution according to which, when there are distortionary taxes in the economy ($\gamma > 0$), at the optimal pollution level the marginal environmental damage is higher than the marginal abatement cost. In that case, the optimal pollution level is defined by:

$$(19) \quad \frac{\partial D}{\partial x}\left(\frac{1}{1+\gamma}\right) = -\frac{\partial c}{\partial X} \qquad \text{(with pre-existing tax distortions).}$$

Second, if in addition to pre-existing tax distortions there is also costly and imperfect monitoring ($v > 0$ and $0 < z < 1$), at the optimal pollution level there will be a greater distance between the marginal damage and the marginal abatement cost. In that case the optimal pollution level will be defined by:

$$(20) \quad \frac{\partial D}{\partial x}\left(\frac{1}{(1+\gamma)(1+(v/\bar{m}(1+2z)))}\right) = -\frac{\partial c}{\partial X} \qquad \text{(and costly monitoring).}$$

Let us come back now to the case where monitoring is costless and analyze the effects of asymmetric information. In that case, the Agency will need to modify the tax bill and the inspection probability in order to preserve the incentives for the firms to reveal their true type. Then the optimal pollution program for any value of θ will be defined by:

$$(20) \quad \left[\frac{\partial D}{\partial x} - \gamma\frac{F(\theta)}{f(\theta)}\right]\frac{1}{1+\gamma} = -\frac{\partial c}{\partial X} \qquad \text{(Asymmetric information).}$$

Again, the marginal abatement cost is lower than the marginal damage and the resulting optimal pollution is identical to that of the basic regulation model with asymmetric information developed by Baron and Myerson [1982] and Laffont and Tirole [1992] and applied to environmental taxation by Laffont [2000]. The Pigouvian solution will only be efficient for the lower cost firm (where $\theta = \underline{\theta}$ and consequently for $F(\theta) = 0$). For all other situations, as the Agency will need to modify environmental policy to obtain an honest revelation of the private information, the marginal abatement cost will be lower than the marginal environmental damage at the optimal pollution level. Note also that asymmetric information is not sufficient to abandon the Pigouvian prescription, as the marginal benefit of public revenue must also be higher than zero ($\gamma > 0$). In other words, the existing distortionary taxes in the economy are the reason why, in presence of asymmetric information, optimal environmental taxes are lower than Pigouvian taxes (and nothing prevents them from being negative).

Finally, for the general model, allowing for pre-existing tax distortions, asymmetric information, and costly and imperfect monitoring, the optimal program can be described by:

$$\left[\frac{\partial D}{\partial x} - \gamma \frac{F(\theta)}{f(\theta)}\right] \frac{1}{1+\gamma(1+(v/m(1-2z)))} = -\frac{\partial c}{\partial X} \qquad \text{(General model).} \tag{21}$$

Starting from the Pigouvian tax we can say that any of the problems analyzed in this paper will lead to optimal policies where there is an increasing distance between the marginal damage and the marginal abatement cost as we introduce further complications in the institutional setting where the environmental policy is applied. All of these complications will also result in further reduction in the optimal pollution tax and increasing levels of optimal pollution. This is shown graphically in Figure 2.

The optimal Pigouvian program for a singular firm is defined in point A. Allowing for tax distortions will reduce the optimal tax and increase the optimal pollution to point B. If, additionally, we allow for costly monitoring and enforcement there will be further reductions in the optimal tax that will result in higher pollution as represented in point C. Furthermore, if there is also asymmetric information, and the firm does not have the lowest possible abatement cost, there will be further reductions in the severity of the optimal environmental policy as represented by point D.

6. Conclusion. We presented a general model which allows for the definition of the optimal environmental policy when there is private information, costly and imperfect monitoring and when the environmental policy is applied in a context where there are pre-existing distortionary taxes in the economy. We first define the kind of pollution programs that could be implemented in the economy according to the incentive compatibility condition and derive the optimal policy

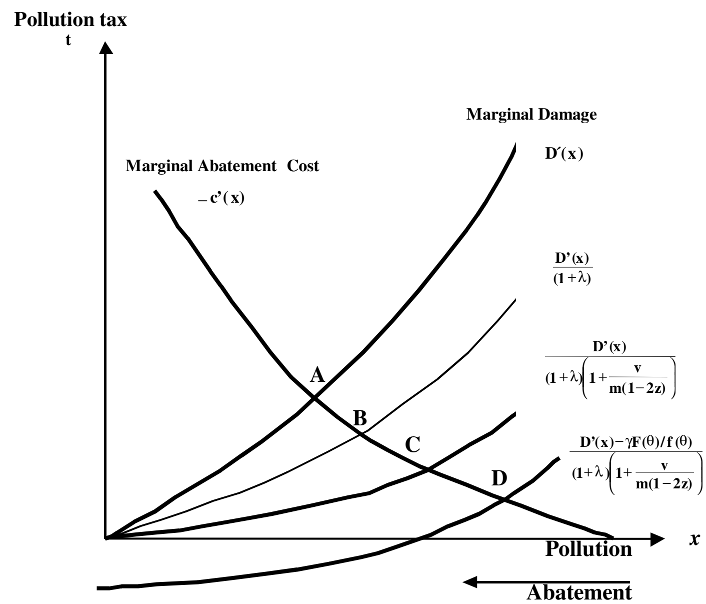

FIGURE 2. The optimal pollution program for a single firm.

instruments that allow for the implementation of any feasible pollution program.

The main conclusion is that, when there are private and public costs for enforcement in addition to private information, the optimal policy will lead to greater emissions and lower environmental taxes than in the ideal Pigouvian situation where emissions are determined by the equality between marginal damage and marginal abatement cost. Pre-existing distortionary taxes also exacerbate the effects of asymmetric information on the optimal environmental tax.

The optimal policy in the general model also enables us to analyze several particular cases that are "nested" in the model and that have already been studied in many fields of economics ranging from the theory of optimal taxation to enforcement and incentives theory.

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Appendix

In this section the following proposition is demonstrated.

Necessary condition for implementability. A Pollution Program $x(\theta)$ is incentive-compatible, or implementable, through pollution taxes and expected fines if it is nondecreasing in θ.

The proof is derived from the necessary and sufficient conditions of the cost minimizing problem for each firm type.

Let us define, for a simplified exposition, the following expected transfer function for a firm that is revealed to be of type θ', pollutes $x(\theta')$, pays the corresponding tax bill $(T(x(\theta')) = T(\theta'))$, is inspected with a known probability $(\lambda(x(\theta')) = \lambda(\theta'))$ and, in the case of negative auditing, pays the fine $m(x(\theta')) = m(\theta'))$:

$$\Gamma(\theta') = \Gamma(\theta') + \lambda(\theta')m(\theta')z. \tag{A.1}$$

The cost minimizing problem of the firm of type θ that can declare to be of any type θ' can be described as:

$$\underset{\theta'}{\text{Min}}\, \phi(\theta, \theta') = \varphi(x(\theta'), \Gamma(\theta'), \theta). \tag{A.2}$$

The necessary and sufficient conditions for truth telling, that is, $\theta' = \theta$, are:

$$\left.\frac{\partial \phi}{\partial \theta}\right|_{(\theta,\theta)} = \frac{\partial \phi}{\partial x}\frac{\partial x}{\partial \theta'} + \frac{\partial \phi}{\partial \Gamma}\frac{\partial \Gamma}{\partial \theta'} = 0 \tag{A.3}$$

$$\left.\frac{\partial^2 \phi}{\partial \theta^2}\right|_{(\theta,\theta)} > 0. \tag{A.4}$$

The sufficient condition for a decision to be implementable can be deduced as follows.

Differentiating necessary condition (A.3) with respect to its two arguments yields:

$$\left.\frac{\partial \phi^2}{\partial \theta'^2}\right|_{(\theta,\theta)} = -\left.\frac{\partial^2 \phi}{\partial \theta' \partial \theta}\right|_{(\theta,\theta)}. \tag{A.5}$$

This allows one to rewrite the second-order condition as:

$$\left.\frac{\partial\phi^2}{\partial\theta'^2}\right|_{(\theta,\theta)} = \frac{\partial}{\partial\theta}\left(\frac{\partial\phi}{\partial x}\right)\frac{\partial x}{\partial\theta'} + \frac{\partial}{\partial\theta}\left(\frac{\partial\phi}{\partial\varsigma}\right)\frac{\partial\varsigma}{\partial\theta'}. \tag{A.6}$$

The necessary condition to be fulfilled by the expected transfer function can be obtained by using the first order condition:

$$\frac{\partial\varsigma}{\partial\theta'} = -\frac{(\partial\phi/\partial x)}{(\partial\phi/\partial\varsigma)}\frac{\partial x}{\partial\theta}. \tag{A.7}$$

Introducing the previous equation in condition (A.7), and grouping terms, we obtain the following equivalent expression for the second order condition:

$$\frac{\partial([(\partial\phi/\partial x)]/[(\partial\phi/\partial\Gamma)])}{\partial\theta}\frac{\partial x}{\partial\theta} < 0. \tag{A.8}$$

In other words, a pollution program $(x(\theta))$ is incentive-compatible, and implementable through taxes and fines, if $x(\theta)$ and the marginal rate of substitution between emissions (x) and expected transfers (Γ) vary systematically with the firm type. The marginal rate of substitution is negative, as firms will always prefer more pollution and low taxes and fines. Furthermore, a high value of θ also implies a high marginal abatement cost. Then firms with higher values of θ will also require higher compensation to reduce its pollution in one unit and will increase less its pollution when the tax bill is reduced marginally. If the marginal rate of substitution between emissions and transfers is decreasing in θ (the first factor on the lefthand side in (A.8) is negative) we can conclude that condition (A.8) requires a pollution program that was non-decreasing in (θ).

ENDNOTES

1. By policy we mean a set formed by both an objective and some policy instruments that allow for the realization of such an objective. An objective is an overall pollution level or, more exactly, a pollution profile defining the emission level expected by each one of the polluting firms. Policy instruments are, for example, taxes, inspections to the firms, noncompliance fines, etc.

2. Evidently if, instead of taxes, the instrument used to improve the environment consists in some form of legal regulation or a tradable permit that is given for free

to the polluter, then there is no revenue available to offset any of the newly created distortions.

3. According to Parry [1999] $1+\gamma$ is equivalent to "the resource value of a dollar plus the incremental efficiency loss from higher taxes necessary to raise an extra dollar revenue."

4. The only practical implication of assuming a positive second dividend is that the parameter of γ of our model will also be higher than zero. As explained below, the size (not the sign) of γ plays a crucial role in defining optimal taxes and pollution levels and the main theoretical results still hold in the case of a negative double dividend.

5. Different from others (see, e.g., Swierbinski [1994] and Spulber [1988]), in our case the firm's decision variable is the emission level and not the emission reduction over a maximum permitted level.

6. Apart from its mathematical lack of difficulty, this function is compatible with an overall cost function that is separable in emissions. This function is common in the literature, and additional explanations can be found in, e.g., Swierzbinsky [1994], Russell [1990], Spulber [1988] and Nichols [1984].

7. We use a capital T to denote the total tax paid by the firm and reserve the lowercase t for the unitary pollution tax.

8. Monitoring technology can induce two types of mistakes: first, there are some measure errors which occur with a certain probability $(1-a)$ and, second, the Agency can accept (with a certain probability b) the measure obtained by its instruments. Then z, the probability of judging the firm behavior erroneously, will be equal to $a(1-b)+(1-b)a$. In a different context, probability z was defined in the same way by Laffont and Tirole [1992, Chapter 12] to study the cost padding regulation problem. For a wide justification of the application of this probability to environmental auditing, also see Russell [1990].

9. This is the meaning of the assumption that a high compliance cost firm also has higher marginal abatement cost than a low cost firm.

10. This is the proposition that is proved by the general model in the Appendix.

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