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On the Regulation of Unobserved Emissions

by

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On the regulation of unobserved emissions

Yacov Tsur[*] Harry de Gorter[◇]

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Abstract

Pollution is a byproduct of economic activities and the latter often entail observables. A case in point is production-induced emissions with observed outputs. We offer a mechanism for regulating nonpoint source pollution based on individual firms' ouptut-cost data without the use of ambient (aggregate) indicators. The mechanism implements the optimal output-abatement-emission allocation and gives rise to the full information outcome when the social cost of transfers is nil. A positive social cost of transfers decreases both output and abatement, though the effect on emission is ambiguous.

Keywords: Abatement, asymmetric information, nonpoint source pollution, regulation.

JEL classification: H23, L51, Q54, Q58

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1 Introduction

Regulating nonpoint source pollution under asymmetric information is complicated because of the difficulty in using individual effluent charges (taxes) or quotas (permits). The bulk of the regulation literature dealing with such situations relies in one way or another on policy instruments based on ambient (aggregate) indicators (Segerson 1988, Xepapadeas 1991, 1992, Cabe and Herriges 1992, Laffont 1994).[1] The implementation of ambient-based policies is limited by a number of well known (and well documented) factors, such as the indirect relation between individual actions (emission, abatement) and individual policy response (see discussion in Karp 2005). Attempts to overcome these limitations combine ambient and individual instruments, such that the former serves as a threat, inducing potential polluters to comply with the desirable policy or reveal their true emission in order to avoid the collective penalty (Xepapadeas 1995, Segerson and Wu 2006, Suter et al. 2010). When the threat is effective, it need not be exercised in actual practice and the enforceability problem alluded to above is avoided. However, the same enforceability problem may render threats imposed by ambient policy instruments non-credible, in which case the difficulty of using such policies persists.

We propose a regulation mechanism that does away with ambient (aggregate) indicators altogether. The underlying idea is based on the observation that pollution is an unintended consequence (a byproduct) of economic activities that often entail observables. This observation is, of course, not surprising and indeed most nonpoint regulation models account for the underlying pro-

[1] An exception is the regulation mechanism developed by Chambers and Quiggin (1996), which exploits uncertainty and farmers' risk aversion to specify a regulation scheme based only on the observed realizations of states of the world.

duction processes that cause the pollution (e.g., Segerson 1988, Xepapadeas 1991, Laffont 1994). The innovation here is in contracting individual firm's solely based on their (individual) observable production (output and cost) data, without any reliance on ambient indicators.[2]

We consider a situation where emission is a byproduct of production and depends, in addition to output, on abatement efforts. Examples include emission from smokestack industries, where abatement involves installing end-of-pipe equipment, or emission/pollution from land use and agricultural activities, where abatement includes forest management and waste treatment processes.[3] The regulator does not observe individual emissions nor abatement efforts, and information regarding individual producers/polluters efficiencies (types) is private. The observable (contractible) data are output and total cost, based on which contracts are designed to induce the desirable output, abatement and emission. The firm's total cost consists of production and abatement costs. The abatement effort in our model is similar to the cost reduction effort in Laffont and Tirole (1986) and the use of cost reimbursement is therefore similar. While in Laffont and Tirole (1986) the entire firm's cost is reimbursed, here only part of the cost – that due to abatement – is reimbursed. Our mechanism is so designed such that, by observing total cost, the regulator can infer the firm's abatement cost and reimburses it accordingly.

When the social cost of transfers is nil, the mechanism implements the first-best (full information) output-abatement-emission allocation. When transfers entail social costs, individual polluters can extract information rents and the

[2]A similar idea was used by Smith and Tsur (1997) to price unmetered irrigation water.

[3]Agriculture and other land use sectors are major contributors to global greenhouse gas emission (Stern 2007, pp. 196-197) and typically consist of many heterogeneous producers, thus are likely candidates for a nonpoint source pollution situation.

ensuing allocation deviates from its full information counterpart. We show that both output and abatement are smaller in this case, though the effect on emission is ambiguous.

The next section describes the moral hazard (unobserved abatement and emission) and adverse selection (asymmetric information) setup and specifies the production-abatement-emission relationships. Section 3 discusses the full information case and summarizes properties that turn out to be useful in developing the regulation mechanism in the general case. Section 4 formulates the regulation mechanism, discusses implementation and verifies the optimal properties of the ensuing output-abatement-emission allocation. Section 5 concludes and the appendix contains technical derivations.

2 Setup

We ignore uncertain conditions affecting emissions, due e.g. to weather.[4] A polluter may be a farmer or a group of farmers, a firm or a group of firms, an industry or even a country. We generically refer to the polluter as the "firm" and to the regulating agency as the "regulator." The production-abatement-emission technologies are formulated in the next subsection and the external (environmental) damage is specified in subsection 2.2. The asymmetric information (adverse selection) and observation (moral hazard) structures are described in subsection 2.3.

[4]Uncertain emission effects become pronounced when agents (firms in the present case) and/or the regulator are risk averse (see Chambers and Quiggin 1996, Chambers 2002, for pollution cum crop-insurance regulation under uncertainty). Here we assume that firms and the regulator are risk neutral.

2.1 Output, abatement and emission

Situations of nonpoint source pollution occur in the presence of many heterogeneous firms and it is therefore reasonable to assume a competitive output market, where firms face a flat output demand at the level of the (exogenously determined) output price p. Firm i enjoys the payoff $py_i - C_i(y_i, \beta_i)$, where y_i is output, $C_i(\cdot,\cdot)$ is a production cost function and $\beta_i \in [0, \bar{\beta}_i]$ represents the firm's type (the zero lower bound is assumed for convenience and can be replaced by any lower bound). The cost function is increasing and convex in output (the firm subscript i is suppressed when no confusion arises): $C_1(y,\beta) \equiv \partial C(y,\beta)/\partial y > 0$ and $C_{11}(y,\beta) \equiv \partial^2 C(y,\beta)/\partial y^2 > 0$. We adopt the convention that a higher β means more efficient firm, so both $C(y,\beta)$ and $C_1(y,\beta)$ decrease with β. We assume that there exists some finite (possibly very large) output $\bar{y}$ satisfying $C_1(\bar{y},\beta) = 0$ for all $\beta \in [0,\bar{\beta}]$. Additional cost properties (including third derivatives) will be used. We summarize the properties of C in:

$$C_1 > 0,\ C_2 < 0,\ C_{11} > 0,\ C_{12} < 0,\ C_{111} \geq 0,\ C_{112} \leq 0,\ C_{122} \geq 0 \tag{2.1}$$

for all $y > 0$ and $\beta \in [0,\bar{\beta}]$, where subscripts 1 and 2 signify partial derivatives with respect to the first and second argument, respectively (e.g., $C_{12} \equiv \partial^2 C/\partial y \partial \beta$).

Emission is an unintended consequence (a byproduct) of production and depends, in addition to output, on abatement efforts (cost) a according to

$$e = G(a,\beta)y, \tag{2.2}$$

where $G(a,\beta)$ is emission per output, representing abatement technology.[5]

[5]The proportional specification of (2.2) simplifies the exposition; the analysis accommo-

$G(a,\beta)$ decreases at a diminishing rate with abatement: $G_1 \equiv \partial G/\partial a < 0$ and $G_{11} \equiv \partial^2 G/\partial a^2 > 0$. Regarding type dependence, it is plausible to suppose that production efficiency goes together with abatement efficiency, so $G_2 \equiv \partial G/\partial \beta < 0$ and $G_{12} \equiv \partial^2 G/\partial a \partial \beta < 0$. We summarize the properties of G in:

$$G_1 < 0,\; G_2 < 0,\; G_{11} > 0,\; G_{12} < 0,\; G_{111} \geq 0 \tag{2.3}$$

for all $a \in [0,\infty)$ and $\beta \in [0,\bar{\beta}]$.

The abatement cost and marginal cost functions can be deduced from (2.2) as follows. Let $g^0(\beta) \equiv G(0,\beta)$ represent the abatement-free emission per unit output of a type-β firm. Given β, let $\Gamma(\cdot,\beta) : [0, g^0(\beta)] \mapsto \mathbb{R}_+$ be the inverse of $G(\cdot,\beta)$, so that $\Gamma(g^0(\beta),\beta) = 0$ and $\Gamma(\cdot,\beta)$ is decreasing. The cost of reducing per-output emission from $g^0(\beta)$ to $g = e/y < g^0(\beta)$ is given by $\Gamma(g,\beta)$. The corresponding marginal abatement cost is $M(g,\beta) = -\Gamma_1(g,\beta) \equiv -\partial\Gamma(g,\beta)/\partial g$, so $\Gamma(g,\beta) = \int_g^{g^0(\beta)} M(z,\beta)dz$.

The unregulated output level of a type-β firm, denoted $y^0(\beta)$, solves $C_1(y,\beta) = p$, and the corresponding unregulated emission level is $e^0(\beta) = g^0(\beta)y^0(\beta)$. Obtaining the emission e at output level y ($e/y \leq g^0(\beta)$) entails the abatement cost $\Gamma(e/y,\beta)$.

2.2 Environmental cost

Aggregate emission $E = \sum_i e_i$ inflicts environmental damage with the associated cost $D(E)$, which is typically increasing and convex. We assume a linear environmental cost:

$$D(E) = \tau E. \tag{2.4}$$

dates a general emission process $\tilde{G}(y,a,\beta)$ that satisfies certain properties.

The environmental cost generated by a type-β firm producing the output level y and expending the abatement a is $\tau G(a,\beta)y$.

2.3 Observation and information

The regulator observes output y and total cost $C+a$ but not the abatement cost a. Information regarding the firm's type is private and the regulator knows β up to the probability distribution $F(\beta)$, with a density $f(\beta)=F'(\beta)$. We assume that $f(\beta)>0$ for all $\beta\in[0,\bar{\beta}]$ and that the hazard function $h(\beta)=f(\beta)/[1-F(\beta)]$ is nondecreasing.

Based on the available information, the regulator seeks a mechanism that induces the firm to choose the socially optimal output and abatement. It is expedient, before developing the mechanism (in Section 4), to summarize properties of the complete information case.

3 Full information

We specify the conditions ensuring the existence and uniqueness of an optimal output-abatement-emission allocation under full information. These conditions turn out to be useful in deriving properties of the regulation mechanism in Section 4.

Suppose output and abatement are observed by all and firms types are common knowledge. Consider regulation via the transfers t_i (from the regulator to firm i), giving rise to the welfare

$$\sum_i \{py_i - C_i(y_i,\beta_i) - a_i + t_i - \tau G_i(a_i,\beta_i)y_i - (1+\lambda)t_i\},$$

where λ is the social cost of transfer (i.e., a transfer of one dollar generates a deadweight loss of \$$\lambda$ due, e.g., to transactions costs or distortions). Letting

$$\pi_i = py_i - C_i(y_i, \beta_i) - a_i + t_i \tag{3.1}$$

represent firm i's post-transfer profit, social welfare can be expressed as

$$\sum_i \{(1+\lambda)(py_i - C_i(y_i, \beta_i) - a_i) - \tau G_i(a_i, \beta_i) y_i - \lambda \pi_i\}. \tag{3.2}$$

The optimal y_i, a_i and t_i (or π_i) maximize (3.2) subject to the participation constraints $\pi_i \geq 0$ and nonnegativity of y_i and a_i. The structure of the welfare (3.2) implies that the maximization can be carried out for each firm separately and proceed in two steps: first, the output-abatement allocation (y_i^*, a_i^*) that maximize

$$J_i(y_i, a_i) = (1+\lambda)[py_i - C(y_i, \beta_i) - a_i] - \tau G(a_i, \beta_i) y_i \tag{3.3}$$

is chosen; second, the optimal transfer is set under the participation constraint $\pi_i \geq 0$. Dropping the firm's subscript i, the necessary conditions for output-abatement of a given (any) firm are:

$$p - C_1(y, \beta) = \frac{\tau G(a, \beta)}{1+\lambda}\ , \tag{3.4a}$$

$$-G_1(a, \beta) y = \frac{1+\lambda}{\tau} \tag{3.4b}$$

and the optimal transfer is set such that

$$\pi = 0. \tag{3.4c}$$

In (3.4a) and (3.4b) the "$=$" signs change to "$\leq$" at the corners of $y = 0$ and $a = 0$, respectively.

Following (3.4b), define

$$q(a,\beta) \equiv \frac{1+\lambda}{-G_1(a,\beta)\tau}. \tag{3.5}$$

Substituting q for y in (3.4a) gives the condition

$$C_1(q(a,\beta),\beta) + \frac{\tau}{1+\lambda}G(a,\beta) = p. \tag{3.6}$$

Suppose

$$C_{11}(q(0,\beta),\beta)q_1(0,\beta) + \frac{\tau}{1+\lambda}G_1(0,\beta) > 0 \tag{3.7}$$

for any $\beta \in [0,\bar{\beta}]$. Using (2.1), (2.3) and (3.5), it can be verified that (3.7) implies[6]

$$C_{11}(q(a,\beta),\beta)q_1(a,\beta) + \frac{\tau}{1+\lambda}G_1(a,\beta) > 0 \text{ for all } a \geq 0, \tag{3.8}$$

i.e., the left-hand side of (3.6) is monotonic in a. If in addition, for any $\beta \in [0,\bar{\beta}]$, there exist some finite $\bar{a}$ (possibly very large) such that

$$C_1(q(0,\beta),\beta) + \frac{\tau G(0,\beta)}{1+\lambda} < p \;\; and \;\; C_1(q(\bar{a},\beta),\beta) + \frac{\tau G(\bar{a},\beta)}{1+\lambda} > p, \tag{3.9}$$

then (3.6) admits a unique solution $a^* \in [0,\bar{a}]$. In this case, (3.4a)-(3.4b) admit a unique, positive solution (a^*, y^*) with $y^* = q(a^*,\beta)$.

Sufficiency requires that $J(y,a)$, defined in (3.3), is concave at (y^*, a^*), which follows from:

Lemma 1. *Given (2.1), (2.3) and (3.8), $J(y,a)$ is concave on the domain*

[6] Notice from (3.5) and (2.3) that $q_1 \equiv \partial q/\partial a > 0$ and $q_{11} \equiv \partial^2 q/\partial a^2 > 0$ and use properties of C and G.

$$y \geq q(a, \beta), \ (y, a) \in \mathbb{R}_+^2. \tag{3.10}$$

The proof is given in Appendix A. Since (y^*, a^*) satisfies (3.10) (cf. (3.4b) and (3.5)), it also satisfies the sufficient condition.

We summarize the above discussion in:

Proposition 1. *Under (2.1), (2.3), (3.8), (3.9) and (3.10), equations (3.4a)-(3.4b) admit a unique, positive solution* (y^*, a^*) *and this solution is the socially optimal output-abatement allocation.*

Under full information there are various ways to implement the optimal allocation, e.g., via the Pigouvian tax $\tau/(1+\lambda)$ on emission or an output tax of $\tau G(a, \beta)/(1+\lambda)$ or a transfer $t = -\tau G(a, \beta) y/(1+\lambda)$. We proceed to develop a regulation mechanism in the case where abatement and emission are unobserved and information regarding firms types is private.

4 The regulation mechanism

We show in Appendix B that, like in the previous full-information case, the optimal output-abatement-emission allocation can be attained by regulating each firm separately also in the general case (where emission and abatement are unobserved and firms types are private information). We thus consider the regulation of an individual (any) firm. The mechanism consists of transfer and abatement functions, $\hat{t}(y)$ and $\hat{a}(y)$ defined in terms of output, and proceeds along the following steps: (i) The regulator announces the functions $\hat{t}(y)$ and $\hat{a}(y)$; (ii) the firm chooses output y and abatement $\hat{a}(y)$; (iii) upon observing y, the regulator pays the transfer $\hat{t}(y)$ and reimburses the firm for the abatement $\hat{a}(y)$. The transfer $\hat{t}(\cdot)$ is so specified that the firm's output choice is socially optimal. Since output is observable, using $\hat{t}(\cdot)$ to affect the firm's output choice is straightforward. Implementing abatement via the $\hat{a}(\cdot)$ function is more subtle since abatement is unobserved. We return to this issue after verifying (below) the desirable properties of the mechanism.

4.1 Specification of $\hat{t}(\cdot)$ and $\hat{a}(\cdot)$

The derivation of the transfer $\hat{t}(\cdot)$ and abatement $\hat{a}(\cdot)$ functions builds on the following Direct Revelation Mechanism: The regulator announces the functions $Y(\cdot)$, $A(\cdot)$ and $T(\cdot)$, following which the firm reports its type b. Upon receiving the report b, the regulator assigns the contract $\{Y(b), A(b), T(b)\}$, indicating that the firm produces $Y(b)$, spends $A(b)$ on abatement activities and receives the transfer $T(b)$.[7]

The mechanism is truthful if the firm will (voluntarily) report its type honestly, i.e., $b = \beta$. The firm's payoff when it reports b is

$$\tilde{\Pi}(b, \beta) = pY(b) - C(Y(b), \beta) - A(b) + T(b). \tag{4.1}$$

Necessary condition for truth telling is $\tilde{\Pi}_1(\beta, \beta) \equiv \partial\tilde{\Pi}(b, \beta)/\partial b|_{b=\beta} = 0$ or

$$[p - C_1(Y(\beta), \beta)]Y'(\beta) - A'(\beta) + T'(\beta) = 0. \tag{4.2}$$

Given $C_{12} < 0$ (cf. (2.3)), the monotonicity condition

$$Y'(x) \geq 0 \; \forall \; x \in [0, \bar{\beta}] \tag{4.3}$$

is sufficient for truth telling.[8]

[7] In general, a firm's contract depends on the firm's own report and on the reports of all other firms (in which case the mechanism is stochastic, since from the viewpoint of each firm the other firms types are uncertain). We verify in Appendix B that the optimal outcome can be attained by a deterministic contract, which depends only on the firm's own report.

[8] This can be shown as follows (Laffont and Tirole 1993, p. 121). Suppose $b \neq \beta$ yields a

The firm's payoff under honest reporting is

$$\Pi(\beta) = pY(\beta) - C(Y(\beta), \beta) - A(\beta) + T(\beta). \tag{4.4}$$

Invoking (4.2),

$$\Pi'(\beta) = -C_2(Y(\beta), \beta). \tag{4.5}$$

Since $C_2 < 0$ (cf. (2.3)), $\Pi(\cdot)$ is increasing and requiring

$$\Pi(0) = 0 \tag{4.6}$$

ensures a nonnegative profit for all firm types.

Noting (3.2), the firm's contribution to expected social welfare is

$$\int_0^{\bar{\beta}} \{(1+\lambda)[pY(b) - C(Y(b), b) - A(b)] - \tau G(A(b), b)Y(b) - \lambda\Pi(b)\} f(b)db \tag{4.7}$$

The regulator seeks the functions $Y(b)$, $A(b)$ and $\Pi(b)$ that maximize (4.7) subject to (4.3), (4.5) and (4.6).

Consider the subproblem of maximizing (4.7) subject to (4.5)-(4.6), ignoring the monotonicity constraint (4.3). This is a standard Optimal Control

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larger payoff:

$$\tilde{\Pi}(b, \beta) > \tilde{\Pi}(\beta, \beta) \Rightarrow \int_\beta^b \tilde{\Pi}_1(x, \beta)dx > 0,$$

which invoking the necessary condition, $\tilde{\Pi}_1(x, x) = 0 \; \forall x \in [0, \bar{\beta}]$, can be expressed as

$$\int_\beta^b [\tilde{\Pi}_1(x, \beta) - \tilde{\Pi}_1(x, x)]dx = \int_\beta^b \int_x^\beta \tilde{\Pi}_{12}(x, z)dzdx > 0.$$

Now, $\tilde{\Pi}_{12}(x, z) = -C_{12}(q(x), z)Y'(x)$ and $C_{12} \leq 0$. If $b > \beta$, then $x \geq \beta$ and the above inequality becomes

$$-\int_\beta^b \int_\beta^x \tilde{\Pi}_{12}(x, z)dzdx > 0 \Rightarrow \int_\beta^b \int_\beta^x C_{12}(Y(x), z)Y'(x)dzdx > 0,$$

which is impossible when $Y'(x) \geq 0 \; \forall x \in [0, \bar{\beta}]$, ruling out the possibility that $\tilde{\Pi}(b, \beta) > \tilde{\Pi}(\beta, \beta)$ for $b > \beta$. Likewise, when $b < \beta$, the inequality reads $-\int_b^\beta \int_x^\beta \tilde{\Pi}_{12}(x, z)dzdx = \int_b^\beta \int_x^\beta C_{12}(x, z)Y'(x)dzdx > 0$, which is again impossible when $Y'(x) \geq 0$, ruling out the possibility $b < \beta$.

problem with two controls, Y and A, and one state, Π. Let $Y^*(b)$, $A^*(b)$ and $\Pi^*(b)$ denote the solution of this subproblem. We verify in Appendix C that $Y^*(b)$ and $A^*(b)$ satisfy

$$p - C_1(Y^*(b), b) = \frac{\tau G(A^*(b), b)}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{1-F(b)}{f(b)} C_{21}(Y^*(b), b) \tag{4.8}$$

and

$$-G_1(A^*(b), b)Y^*(b) = \frac{1+\lambda}{\tau}. \tag{4.9}$$

Using (4.5)-(4.6), we obtain

$$\Pi^*(b) = \int_0^b -C_2(Y^*(z), z)dz \tag{4.10}$$

and (4.4) then gives

$$T^*(b) = \Pi^*(b) - [pY^*(b) - C(Y^*(b), b) - A^*(b)]. \tag{4.11}$$

It turns out that $Y^*(\cdot)$, $A^*(\cdot)$ and $\Pi^*(\cdot)$ are also the optimal solutions for the problem of maximizing (4.7) subject to (4.5)-(4.6) and the monotonicity constraint (4.3). This follows from:

Lemma 2. *Under (2.1), (2.3) and (3.7), $Y^{*\prime}(b) > 0$ and $A^{*\prime}(b) > 0$ for all $b \in [0, \bar{\beta}]$.*

The proof is given in Appendix D.

The optimal output and abatement are, respectively,

$$y^{*\lambda} \equiv Y^*(\beta) \tag{4.12}$$

and

$$a^{*\lambda} \equiv A^*(\beta). \tag{4.13}$$

With a monotonic $Y^*(\cdot)$, the inverse function $\varphi \equiv Y^{*-1} : \mathbb{R}_+ \mapsto [0, \bar{\beta}]$ exists, is increasing and satisfies, noting (4.12),

$$\varphi(y^{*\lambda}) = \beta. \tag{4.14}$$

Following (4.10), let

$$\hat{\pi}(y) = \int_{Y^*(0)}^{y} -C_2(z, \varphi(z))\varphi'(z)dz \tag{4.15}$$

for $y \geq Y^*(0)$. The functions $\hat{t}(\cdot)$ and $\hat{a}(\cdot)$ are now defined by:

$$\hat{t}(y) \equiv \hat{\pi}(y) - [py - C(y, \varphi(y))] \tag{4.16}$$

and

$$\hat{a}(y) \equiv A^*(\varphi(y)). \tag{4.17}$$

4.2 Implementation

The mechanism based on the transfer and abatement functions specified in (4.16) and (4.17) is called the $[\hat{t}, \hat{a}]$ mechanism. We show that:

Proposition 2. *The $[\hat{t}, \hat{a}]$ mechanism implements the optimal output-abatement allocation $(y^{*\lambda}, a^{*\lambda})$.*

Proof. Noting (4.16), the firm's post-transfer profit, $py - C(y, \beta) + \hat{t}(y)$, equals

$$C(y, \varphi(y)) - C(y, \beta) + \hat{\pi}(y).$$

The profit maximizing output satisfies, noting (4.15),

$$C_1(y, \varphi(y)) - C_1(y, \beta) = C_{12}(y, \tilde{\beta})[\varphi(y) - \beta] = 0$$

for some $\tilde{\beta}$ between β and $\varphi(y)$. Since $C_{12}(y, \cdot) < 0$ and $\varphi(\cdot)$ is increasing, $y^{*\lambda}$ (cf. (4.12)) is the unique profit maximizing output, implying that the transfer $\hat{t}(\cdot)$ implements the optimal output $y^{*\lambda}$.

Noting (4.14), the output $y^{*\lambda}$ identifies β, which together with (4.13) and (4.17) implies $\hat{a}(y^{*\lambda}) = a^{*\lambda}$, giving rise to the optimal abatement. $\square$

As was noted above, implementing the optimal output via $\hat{t}(\cdot)$ is straightforward since output is observable. Implementing the abatement via $\hat{a}(\cdot)$ is more subtle since abatement is unobserved. How can the regulator verify that the firm actually carries out the abatement $\hat{a}(y^{*\lambda})$ when he cannot observe abatement efforts in actual practice? After all, receiving an abatement subsidy and performing abatement activities are two different things: the first is mutually observed while the second is known only to the firm. This problem is resolved when the regulator observes total cost $C + a$. This is so because the firm's output choice reveals the firm's type β (cf. equation (4.14)), hence ex post (after y has been observed and the true type β revealed) the regulator can calculate the production cost $C(y^{*\lambda}, \beta)$ and subtract from the (observed) total cost $C + a$ to obtain the abatement cost.[9]

When $\lambda = 0$ (zero social cost of transfers), the $[\hat{t}, \hat{a}]$ mechanism implements the complete information allocation (y^*, a^*), defined by (3.4a)-(3.4b). To see this, note that $y^{*\lambda} = Y^*(\beta)$ and $a^{*\lambda} = A^*(\beta)$, where $Y^*(\beta)$ and $A^*(\beta)$ solve (4.8)-(4.9) with $b = \beta$. But when $\lambda = 0$, (4.8) is the same as (3.4a) and (4.9) is the same as (3.4b). Since the solution of (3.4a)-(3.4b) is unique (Proposition 1), the two solutions must be the same. Under zero social cost of transfers, the regulator can nullify the firm's information rent and the optimal regulations attains the complete information outcome.

[9]If the total cost is unobserved, some extraneous threat is needed to motivate the firm to carry out the abatement paid for by the regulator, e.g., the threat of the judicial (court) system if caught cheating entails a penalty.

When $\lambda > 0$, (4.8) implies (recalling $C_{12} < 0$),

$$p - C_1(q(a^{*\lambda}, \beta), \beta) - \frac{\tau G(a^{*\lambda}, \beta)}{1 + \lambda} > 0$$

where, $q(a, \beta) = -(1+\lambda)/(\tau G(a, \beta))$ is defined in (3.5). Likewise, from (3.4a),

$$p - C_1(q(a^*, \beta), \beta) - \frac{\tau G(a^*, \beta)}{1 + \lambda} = 0.$$

Subtracting the latter from the former gives

$$C_1(q(a^*, \beta), \beta) - C_1(q(a^{*\lambda}, \beta), \beta) + \frac{\tau}{1 + \lambda}\left[G(a^*, \beta) - G(a^{*\lambda}, \beta)\right] > 0.$$

The above inequality can be expressed as

$$\int_{a^{*\lambda}}^{a^*} \left[C_{11}(q(s, \beta), \beta) q_1(s, \beta) + \frac{\tau}{1 + \lambda} G_1(s, \beta)\right] ds > 0.$$

In view of (3.8), the integrand (the term inside the square brackets) is positive, implying $a^{*\lambda} < a^*$, hence $y^{*\lambda} = q(a^{*\lambda}, \beta) < q(a^*, \beta) = y^*$. We summarize the above discussion in:

Proposition 3. (*i*) *When $\lambda = 0$ (zero social cost of transfers), the $[\hat{t}, \hat{a}]$ mechanism implements the optimal, full information allocation: $y^{*\lambda} = y^*$ and $a^{*\lambda} = a^*$.* (*ii*) *When $\lambda > 0$, the mechanism gives rise to smaller output and abatement: $y^{*\lambda} < y^*$ and $a^{*\lambda} < a^*$.*

In the case of positive social cost of transfers, noting that $G(\cdot, \beta)$ is decreasing, emission, $G(a^{*\lambda}, \beta) y^{*\lambda}$, may exceed or fall short of its full information counterpart ($G(a^*, \beta) y^*$), depending on the specifications of the underlying production and abatement technologies and the asymmetric information.

5 Concluding comments

Based on the relationship between unobserved pollution and observed output, we offer a mechanism to regulate nonpoint source pollution designed for each individual polluter (firm) separately. The mechanism consists of two functions, a transfer function and an abatement function, defined in terms of the firm's observable output. The transfer function is so specified as to induce the firm to choose the socially optimal output level. Given the output choice, the abatement function determines the optimal abatement efforts. The firm's output choice resolves the asymmetric information (adverse selection) and allows implementation of optimal abatement when the firm's total cost (production and abatement) is observable. If total cost is unobserved, an additional device is needed to ensure that the firm actually incurs the abatement cost for which it has been reimbursed. Such a device may well be the threat of a court system – when not performing an activity for which a firm has been paid for is considered liable.

When the social cost of transfers is nil, the mechanism implements the optimal, full-information output-abatement-emission allocation. When the social cost of transfers is positive, the optimal output and abatement, implemented by the mechanism, are smaller than their complete information counterparts, though emission may be larger or smaller (less abatement increases emission while smaller output decreases emission).

Two extensions are straightforward. First, the participation constraint (4.6), which ensures that no firm will close down and cease production, can be changed to force inefficient firms (say, with β below some threshold level) to cease production, with a more pronounced effect on aggregate emission. This can be an alternative to existing approaches, based on combinations of taxes and tradeable permits (see discussion in Montero 2008), which may be vulnerable to the nonpoint nature of individual emissions and the need to use ambient (aggregate) indicators.

Second, the emission process can be extended to accommodate a wider range of real world situations, such as reduction of greenhouse gas emission in land use and agricultural production. Abatement in these sectors can come in the form of soil carbon sequestration practices by changing tillage, crop rotations, cover crops and grazing practices, as well as purchase of carbon offsets (Hahn and Richards 2010, Bushnell 2010). Extending the mechanism to accommodate intertemporal emission processes with stock externality remains a challenge for future research.

Appendix

A Proof of Lemma 1

Noting that $J_{yy} \equiv \partial^2 J/\partial y^2 < 0$ and $J_{aa} \equiv \partial^2 J/\partial a^2 < 0$, we need to show that the determinant of the Hessian matrix of $J(y, a)$,

$$H_J = (1+\lambda)C_{11}(y,\beta)\tau G_{11}(a,\beta)y - \tau^2 G_1^2(a,\beta),$$

is nonnegative. In view of $C_{111} \geq 0$ (cf. (2.1)) and (3.10)

$$H_J \geq (1+\lambda)C_{11}(q(a,\beta),\beta)\tau G_{11}(a,\beta)q(a,\beta) - \tau^2 G_1^2(a,\beta),$$

so we need to show that the term on the right-hand side above is nonnegative or, alternatively, that

$$\frac{1+\lambda}{\tau}\frac{1}{-G_1(a,\beta)}C_{11}(q(a,\beta),\beta)G_{11}(a,\beta)q(a,\beta) + G_1(a,\beta) \geq 0. \tag{A.1}$$

Noting (3.5), (3.10) and $q_1(a,\beta) \equiv \partial q/\partial a = \frac{1+\lambda}{\tau}G_{11}/G_1^2$, (A.1) becomes

$$C_{11}(q(a,\beta),\beta)q_1(a,\beta)[-G_1(a,\beta)q(a,\beta)] + G_1(a,\beta) \geq 0.$$

Since $(-G_1)q = (1+\lambda)/\tau$ (cf. (3.5)), the above inequality can be rendered as

$$C_{11}(q(a,\beta),\beta)q_1(a,\beta) + \frac{\tau}{1+\lambda}G_1(a,\beta) \geq 0,$$

which follows from (3.8).

B Optimality of deterministic mechanisms

In general, contracts are specified in terms of functions that depend on the reports of all firms (mechanisms based on such contracts are stochastic, since from the viewpoint of a single firm, the other firms types are uncertain). We verify that the maximal expected welfare can be attained by a deterministic mechanism, where contracts are specified for each firm separately and depend only on the firm's own report.

Denote by B_{-i} the vector of the true types of all firms except firm i. The mechanism is truthful if firm i will (voluntarily) report its type honestly, i.e., $b_i = \beta_i$, when all other firms report honestly. Firm i's expected payoff when it reports b_i and all other firms report their true types is

$$\pi_i(b_i, \beta_i) = E_{B_{-i}}\{py_i(b_i, B_{-i}) - C_i(y_i(b_i, B_{-i}), \beta_i) - a_i(b_i, B_{-i}) + t_i(b_i, B_{-i})\}. \tag{B.1}$$

The firm will report honestly if $\pi_i(\beta_i, \beta_i) \geq \pi_i(b_i, \beta_i)$ $\forall b_i \in [0, \bar{\beta_i}]$. The necessary condition for truthtelling is $\pi_{i1}(\beta_i, \beta_i) \equiv \partial\pi_i(b_i, \beta_i)/\partial b_i|_{b_i=\beta_i} = 0$ or

$$E_{B_{-i}}\{[p - C_{i1}(y_i(\beta_i, B_{-i}), \beta_i)]y_{i1}(\beta_i, B_{-i}) - a_{i1}(\beta_i, B_{-i}) + t_{i1}(\beta_i, B_{-i})\} = 0. \tag{B.2}$$

Firm i's payoff under honest reporting is

$$\tilde{\pi}_i(\beta_i) = E_{B_{-i}}\{py_i(\beta_i, B_{-i}) - C_i(y_i(\beta_i, B_{-i}), \beta_i) - a_i(\beta_i, B_{-i}) + t_i(\beta_i, B_{-i})\}. \tag{B.3}$$

Differentiating with respect to β_i, invoking (B.2), gives

$$\tilde{\pi}_i'(\beta_i) = E_{B_{-i}}\{-C_{i2}(y_i(\beta_i, B_{-i}), \beta_i)\}. \tag{B.4}$$

Since $C_{i2} < 0$ (cf. (2.1)), $\tilde{\pi}_i(\cdot)$ is increasing and requiring

$$\tilde{\pi}_i(0) = 0 \tag{B.5}$$

ensures a nonnegative profit for all types.

Social welfare (3.2) generalizes to

$$v = \sum_i E_{\beta_i}\{E_{B_{-i}}\{J_i(y_i(\beta_i, B_{-i}), a_i(\beta_i, B_{-i}))\} - \lambda \tilde{\pi}_i(\beta_i)\} \tag{B.6}$$

where $J_i(y_i, a_i)$ is defined in (3.3). The regulator seeks the functions $y_i(\cdot, \cdot)$, $a_i(\cdot, \cdot)$ and $\tilde{\pi}_i(\cdot)$ that maximize v subject to (B.4) and (B.5). Let v^* be the optimal expected welfare, i.e., the value (B.6) evaluated at the optimal mechanism. Then,

Proposition B.1. *Under (2.1), (2.3) and (3.8), v^* can be realized by deterministic contracts $\{Y_i(\cdot), A_i(\cdot), T_i(\cdot)\}$, each depending on firm i's own report.*

Proof. We begin by showing that the optimal mechanism satisfies (3.10), i.e.,

$$y_i(\beta_i, B_{-i}) \geq q(a_i(\beta_i, B_{-i}), \beta_i) \ \forall i. \tag{B.7}$$

Suppose otherwise, that $y_i < q(a_i, \cdot)$. Then (recalling $J_a(q, a) = 0$, $J_{aa} < 0$ and $q_1 > 0$), as long as $y_i < q(a_i, \cdot)$, decreasing a_i (keeping y_i constant) increases J_i without any effect on $\tilde{\pi}_i$ (which depends on y_i via (B.4)-(B.5)), thereby increasing the term inside $E_{\beta_i}\{\cdot\}$ in (B.6) and the ensuing value, which cannot be optimal. We thus confine attention to the domain $(y_i, a_i) \in \mathbb{R}_+^2$ satisfying (B.7) (or (3.10)), over which (Lemma 1) $J_i(y_i, a_i)$ is concave.

We can now show that to any stochastic mechanism there corresponds a deterministic mechanism that performs at lease as well, in that it generates an expected welfare which is at least as large as that generated by the underlying stochastic mechanism. Let $Y_i(\beta_i) \equiv E_{B_{-i}}\{y_i(\beta_i, B_{-i})\}$ and $A_i(\beta_i) \equiv E_{B_{-i}}\{a_i(\beta_i, B_{-i})\}$. Then, using the concavity of $J_i(y, a)$, we obtain (Jensen's inequality),

$$E_{B_{-i}} J_i(y_i(\beta_i, B_{-i}), a_i(\beta_i, B_{-i})) \leq J_i(Y_i(\beta_i), A_i(\beta_i)).$$

Moreover, $C_{211} \leq 0$ (cf. (2.1)) implies $E_{B_{-i}}\{-C_{i2}(y_i(\beta_i, B_{-i}), \beta_i)\} \geq -C_{i2}(Y_i(\beta_i), \beta_i)$ for all $\beta_i \in [0, \bar{\beta_i}]$, hence

$$\tilde{\pi}_i(\beta_i) = \int_0^{\beta_i} E_{B_{-i}}\{-C_{i2}(y_i(x, B_{-i}), x)\}dx \geq \int_0^{\beta_i} -C_{i2}(Y_i(x), x)dx = \Pi_i(\beta_i),$$

where Π_i is obtained from $\Pi_i'(\beta_i) = -C_{i2}(Y_i(\beta_i), \beta_i)$ and $\Pi_i(0) = 0$. It follows that the expected welfare (B.6) corresponding to the deterministic mechanism $(Y_i(\cdot), A_i(\cdot), T_i(\cdot))$, where $T_i(\cdot)$ is derived from $\Pi_i(\cdot)$ according to (4.11), is at least as large as that obtained under the underlying stochastic mechanism. $\square$

C Derivation of $Y^*(\cdot)$ and $A^*(\cdot)$

With $\mu(b)$ representing the costate variable, the Hamiltonian corresponding to the subproblem of maximizing (4.7) subject to (4.5)-(4.6) is

$$\begin{aligned}\mathcal{H}(b) = \{&(1+\lambda)[pY(b) - C(Y(b), b) - A(b)] - \tau G(A(b), b)Y(b) - \lambda\Pi(b)\}f(b) \\ &- \mu(b)C_2(Y(b), b).\end{aligned}$$

Necessary conditions for an interior optimum include

$$\{(1+\lambda)[p - C_1(Y^*(b), b)] - \tau G(A^*(b), b)\}\, f(b) - \mu(b)C_{21}(Y^*(b), b) = 0, \quad \text{(C.1)}$$

$$-G_1(A^*(b), b)Y^*(b) = \frac{1+\lambda}{\tau}, \quad \text{(C.2)}$$

$$\mu'(b) = \lambda f(b) \quad \text{(C.3)}$$

and the transversality condition, associated with free $\Pi(\bar{\beta})$,

$$\mu(\bar{\beta}) = 0. \quad \text{(C.4)}$$

Integrating (C.3), using (C.4), gives

$$-\mu(b) = \lambda[1 - F(b)]. \tag{C.5}$$

Substituting (C.5) in (C.1) and rearranging gives (4.8) and (C.2) gives (4.9).

D Proof of Lemma 2

Totally differentiate (4.8), using (4.9) to express

$$A^{*\prime} = \frac{-G_1 Y^{*\prime}}{G_{11} Y^*} - \frac{G_{12}}{G_{11}}, \tag{D.1}$$

gives $Y^{*\prime} D_1 = D_2$, where

$$D_1 = -C_{11} + \frac{\tau}{1+\lambda} \frac{G_1^2}{G_{11}} \frac{1}{Y^*} + \frac{\lambda}{(1+\lambda)h} C_{211},$$

and

$$D_2 = C_{12}\left(1 + \frac{\lambda}{1+\lambda}\frac{h'}{h^2}\right) - \frac{\lambda}{(1+\lambda)h} C_{212} - \frac{\tau G_1 G_{12}}{(1+\lambda) G_{11}} + \frac{\tau G_2}{1+\lambda}$$

(the arguments $Y^*(b)$, $A^*(b)$ and b are suppressed for convenience). The non-decreasing hazard ($h' \geq 0$) together with (2.1) and (2.3) imply that $D_2 < 0$. We show that $D_1 < 0$.

Noting (2.1), the right-most term of D_1 is non-positive, so we need to show

$$-C_{11} + \frac{\tau}{1+\lambda} \frac{G_1^2}{G_{11}} \frac{1}{Y^*} < 0. \tag{D.2}$$

Recalling (3.5), multiply (D.2) by the positive

$$q_1 = \frac{1+\lambda}{\tau} \frac{G_{11}}{G_1^2}$$

to obtain

$$-C_{11}q_1 + \frac{1}{Y^*} < 0.$$

Invoking (C.2), the left-hand side above can be expressed as

$$-C_{11}q_1 - \frac{\tau}{1+\lambda}G_1, \tag{D.3}$$

which equals the negative of the left-hand side of (3.8) evaluated at $a = A^*$ and $\beta = b$, verifying inequality (D.2) and, thereby, $Y^{*\prime} > 0$. $A^{*\prime} > 0$, then, follows from (2.3) and (D.1).

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