Emission tax on a monopolistic polluter with unknown costs

~ **Sawaki, Hisashi** *(Okayama University, Japan)*

Abstract: *Simple emission taxes chosen by a regulator who does not know the precise costs of a regulated monopolistic firm are examined. When the costs of both producing the final products and abating pollution are not known, but are known to be related, the regulator can cause the firm to reveal its costs truthfully by postponing its decision on a tax rate until it has inspected abatement equipment. Depending on the basic parameters, this postponement can increase social welfare.*

Key words: Effluent Tax; Environmental policy; Monopolistic Polluter; Incomplete information; Signaling.

1. Introduction

In practical policy-making, environmental regulators rarely know the abatement costs of the firms they regulate as clearly as the firms do. With such asymmetric information, the timing of environmental policy can become a delicate issue. On the one hand, if the regulator commits to a policy before the firms take any action, it is able to exploit first-mover advantages. On the other hand, if the regulator delays its policy decisions until after the regulated firms make some abatement investments, the regulator might be able to learn something about the firms' private costs. Such a delay of regulation may also induce the firms to voluntarily distort their investments to signal their private information, if the firms are strategic enough to recognize their actions can influence the regulator's decisions. By taking strategic actions and thereby revealing their true efficiencies, firms might expect to induce less stringent regulatory policies. If these actions are welfare-improving, there is a possibility for the regulator to exploit them.

Some anecdotal evidence shows that regulated firms recognize that their actions can influence future regulation in some circumstances. Consider a quote from Brent Blackwelder, president of Friends of the Earth: "While some of the environmental changes now emerging in corporate America are genuine and welcome…a few are being specifically designed to preempt more stringent public policies from emerging." Another quote from a Monsanto executive goes: "[Taking the first steps toward pollution control] allows a company to play a key role in shaping the way its industry is regulated."

If a government also acts strategically, it will consider the possibility of exploiting strategic behavior by firms. Letting firms with private information take the first action and then exploiting their voluntary efforts may be more optimal in terms of social welfare than committing to a specific policy before the firms take any action.

The objective of this paper is to investigate strategic environmental policies when a government regulates a monopolistic polluter without precise knowledge of the firm's pollution abatement costs and its policy instrument is restricted to simple linear emission taxes. Specifically, the paper focuses on the timing of environmental policy: it asks whether a government can cause a firm to truthfully reveal relevant information by delaying its policy decision. It shows that this can actually be achieved under specific assumptions. The model developed below assumes that the marginal cost of producing goods, as well as that of abating effluent, is unknown to the government, but that these costs are known to be related to each other and to reflect the firm's overall technological efficiency. These are the only assumptions specific to this model and all other assumptions are made for the sake of tractability.

Under these assumptions, it is shown that what enables the government to identify the firm's true costs is the signaling behavior of the firm itself to induce less stringent policies. This signaling explains what, at least seemingly, resembles 'voluntary' environmental protection undertaken by firms and turns out to be welfare-improving, depending on the basic parameters.

2. Literature review

The literature related to environmental regulation under uncertainty is increasing. Arrow and Fisher (1974), Kelly and Kolstad (1999), and Pindyck (2000) among others have analyzed the effect of uncertainty and irreversibility on environmental policy. However, the focus of these models is not on informational asymmetry.

In an early paper, Weitzman (1974) investigated whether price or quantity controls are preferable when a regulator is uncertain about industry costs. Following Weitzman, mechanism design literature has analyzed optimal environmental policy under asymmetric information without restricting a regulator's instrument to a linear policy. This approach, which is different from that of this paper, is taken, for instance, by Kwerel (1977) and Ellis (1992). See also Baliga and Maskin (2003).

The effect of informational asymmetry on environmental regulation in dynamic settings are investigated in Newell and Pizer (2003) and Hoel and Karp (2001) among others. However, these papers treat regulated firms as non-strategic price takers.

Moledina et al. (2003) consider dynamic environmental policy under asymmetric information, assuming that firms are strategic. However, in their model the regulator is naïve and abides by a simple non-strategic policy rule; therefore, outcomes are that the firms successfully cheat the regulator by sending untrue signals of their nature.

In the sense that both the regulator and polluters are assumed to be strategic, Yao (1988) and Denicolo (2000) are probably the papers most closely related to the one here. There are, however, some obvious differences. Yao (1988) considers a situation in which a regulator with incomplete information about technological capability imposes standards on automobile emissions. In his model, industry distorts a research investment downward to signal their umcompetitiveness. Denicolo (2000) analyzes a duopoly, not monopoly, model that has a feature similar to a 'beer-quiche' game in the sense that a Sender (one of the two firms) signals its type by choosing from two actions (using either a good or a bad technology) and a Receiver (the regulator) responds with one of two actions (whether to regulate or not to regulate). The purpose of the signaling is to induce the regulator to impose more, not less, stringent pollution regulation and thus raise the rival's costs. There is also a more essential difference between those two papers and this one; this paper focuses on the timing of the environmental regulation and compares welfare under different policy regimes.

As discussed in Section 8, an important conclusion of the present paper is that under some circumstances discretion (i.e., making a later decision about the tax rate) beats rules (i.e., committing to a tax rate before learning the costs of the firm) in terms of social welfare. However, it should be stressed that discretion in this context does not mean negligence of an important but uninviting task for a time. Rather, it means that the government promises the introduction of a future effluent tax, but delays its rate decision so as to induce efforts on part of the firm.

The rest of this paper is organized as follows. Section 3 introduces the model. Section 4 examines the Abatement-First Case, in which the firm spends on sunk costs for abatement activities first and then the government decides on a tax rate. Section 5 analyzes the Tax-First Case. Section 6 is devoted to welfare considerations. Section 7 discusses alternative setups. The final section compares the result of this model with those of rule-versus-discretion models, as mentioned above.

3. The Model

A simple model of effluent control is developed, in which a government regulates a monopolistic firm producing final products that generates external damages. For a more concrete example, let us assume that the externality in question is air pollution. The firm produces output Y and discharges smoke S, generating D(S) in external damage. The firm's cost function can be written as $C(Y,A)$, where $A \geq 0$ is the abatement expense of pollution treatment, with $C_1 > 0$ and $C_2 > 0$, where the subscripts denote partial derivatives. If the government imposes a tax t per unit of smoke discharged, the firm's profit will be,

$$\pi = pY - C(Y,A) - tS$$

where p is the price of the product. In the absence of taxes, the firm will set A = 0.

For tractability, the model uses the following parametric specifications. The inverse demand function is assumed to take the simple linear form $p = f(Y) = \delta - Y$. It is also assumed that the cost function is linear in output and abatement expenses:

$$C(Y, A) = cY + acA$$

A key assumption here is that the marginal costs of production and abatement are positively related, reflecting the firm's overall technological efficiency, which the government cannot directly observe.[1] Although a more complete analysis should involve the research and development (R&D) activities carried out by the firm so as to affect these marginal costs, this paper focuses on a short time-horizon for which the firm's efficiency is predetermined.[2] The parameter c is assumed to be a random variable that takes on the values c^H and c^L with probabilities m and 1-m, respectively. That is, m is the prior probability that the firm is a high-cost or less efficient type. While the firm itself knows the exact value of c, the regulator knows only the above distribution.

It is assumed that S is increasing in Y and decreasing in A and that the effect of pollution abatement diminishes as abatement expenditure increases. An expression that satisfies these conditions and is relatively tractable is:

$$S(Y, A) = vY - \sqrt{A} \quad (1)$$

The robustness of the conclusions of the model to other variants of the pollution function as well as more general functions is briefly discussed in Section 7. The damage function is assumed to be linear in S: $D(S) = S(Y, A)$, which implies that the marginal damage is unity. The parameters δ, a, and v are all positive constants and publicly known.

The sum of consumers' and producers' surpluses minus external damages is used as a measure of social welfare:

$$W = \int_0^Y f(Y)dY - C(Y, A) - S(Y, A)$$

4. Abatement-first case

This section examines a situation in which the regulator postpones its decision on a pollution tax rate until it has inspected the firm's abatement efforts. Abatement expenses are treated as sunk costs paid before production of the final products starts: e.g., the costs of constructing air-cleaning equipment, attaching scrubbers for stacks, etc.[3] The government is assumed to be able to observe the abatement effort (e.g., is able to inspect constructed equipment), as opposed to the firm's costs.

The timing of the game in this section is as follows: before the game starts, Nature chooses the firm's efficiency, c^H or c^L; in the first stage, the firm decides on its abatement level; in the second stage, the government chooses t after observing the abatement level, but not knowing the firm's efficiency; in the third stage, the firm chooses Y and generates smoke accordingly. This sequence is well recognized by both players.

The solution concept used here is a perfect Bayesian equilibrium (PBE), the definition of which is given in the context of the current model as follows: the firm and the regulator maximize their respective payoffs given each other's strategy and the regulator's set of beliefs about the firm's cost type; and the set of the beliefs is updated by the actual strategy of the firm on the equilibrium path using Bayes' rule.

Denoting the abatement level as $B \equiv \sqrt{A}$ and using the specifications from the previous section, the firm's profit can be rewritten as

$$\pi^i = (\delta - Y)Y - (c^iY + ac^iB^2) - t \times (vY - B)$$

i =H,L. (2)

In the third stage, the firm maximizes this profit with respect to Y taking t and B as parameters. The first-order condition yields:

$$Y^i = (\delta - c^i - tv)/2 \quad (3)$$

The government's objective function when confronted with a type c^i firm is:

$$W^i = \delta Y - Y^2/2 - (c^iY + ac^iB^2) - (vY - B) \quad (4)$$

where Y is given by Eq. (3). In the second stage, the government updates the prior m to a posterior probability by observing B, and then maximizes the expected welfare, $EW \equiv nW^H + (1-n)W^L$ with respect to t, taking B as given, where n is the posterior that the firm is of type c^H. The first-order condition for the above maximization yields:

$$t = 1 - (\delta - \hat{c} - v)/v, \quad (5)$$

where $\hat{c} \equiv nc^H + (1-n)c^L$ is the updated belief of the regulator about the firm's cost. It is noteworthy that the government imposes a lower emission tax on a firm believed to be more efficient (with a smaller $\hat{c}$). The reason for this is that once B has been set by the firm, $\hat{c}$ is the belief about the production cost, not the abatement cost. The government, which believes a smaller $\hat{c}$, then assigns a larger weight in its payoff based on its concern about the product market rather than about pollution. Substituting Eq. (5) into Eq. (2) yields:

$$Y^i = (2\delta - c^i - \hat{c} - 2v)/2. \quad (6)$$

To focus on interior solutions, I assume the following.

Assumption 1. $\delta - c^H - v > 0$.

In the first stage, the firm determines its abatement level strategically, taking into account all the above considerations. Substituting Eqs. (5) and (6) derives the firm's profit as a function of its true type, the belief held by the regulator about its type, and a signal sent by the firm:

$$\pi(c^i, \hat{c}, B) \equiv \left(\frac{2\delta - c^i - \hat{c} - 2v}{2}\right)^2 - acB^2 + \left(\frac{-\delta + \hat{c} + 2v}{v}\right)B$$

i =H,L (7)

As a benchmark I first derive a solution under complete information. As before, letting subscripts denote partial derivatives, I solve $\pi_3(c^i, c^i, B) = 0$ for B:

$$B^{i,Comp} = \frac{-\delta + c^i + 2v}{2a^i v}. \quad (8)$$

Again, to limit attention to interior solutions, I make the following assumption.

Assumption 2. $-\delta + c^L + 2v > 0$.

Returning to the incomplete information case, I take the derivative of the profit with respect to $\hat{c}$:

$$(9) \quad \pi_2(c^i, \hat{c}, B) = -\frac{2\delta - c^i - \hat{c} - 2v}{2} + \frac{B}{v}.$$

Now the final assumption is made.

Assumption 3. The model focuses on a situation in which smoke S = vY–B is positive.

That is, I exclude the situation in which the firm cleans air more than when it produces nothing, and receives subsidies instead of having taxes imposed. Since the first term of the RHS of Eq. (9) is $-Y^i$ [see Eq. (6)], Assumption 3 ensures that $\pi_2 < 0$. This fact leads to the following lemma.

Lemma 1 (Belief Monotonicity). Regardless of whether it is type c^H or c^L, the firm would like the regulator to believe that it is more efficient (smaller $\hat{c}$).

This leads to an incentive for a type c^H firm to mimic type c^L, and thus any report about its type submitted by the firm itself is not credible and carries no information as long as it is 'cheap talk,' i.e., a non-binding costless report.

To derive PBE, Figure 1 depicts isoprofit curves for the firm that are derived by equating Eq. (7) to some constant profit levels in $(B, \hat{c})$ space. Each isoprofit curve has an inverse-U shape (see Steps 1 and 2 in Appendix 1) and bold (thin) lines represent isoprofit curves for a type c^H (c^L) firm. Reflecting Lemma 1, the lower the location of an isoprofit curve, the larger is the firm's profit. Solving

$$\pi_3(c^i, \hat{c}, B) = -2a\ ^{i}B + (-\delta + \hat{c} + 2v)/v = 0$$

yields , $\hat{c} = 2ac^i vB + \delta - 2v$

which is shown in Figure 1 as two upward-sloping dotted straight lines. The straight line for i =L is located to the right of that for i=H. On this line, each indifference curve reaches its highest point, and the outcome achieved under complete information, Eq. (8), corresponds to points X and Y in Figure 1.

To describe equilibrium, we denote the profit that a high-cost type firm achieves under complete information as $\pi^{H,Comp}$, label the point at which the isoprofit curve corresponding to $\pi^{H,Comp}$ intersects the horizontal line $\hat{c} = c^L$ as point Z, and denote the abatement level corresponding to point Z as B^* (see Figure 1).

It is known that a signaling game with binary types can have many PBEs (pooling, hybrid, and separating equilibria) since Bayes' rule does not restrict the updating of beliefs following deviations from the equilibrium path. However, most of these off-equilibrium-path beliefs are unreasonable. To eliminate equilibria with unreasonable beliefs, this model uses 'intuitive criterion' developed by Cho and Kreps (1987). Since the model here satisfies the single-crossing condition, there is a unique intuitive outcome (selected by the criterion) that is the most efficient separating equilibrium outcome of all the PBE outcomes.

Proposition 1. In the unique intuitive outcome in the Abatement-First Case, a type c^H firm chooses abatement level $B^{H,Comp}$ and a type c^L firm chooses abatement level $Max(B^*, B^{L,Comp})$, which is greater than $B^{H,Comp}$. By observing the abatement level, the regulator is able to tell with certainty with which type it is confronted.

The proof of this result is given in Appendix 1. Intuitively, recall that Lemma 1 states that the firm would like to be believed to be more efficient. In particular, when point Y is to the left of point Z (i.e., when $B^* > B^{L,Comp}$), as in Figure 1, if a type c^L firm selects its complete-information abatement level (point Y), then a type c^H firm deviates from point X to Y. In any separating PBE, therefore, an efficient type (c^L) must choose an abatement level that is at least B^*

to 'run away' from the less efficient type. This upward bias in abatement effort generated by an efficient type firm is called 'distortion', and the intuitive criterion selects the separating PBE with minimum distortion (i.e., $B^* - B^{L,Comp}$) as a unique outcome. I call this a 'Distortion' Case.

On the other hand, when $B^* \leq B^{L,Comp}$, unlike in Figure 1, $B^{L,Comp}$ is large enough to prevent the less efficient type from mimicking an efficient firm, and thus the same outcome as under complete information emerges (a 'No-Distortion' Case).

The following corollary states that Distortion Cases are more pervasive than No-Distortion Cases.

Corollary 1. The No-Distortion Cases, in which type c^L selects $B^{L,Comp}$ in the unique outcome,

(i) never take place if $\delta - 2v \geq 0$, and

(ii) do not take place unless $c^H - c^L$ is sufficiently large, even if $\delta - 2v < 0$.

The proof of this result, as well as the meaning of 'sufficiently large', can be found in Appendix 2.

Thus, in many situations, an efficient firm (type c^L) distorts its abatement effort upward so as to discriminate itself from the less efficient type (c^H). This phenomenon, at least seemingly, resembles what is called 'voluntary' environmental protection undertaken by firms.

Several papers have addressed the question as to why firms engage in environmental protection beyond their requirements. Some argue that firms might benefit from the favorable public image of being 'greener.'[5] Maxwell, Lyon, and Hackett (2000) explain firms' overabatement activities as efforts to preempt future regulations, similarly to the current paper. However, in their paper information is complete and thus firms' activities do not have an element of signaling behavior. They focus on the case in which consumers will successfully lobby for new regulations if the firms take no voluntary actions. The objective of the firms in their model is to prevent such successful lobbying by consumers. In Denicolo (2000), cited in the introduction, overcompliance comes from rivalry between two firms. In my model, overabatement occurs without consumer interest groups or a competing firm.

Porter and van der Linde (1995) argue that pollution is a manifestation that firms are inefficient. Likewise, in this paper, less abatement effort is a manifestation that firms are inefficient. In spite of this resemblance, however, their main conclusion is very different from the context of this paper. They insist that stringent environmental regulation induces innovation and works to a polluting firm's advantage. In the model developed here, even after the imposition of an effluent fee, the marginal costs of production and abatement remain unchanged. Indeed, the fact that abating pollution is costly is the very reason that it can be used as a means of signaling.

Before proceeding to the next section, I briefly mention the tax rate and output levels selected in this Abatement-First Case. As the regulator distinguishes which type it faces in the unique outcome, it chooses the tax rate in Eq. (5) with $\hat{c}$ replaced by c^i. Then the output level chosen by the firm is Eq. (6) with $\hat{c} = c^i$. Thus,

$t^* = 1 - (\delta - c^i - v)/v$ and

$$Y^{i*} = \delta - c^i - v, \qquad \text{i =H,L.} \qquad (11)$$

5. Tax-first case

This section examines a more familiar sequence of the game: a Tax-First Case, in which the regulator sets an emission tax before the firm decides on abatement and production. In this case the regulator is not able to induce the firm to truthfully reveal its type, since the regulator is assumed to move first and have only a simple linear tax as a policy instrument.

Proceeding backward, in the second stage, the firm selects B and Y to maximize its profit in Eq. (2), taking t as given:

$$B^i = t/(2a^i) \text{ and } Y^i = (\delta - c^i - tv)/2$$

i =H,L. (12)

In the first stage, the government maximizes $EW \equiv mW^H + (1-m)W^L$ with respect to t, where m is the prior, and W^i is given by Eq. (4), in which B^i and Y^i are expressed in (12). The resulting tax rate is:

$$t^{**} = 1 - \frac{av(\delta - Ec - v)}{av^2 + 2E(1/c)}$$

where $Ec \equiv mc^H + (1-m)c^L$

$$E(1/c) \equiv m(1/c^H) + (1-m)(1/c^L).$$

As reported by Barnett (1980) and others, the optimal effluent fee is less than the marginal external damage in this monopoly set-up; if the regulator sets a Pigouvian tax (unity here), this would further restrict the already suboptimal monopolist's output.

The resulting output and abatement levels are:

$$B^{i**} = t^{**}/(2a^i) \text{ and}$$

$$Y^{i**} = (\delta - c^i - t^{**}v)/2'$$

i =H,L (14)

6. Welfare considerations

First of all, it is straightforward to show from Eqs. (4), (8), (11), (13), and (14) that under complete information, welfare in the Tax-First Case is always higher than welfare in the Abatement-First Case.

Returning to the incomplete-information case, the rest of this section compares ex ante welfare levels achieved under the above two sequences of the game of incomplete information: the Abatement-First Case and the Tax-First Case.

First, for later discussion, I derive optimal abatement and production levels achieved in a command-and-control economy with complete information, which is excluded in the set-up of this paper. Taking derivatives of Eq. (4) with respect to Y and B yields:

$$B^{i,Command} = 1/(2a^i) \quad \text{and}$$

$$Y^{i,Command} = \delta - c^i - v$$

i =H,L (15)

In a welfare comparison, a key question is through which channels does movement from the Tax-First Case to the Abatement-First Case generate a difference in welfare. There are three possible sources for bringing about such a difference. First, the regulator loses its first-mover advantage in affecting abatement levels. Second, an efficient firm distorts its abatement effort upward (in the

Distortion Case), which may offset the first effect. Third, by inspecting abatement equipment, the regulator distinguishes which type it faces, and thus can induce output equivalent to that in the command economy [see Eqs. (11) and (15)]. It is noteworthy that the second and third factors are related to the existence of incomplete information.

To observe the overall effects of the above three factors on welfare, simulations were carried out. One difficulty in deriving a general conclusion comes from the complexity of the functional form of B^*, which is shown in Eq. (A3) in Appendix 2.

The procedure for simulations is as follows. The parameters m, δ, a, v, c^H, and c^L are given specific values under Assumptions 1 and 2. Then the ex ante welfare in the Abatement-First Case is:

$$EW^* \equiv mW^{H*} + (1-m)W^{L*}$$

where W^{H*} is calculated using Eq. (4), with $B^{H,Comp}$ in Eq. (8) and Y^{H*} in Eq. (11); W^{L*} is calculated using Eq. (4) with Y^{L*} in Eq. (11) and B^* in Eq. (A3) if $B^* \geq B^{L,Comp}$ (Distortion Case), or $B^{L,Comp}$ in Eq. (8) if $B^* < B^{L,Comp}$ (No-Distortion Case). Ex ante welfare in the Tax-First Case is , $EW^{**} \equiv mW^{H**} + (1-m)W^{L**}$ where W^{i**} is calculated using Eqs. (4), (13), and (14). Finally, EW* is compared with EW**, excluding from the simulation situations that violate Assumption 3.

Simulations were carried out under the following assumptions: m = 0.5; δ is normalized to 10; and $c^L = c^H / 2$. This paper reports a result when v = 5. Figure 2 depicts the result for various values of c^H and a. Note that when v = 5 (Figure 2(a)), the range of c^H permitted by Assumptions 1 and 2 is (0,5). Areas I and III in Figure 2(a) show the ranges in which EW*<=EW** holds. That is, if the parameters fall within this range, the regulator is better off setting its tax rate first. In Area I, since c^H and a are relatively low, the optimal tax rate in a command economy, $B^{L,Command}$ in (15), is high; thus even the upward distorted B^* falls short of $B^{L,Command}$ Therefore, EW* becomes smaller than EW**. In Area III, B^* is too large and thus makes EW* smaller than EW**. By contrast, if the parameters fall within Area II, B^* becomes close to $B^{L,Command}$, and thus improves welfare (EW*>EW**).

Result.*Depending on the basic parameters, the regulator can increase ex ante welfare by choosing the Abatement-First Case, i.e., by postponing its tax decision until after it has inspected the firm's abatement equipment.*

Simulations were carried out for other values of v and showed that if v increases, i.e., if the marginal smoke discharged by producing output increases, then a relatively wider range of the space is covered by Area II (EW*>EW**) (Figure 2(b)). This result contrasts with that of the complete-information case, in which the Tax-First Case always dominates the Abatement-First Case. Under complete information, only the first of the three channels mentioned above, through which the difference in the timing brings about the difference in outcomes, works. Thus, if the regulator, who is a welfare-maximizer, moves first, it is always welfare improving. (Note not for publication: Computer software like

Mathematica can calculate the equations for the borderlines of Area I, II, and III. However the equations are extremely messy and omitted here.)

7. Alternative setups

Now I alter some of the assumptions in the above model. First, if the marginal costs of producing final products and abating pollution have no relationship, e.g., if they are drawn by Nature independently, then signaling by the firm never takes place; the Tax-First Case unambiguously brings about better welfare than the Abatement-First Case. Second, if the two costs have a negative relationship, then distortions, if any, occur in the opposite direction: a firm with higher marginal abatement costs distorts its abatement effort downward.

Next, I check the robustness of the results in this paper in regard to other specifications of the smoke function. Even if

$S(Y,A)=vY-\ln A$ is used instead of Eq.(1), Proposition 1 and the Result are qualitatively unaltered. Another alternative is $S(Y,A)=vY+1/A$, which was assumed in the Katsoulacos and Xepapadeas (1995) model of environmental policy under oligopoly. This set-up has the advantage that since smoke discharged is always positive, Assumption 3 in this paper becomes unnecessary. In this set-up, Proposition 1 remains the same qualitatively: the regulator can distinguish which type of firm it faces in the Abatement-First Case.[6] However, because of computational difficulties, the optimal tax in the Tax-First Case could not be explicitly derived in this set-up. Katsoulacos and Xepapadeas show that the optimal tax falls within a certain range, but this approach is problematic for my purpose of comparing precise welfare levels under two alternative regimes.

Though some variations of the model are considered above, this model remains special in number of ways. For instance, using general demand and/or smoke functions makes the exact level of the over-abatement impossible to determine and the welfare analysis intractable. However, if Lemma 1, as well as the technical single-crossing condition, holds with the same direction, the intuitive criterion selects an outcome that is qualitatively the same as in Proposition 1. With regard to the belief monotonicity (Lemma 1), Tarui and Polasky (2005) point out, although their model does not deal with asymmetric information so that firms neither overabate nor underabate in the sense that they do not distort their actions compared to under complete information, that:

With (emission) taxes that adjust, the firm has a strategic incentive to increase investment because a lower abatement cost function causes the regulator to set a lower tax rate (Tarui and Polasky, 2005, p. 449).

A similar property is inherited in the current paper, as explained immediately after equation (5), resulting in Lemma 1 and thus Proposition 1.

8. Concluding remarks

This paper has shown that under incomplete information about the abatement costs of a monopolistic polluter, a regulator can induce the polluter to signal its costs simply by postponing its tax-rate decisions until an inspection of the firm's abatement equipment. Furthermore, it was shown that under specific parametric assumptions, the firm's signaling behavior induced by this postponement is welfare-improving.

In this final section, I briefly mention the relationship between the results of this paper and those in commitment vs. discretion models. There are several papers that compare environmental policy under rules and discretion (e.g., Biglaiser et al., 1995; Tarui and Polasky, 2005; Requate, 2005). A typical conclusion of those papers is: Rules are more favorable in many cases, if it is possible to commit to them. This is because rules prevent firms taking strategic actions. On the other hand, the introduction of uncertainty brings about the merit of discretion, which allows the regulator to learn about the uncertainty and update its policy. Malik (1991) shows in his model with emission standards that even when there is substantial uncertainty, rules are preferable in most cases.

As for the timing of policy, the Tax-First Case in this paper corresponds to rules, while the Abatement-First Case corresponds to discretion.[8] The merit of discretion is doubled in this paper by the presence of incomplete information. By delaying its decision and allowing the polluter to first make an investment, the regulator not only learns the true costs of the polluter but also induces an efficient firm to conduct overabatement in most cases, which can be preferable under some parametric values. In this sense, the polluter's signaling behavior in this model can ease the time-inconsistency problem.

In many signaling models, distortions in a signal-sender's action have a negative impact on welfare (e.g., Collie and Hviid's [1993, 1994, 1999] series of international trade models).[9] The reason for this is that a signal-sender that is a welfare maximizer sacrifices part of its payoff so as to send a signal in such models. By contrast, distortions in this paper can be welfare-improving for a simple reason: The signal-sender is not a welfare maximizer; distortions caused by the firm when it sends a costly signal inevitably reduce its payoff, i.e., its profit, but can have a positive impact on welfare in the form of increased pollution abatement efforts.

Appendix 1 Proof of Proposition 1

This is given in several steps.

Step 1 Isoprofit curves are hyperbolic.

$\pi(c^i, \hat{c}, B) = \tilde{\pi}^i$, where the LHS is given by Eq.(7) and $\tilde{\pi}^i$ is some constant, can be rewritten as:

$$-ac^iB^2 + \frac{1}{v}B\hat{c} - \frac{1}{4}(\hat{c})^2 + \left(\frac{-\delta + 2v}{v}\right)B$$
$$-\left(\frac{2\delta - c^i - 2v}{2}\right)\hat{c} + \left(\frac{2\delta - c^i - 2v}{2}\right)^2 - \tilde{\pi}^i = 0$$

i=H,L (A1)

Since $(1/v)^2 - 4 \times (-a^{\ i}) \times (1/4) > 0$, Eq. (A1) represents hyperbolic curves in $(B, \hat{c})$ space. Solving the above quadratic equation for $\hat{c}$ yields two solutions. While the larger one has a U shape as the H-H segment of a line in Figure 1, the smaller solution has an inverse-U shape.

Step 2 Of the two solutions for $\hat{c}$, only the smaller one is relevant.

Totally differentiating Eq. (A1) with

respect to B and $\hat{c}$ yields the slope of an isoprofit curve:

$$\frac{d\hat{c}}{dB}=\frac{-\pi_3}{\pi_2}=$$

$$-\left(-2\boldsymbol{a}^{i}B+\frac{-\delta+\hat{c}+2v}{v}\right)\Big/\left(-\frac{2\delta-c^{i}-\hat{c}-2v}{2}+\frac{B}{v}\right)$$

Since $\pi_2 < 0$ holds under Assumption 3 and a small (large) B makes the numerator negative (positive), any isoprofit curve must have an inverse-U shape.

Step 3 The isoprofit curves satisfy the single-crossing condition.

$$\left.\frac{d\hat{c}}{dB}\right|_{i=H}=\left.\frac{d\hat{c}}{dB}\right|_{i=L}$$

Rearranging derives the tangency locus at which two isoprofit curves $\{\tilde{\pi}^H,\tilde{\pi}^L\}$ are tangential to each other:

$$-avB\hat{c}=2avB\times(\delta-v-\hat{c}-B/v)+(1/2)(-\delta+\hat{c}+2v)$$

However, this tangency locus cannot cross the relevant range in $(B,\hat{c})$ space, since the RHS of the above equation is positive under Assumptions 2 and 3. Indeed always holds in the relevant range (see Figure 1). The single-crossing property follows from this fact in conjunction with monotonicity (the profit for the firm is strictly decreasing in $\hat{c}$).

Step 4 Cho and Kreps (1987) show that the Intuitive Criterion selects the 'Riley outcome,' which is the Pareto-efficient separating equilibrium, in a signaling game with binary types of a signal-sender that satisfies the single-crossing condition. In the current model, the Pareto-efficient separating equilibrium outcome is the one in which c^H chooses $B^{H,Comp}$ and c^L selects B^* if $B^* > B^{L,Comp}$ or c^L selects $B^{L,Comp}$ if $B^* \le B^{L,Comp}$.

Appendix 2 Proof of Corollary 1

(i) Suppose that $\delta-2v\ge 0$. Then, from Eq. (8) it is straightforward to show that $B^{L,Comp}\le B^{H,Comp}$. That is, point Y is located to the left of point X, unlike in Figure 1. On the other hand, $B^{H,Comp}<B^*$ always holds by the discussion of Step 2 in Appendix 1. Thus, $B^{L,Comp}<B^*$, which inevitably brings about a Distortion Case.

(ii) Here no assumption is made about the sign of $\delta-2v$. The profit that type c^H obtains under complete information (point X in Figure 1), $\pi^{H,Comp}$, is derived by substituting $c^i=\hat{c}=c^H$ and Eq. (8) into Eq. (7). Then the abatement level that corresponds to point Z in Figure 1, B^*, is derived by solving $\pi^{H,Comp}=\pi(c^H,c^L,B^*)$, where the functional form of the RHS is given by Eq. (7), or equivalently by solving:

$$(\delta-c^H-v)^2+\frac{(-\delta+c^H+2v)^2}{4\boldsymbol{a}^H v^2}=$$

$$\left(\frac{2\delta-c^H-c^L-2v}{2}\right)^2-\boldsymbol{a}^H B^{*2}+\left(\frac{-\delta+c^L+2v}{v}\right)B^*$$

The solution is:

$$B^*=\frac{-\delta+c^L+2v}{2\boldsymbol{a}^H v}+\sqrt{(c^H-c^L)\eta}, \quad \text{(A3)}$$

$$\eta\equiv\boldsymbol{a}^H(4\delta-3c^H-c^L-4v)+(2\delta-c^H-c^L-2v)/v^2>0$$

The inequality comes from Assumption 1. Now carry out comparative statics analysis by increasing c^H, starting from $c^H=c^L$. From Eqs.(A3) and (8) it is obvious that $B^*=B^{L,Comp}(=B^{H,Comp})$, when $c^H = c^L$. To observe the effect of the increase in c^H on B^*, Eq. (A2) is totally differentiated with respect to c^H and B^*:

$$\left(-2(\delta-c^H-v)+\frac{2\delta-c^H-c^L-2v}{2}+\frac{-\delta+c^H+2v}{2ac^H v^2}\right)dc^H$$
$$=\left(-2ac^H B^* + \frac{-\delta+c^L+2v}{v}\right)dB^*$$

When evaluated at $c^H = c^L + \varepsilon$, for a small ε, the coefficient for dB* is close to $-Y^H + B^{H,Comp}/v$ and thus is negative under Assumption 3. From Eq. (A3), it is obvious that the coefficient for dB* is always negative. Therefore, starting from $c^H = c^L$, the increase in c^H increases B^*, while it does not change $B^{L,Comp}$, so $B^* > B^{L,Comp}$ (Distortion Case). However, if c^H becomes large enough to make the coefficient for d^H positive, an increase in c^H starts to reduce B^*. If $\delta - 2v < 0$, a further increase in c^H may bring B^* below $B^{L,Comp}$ (No-Distortion Case). However, in simulations conducted by the author the latter case was rare. In many cases, c^H hits the ceiling set by Assumption 1 before bringing about the No-Distortion Case.

(Endnotes)

1. Of course, it is possible for a firm to engage in R&D activities that are solely meant to reduce production costs and not abatement costs. However, since large uncertainties always surround the outcomes of R&D investments, such R&D may also bring about unforeseen technological advances in pollution control as a by-product. If this is the case, this 'positive' relation case will be more natural than vice versa, although the 'negative' or 'no' relation case is briefly mentioned in the final section.

2. There is a substantial body of literature exploring the effects of various policy instruments on R&D decisions concerning abating technology (see Jaffe et al., 2003 for a review). However, it is unlikely that R&D activities and asymmetric information about abatement costs draw attention at the same time. If a firm makes its R&D decisions strategically to affect its costs and a regulator can observe them, incomplete information of costs as assumed here would not likely become the focus of analysis.

3. In practice, some abatement expenses have to be paid at the same time as or after the production: e.g., running costs of an air-cleaner. Adding these costs complicates the firm's third-stage decision below without giving additional insights, so they are neglected in the model.

4. More formally, Assumption 3 requires that: (i) the upper limit of possible abatement levels, $\overline{B}$, is the level that equates Eq. (9) to zero when $c^i = \hat{c} = c^H$; (ii) $Max(B^{L,Comp}, B^*) < \overline{B}$, where B^* is defined later. The simulations below show that this condition is not too restrictive and is satisfied naturally in most cases.

5. Segerson and Miceli (1998) and Wu and Babcock (1999) analyze voluntary programs for environmental protection in terms of strategic interactions between a regulator and a polluter, but from a different viewpoint from that taken in this paper.

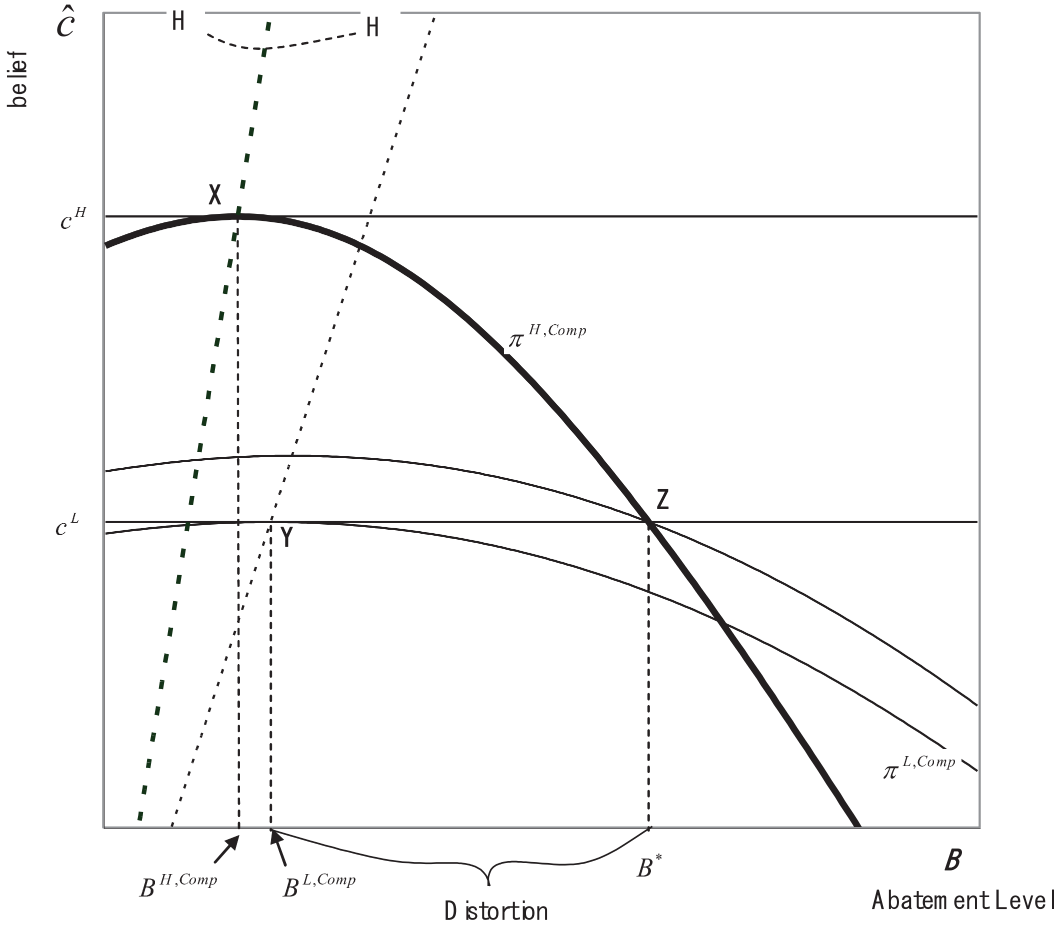
6. The reason for the robust results with respect to Proposition 1 is that Lemma 1 and the single-crossing property explained in Section 4 are also both satisfied in these two alternative set-ups.

7. Also, a continuum of types, $c \in [c^L, c^H]$, can be assumed instead of binary types. In this case, all the types except c^H overabate compared to the complete-information case,

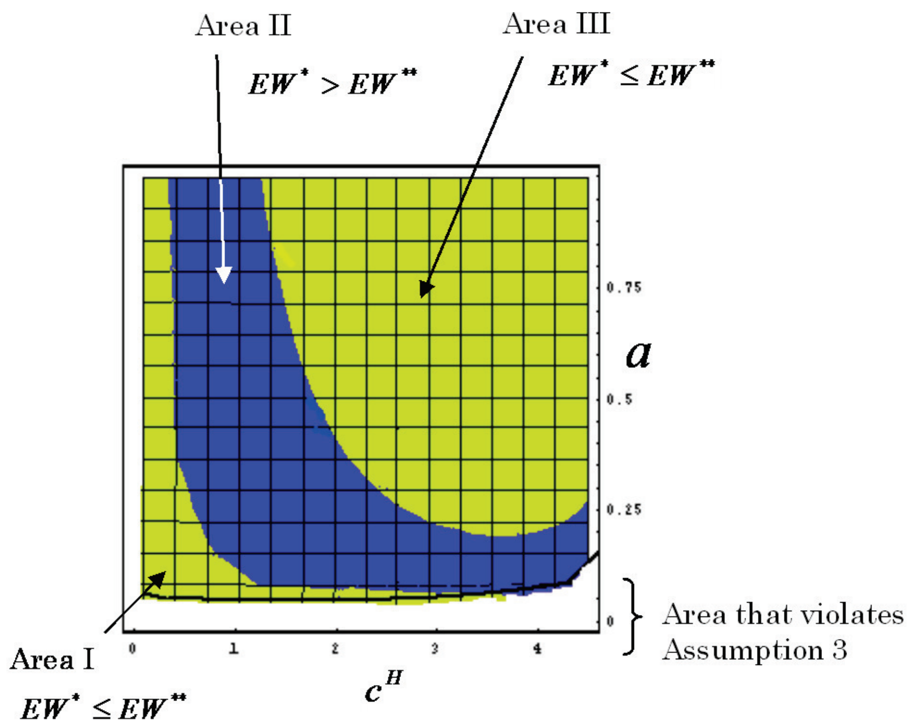
if the regulator postpones its tax-rate decision. With a continuum of types, however, an explicit solution cannot be derived for the same reason as explained in Collie and Hviid (1993, p. 334) and welfare considerations become intractable.

8.There are two reasons why I did not use the terms 'rules' and 'discretion' in the description of the model. First, in the Abatement-First Case of this paper, the government must actively inspect the abatement equipment and this procedure must be recognized by all parties, unlike a usual discretion case where a regulator is anticipated to easily revise its policy. Second, in the papers that deal with the Tax-First Case only (e.g., Katsoulacos and Xepapadeas, 1995), the term 'rule' is not used. This is probably because in these papers the timing of the firms' two decisions (investment and production) does not matter much.

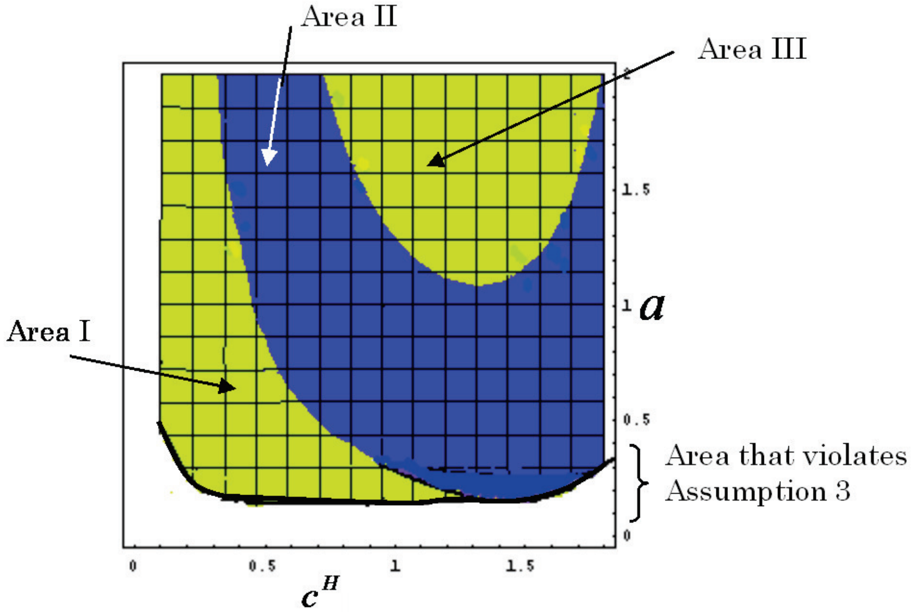
9. An exception is the Vickers (1986) monetary policy model, in which distortions created by the central bank are welfare-improving for a different reason from that in this paper.



(a) Assumptions: m =0.5; δ= 10 $c^L = c^H / 2$ v = 5



(b) Assumptions: the same as above except for v = 8



REFERENCES:

1. **Arrow, Kenneth J. and Anthony C. Fisher**. "*Environmental Preservation, Uncertainty, and Irreversibility*." Quarterly Journal of Economics 88 (1974): 312-19.
2. **Baliga, Sandeep, and Eric Maskin**. "*Mechanism Design for the Environment*." In Handbook of Environmental Economics Vol. 1, edited by Karl-Goran Maler and Jeffrey Vincent, 305-24. Amsterdam: North-Holland, 2003.
3. **Barnett, Andy H**. "*The Pigouvian Tax Rule under Monopoly*." American Economic Review 70(5) (1980): 1037-41.
4. **Biglaiser, Gary, John K. Horowitz, and John Quiggin**. "*Dynamic Pollution Regulation*." Journal of Regulatory Economics 8 (1995): 33-44.
5. **Cho, In-Koo, and David M. Kreps.** "*Signaling Games and Stable Equilibrium*." Quarterly Journal of Economics 102 (1987): 179-221.
6. **Collie, David R., and Morten Hviid.** "*Export Subsidies as Signals of Competitiveness.*" Scandinavian Journal of Economics 95(3) (1993): 327-39.
7. **Collie, David R., and Morten Hviid.** "*Tariffs for a Foreign Monopolist under Incomplete Information.*" Journal of International Economics 37 (1994): 249-64.
8. **Collie, David R., and Morten Hviid**. "*Tariffs as Signals of Uncompetitiveness.*" Review of International Economics 7(4) (1999): 571-79.
9. **Denicolo, Vincenzo.** "*A Signaling Model of Environmental Overcompliance*." University of Bologna,
10. **Ellis, Gregory M.** "*Incentive Compatible Environmental Regulations.*" Natural Resource Modeling 6 (1992): 225-56.
11. **Hoel, Michael, and Larry Karp.** "*Taxes versus Quotas for a Stock Pollutant*." Resource Energy Economics 24 (2001): 367-84.
12. **Jaffe, Adam B., Richard Newell, and Robert Stavins.** "*Technological Change and the Environment.*" In Handbook of Environmental Economics Vol. 1, edited by Karl-Goran Maler and Jeffrey Vincent, 461-516. Amsterdam: North-Holland, 2003.
13. **Katsoulacos, Yannis, and Anastasios Xepapadeas.** "*Environmental Policy under Oligopoly with Endogenous Market Structure.*" Scandinavian Journal of Economics 97(3) (1995): 411-20.
14. **Kelly, David L., and Charles D. Kolstad.** "*Bayesian Learning, Growth, and Pollution.*" Journal of Economic Dynamics and Control 23 (1999): 491-518.
15. **Kwerel, Evan**. "*To Tell the Truth: Imperfect Information and Optimal Pollution Control.*" Review of Economic Studies 44 (1977): 595-601.
16. **Malik, Arun S.** "*Permanent versus Interim Regulations: a Game-Theoretic Analysis.*" Journal of Environmental Economics and Management 21 (1991): 127-39.
17. **Maxwell, John W., Thomas P. Lyon, and Steven C. Hackett.** "*Self-Regulation and Social Welfare: the Political Economy of Corporate Environmentalism.*" Journal of Law and Economics 43 (2000): 583-618.
18. **Moledina, Amyaz A., Jay S. Coggins, Stephen Polasky, and Christopher Costello.** "*Dynamic Environmental Policy with Strategic Firms: Prices versus Quantities.*" Journal of Environmental Economics and Management 45 (2003): 356-76.
19. **Newell, Richard G., and William A. Pizer.** "*Regulating Stock Externalities under Uncertainty.*" Journal of

Environmental Economics and Management 45 (2003): 416-32.

20. **Pindyck, Robert S.** "*Irreversibility and the Timing of Environmental Policy.*" Resource Energy Economics 22 (2000): 233-59.

21. **Porter, Michael E., and Claas van der Linde.** "*Toward a New Conception of the Environment-Competitiveness Relationship*." Journal of Economic Perspective 9(4) (1995): 97-118.

22. **Requate, Till.** "*Timing and Commitment of Environmental Policy, Adoption of New Technology, and Repercussions on R&D.*" Environmental & Resource Economics 31 (2005): 175-99.

23. **Segerson, Kathleen, and Thomas J. Miceli.** "*Voluntary Environmental Agreements: Good or Bad News for Environmental Protection?*" Journal of Environmental Economics and Management 36 (1998): 109-30.

24. **Tarui, Nori, and Stephen Polasky.** "*Environmental Regulation with Technology Adoption, Learning and Strategic Behavior.*" Journal of Environmental Economics and Management 50 (2005): 447-67.

25. **Vickers, John.** "*Signalling in a Model of Monetary Policy with Incomplete Information.*" Oxford Economic Papers 38 (1986): 443-55.

26. **Weitzman, Martin L.** "*Prices vs. Quantities.*" Review of Economic Studies 41 (1974): 477-91.

27. **Wu, JunJie, and Bruce A. Babcock.** "T*he Relative Efficiency of Voluntary vs Mandatory Environmental Regulations*." Journal of Environmental Economics and Management 38 (1999): 158-75.

28. **Yao, Dennis A.** "*Strategic Responses to Automobile Emissions Control: a Game-Theoretic Analysis.*" Journal of Environmental Economics and Management 15 (1988): 419-38.