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On the Regulation of Unobserved Emissions

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Abstract

Regulation of nonpoint source pollution often relies in one way or another on policy instruments based on ambient indicators. For well-known reasons, enforcement of ambient-based policies is, at best, limited. If no individual choices or actions are observed, than ambient-based regulation might be the only feasible approach. Often, some relevant individual indicators, such as output or certain inputs, are observable. For such cases, we offer a regulation mechanism that does away with ambient 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. Special attention is given to the regulation of (unobserved) abatement.

JEL classification: H23, L51, Q54, Q58

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1 Introduction

Regulation of environmental pollution relies in one way or another on emission taxes or quotas. Implementing these instruments is straightforward when individual emissions are observed or can be inferred from readily available information. Both of these conditions fail to hold in situations involving nonpoint source pollution and asymmetric information: nonpoint source pollution is prevalent when emissions emanate from many dispersed polluters and monitoring individual emissions is costly; asymmetric information occurs when individual characteristics affecting choices are the individual's private information.

The bulk of the literature on the regulation of nonpoint source pollution under asymmetric information relies in one way or another on taxes or quotas based on ambient (aggregate) indicators (Segerson 1988, Xepapadeas 1991, 1992, Cabe and Herriges 1992). 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, and references he cites). The common approach of rectifying these limitations entails combining 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.

Any regulation scheme is based in one way or another on observable indicators and since some ambient (or aggregate) indicators are typically observable (or can be measured at a reasonable cost), it is often straightforward to exploit them for regulation purposes in nonpoint source pollution situations. If no relevant individual choices or actions are observable, than ambient-based regulation may be the only feasible approach.[1] However, quite often some individual choices or actions, related to emission, are observable (e.g., outputs or some inputs). In such cases it may be possible to design a regulation mechanism for each individual based on these observed individual indicators. This is the approach taken in this work. We consider a situation in which emission is proportional to output and the proportionality factor depends on abatement. Such situations are ubiquitous and include emission from smokestack, where abatement involves installing end-of-pipe equipment, and emission/pollution from agricultural runoff or animal waste, where abatement entails the application of various treatment technologies.[2]

The regulator does not observe abatement efforts, hence emission is unobserved, and knows the polluter's characteristics (type) up to a probability distribution. The observable (contractible) variable is output, based on which contracts are specified to induce the desirable output, abatement and emission. Our mechanism design draws on Laffont (1994); the main innovation is in the regulation of the unobserved abatement. The mechanism involves transfers.

[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.

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

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 informational rents and the ensuing allocation deviates from its full information (first-best) 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 summarizes properties of the production and abatement technologies. Section 3 summarizes properties of the complete information (reference) case. Section 4 specifies the regulation mechanism, discusses implementation and verifies the optimal properties of the ensuing output-abatement allocation. Sec 5 concludes and the appendix contains technical derivations.

2 Setup

We ignore uncertain conditions affecting emissions, due e.g. to weather,[3] and confine attention to deterministic mechanisms.[4] Thus, although there are many polluters, we consider the regulation of one (any). The polluter may be an individual farmer or firm, a group of farmers or firms (with the same adverse selection character), an industry or a country. We generically refer to the polluter as the "firm" and to the regulating agency as the "regulator." Emission is proportional to output and the proportionality factor depends on

[3]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.

[4]The term "deterministic" in this context refers to the property that the mechanisms is applied to each polluter separately rather than to the entire group of polluters (see Laffont and Tirole 1993, p. 119, for a discussion).

abatement. Properties of the production and abatement technologies are specified in the next subsection. The asymmetric information (adverse selection) and observation (moral hazard) structures are characterized in subsection 2.2.

2.1 Output, abatement and emission

The Firm's output and cost of production are denoted y and $C(y, \beta)$, respectively, where $\beta \in [0, \bar{\beta}]$ is 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 y. Adopting the convention that a higher β is associated with a more efficient firm, both the cost and marginal cost decrease with β, i.e., $C_2 < 0$ and $C_{12} < 0$, where subscripts 1 and 2 signify derivatives with respect to the first and second argument, respectively ($C_1 \equiv \partial C/\partial y$ and $C_{12} \equiv \partial^2 C/\partial y \partial \beta$). Some additional cost function properties (including third derivatives) will be needed and we summarize all properties here:

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

for all $y > 0$ and $\beta \in [0, \bar{\beta}]$.

Emission is proportional to output, $e = g(a)y$, where a represents abatement efforts (cost) and $g : \mathbb{R}_+ \mapsto [\underline{g}, \bar{g}]$ is a decreasing and strictly convex abatement (technology) function satisfying

$$g(0) = \bar{g} > g(\infty) = \underline{g} > 0,\ g'(0) < 0,\ g'(\infty) = 0,\ \text{and } g''(a) > 0\, \forall a \in [0, \infty). \tag{2.2}$$

The convexity of $g(\cdot)$ merely reflects the diminishing marginal productivity of abatement efforts.

Emission inflicts an environmental damage with associated cost which is typically increasing and convex in the emission rate. In the interest of simplicity we assume a linear environmental cost function and let τ represent the cost per unit emission, so the external cost associated with an output-abatement allocation (y, a) is $\tau g(a)y$.

2.2 Observation and information

The regulator observes output y but not the abatement cost a,[5] hence emission $g(a)y$ is not observed either. Information regarding the firm's type is private and the regulator knows β up to the probability distribution $F(\beta)$, with a density $f(\beta) = F'(\beta)$, assumed positive over $[0, \bar{\beta}]$, and a nondecreasing hazard $h(\beta) = f(\beta)/[1 - F(\beta)]$. Based on the information available to him, the regulator seeks a mechanism that will induce the firm to choose the socially optimal output and abatement efforts (cost). Before developing the mechanism in Section 4, we look at the complete information case that will serve as a reference.

3 The reference case: full information

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

Suppose output and abatement are observed by all and the firm's type is common knowledge. Consider regulation via the transfer t (from the regulator to the firm), giving rise to the social welfare

$$py - C(y, \beta) - a + t - \tau g(a)y - (1 + \lambda)t,$$

[5]Total cost, $C + a$, may or may not be observed, with important implications regarding emission regulation, as discussed in Section 4.

where p is the output price, assumed given (and taken parametrically by the firm), and λ is the social cost of transfer (i.e., each dollar of transfer generates a deadweight loss of $\lambda \times 100$ cents due, e.g., to transactions costs or distortions). Letting

$$\pi = py - C(y, \beta) - a + t \tag{3.1}$$

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

$$(1 + \lambda)(py - C(y, \beta) - a) - \tau g(a)y - \lambda\pi. \tag{3.2}$$

The socially optimal y, a and t (or π) maximize (3.2) subject to the participation constraint $\pi \geq 0$ and nonnegativity of y and a. The necessary conditions for optimum are

$$p - C_1(y, \beta) = \frac{\tau g(a)}{1 + \lambda}\ , \tag{3.3a}$$

$$-g'(a)y = \frac{1 + \lambda}{\tau} \tag{3.3b}$$

and

$$\pi = 0, \tag{3.3c}$$

where in (3.3a) and (3.3b) the equal signs change to less or equal at the corners of $y = 0$ and $a = 0$, respectively.

Following (3.3b), define

$$q(a) \equiv \frac{1 + \lambda}{-g'(a)\tau} \tag{3.4}$$

and note, recalling (2.2), that $q'(a) = (1 + \lambda)g''(a)/(\tau g'(a)^2) > 0$. In view of (2.1), there exists some finite $\bar{a}$ for which $p - C_1(q(\bar{a}), \bar{\beta}) = 0$ and $p - C_1(q(a), \beta) \leq 0$ for all $\beta \in [0, \bar{\beta}]$ and large enough a. Suppose that

$$p - C_1(q(0), 0) > \frac{\tau g(0)}{1 + \lambda}. \tag{3.5}$$

Then, for any $\beta \in [0, \bar{\beta}]$ equations (3.3a)-(3.3b) admit a positive solution (a^*, y^*) with $y^* = q(a^*)$. Requiring, in addition, that

$$p - C_1(q(a), \beta) - \frac{\tau g(a)}{1+\lambda}$$

is decreasing in a for any $\beta \in [0, \bar{\beta}]$ ensures that the solution is unique. A sufficient condition for uniqueness is therefore

$$-C_{11}(q(a), \beta) q'(a) - \frac{\tau g'(a)}{1+\lambda} < 0 \text{ for all } \beta \in [0, \bar{\beta}] \text{ and } a \geq 0. \tag{3.6}$$

We summarize the above discussion in

Proposition 1. *Under (2.1), (2.2), (3.5) and (3.6), equations (3.3a)-(3.3b) admit a unique and positive solution* (y^*, a^*) *equals to the socially optimal output-abatement allocation.*

Under complete information there are various ways to implement the optimal allocation, e.g., the transfer $t = -\tau g(a) y/(1+\lambda)$, which is equivalent to a Pigouvian tax of $\tau/(1+\lambda)$ on emission. We proceed to develop a regulation mechanism in the genera case of moral hazard and adverse selection, maintaining throughout properties (2.1), (2.2), (3.5) and (3.6).

4 The regulation mechanism

The mechanism consists of a transfer function $\hat{t}(y)$ and an abatement function $\hat{a}(y)$, defined in terms of (the observable) output, and is implemented along the following steps. The regulator announces the transfer policy $\hat{t}(y)$, based on which the firm chooses output. Upon observing the firm's output, the regulator imposes the abatement $\hat{a}(y)$ – the abatement function evaluated at the observed output choice – and fully reimburses the firm for that cost.

The transfer $\hat{t}(\cdot)$ is so specified that the firm's output choice is socially optimal. Since output is observable, the implementation of $\hat{t}(\cdot)$ – i.e., using it to induce a certain output choice – is straightforward. Implementing the abatement via the $\hat{a}(\cdot)$ function is more subtle since abatement is unobserved. We return to this issue after the implementation properties of the mechanism are verified in Proposition 2.

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 functions $\{Y(\cdot), A(\cdot), T(\cdot)\}$, following which the firm reports its type b. Upon receiving the report b, the regulator assigns the firm 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 $T(b)$.

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 truthtelling 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. (2.1)), the monotonicity condition

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

is sufficient for truthtelling.[6]

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

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. (2.1)), $\Pi(\cdot)$ is increasing and requiring

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

ensures a nonnegative profit for all firm types.

Noting (3.2), the expected social welfare equals

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

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 an Optimal Control problem

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a 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

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

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 $b < \beta$.

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 A that $Y^*(b)$ and $A^*(b)$ satisfy

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

and

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

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 1. *Under (2.1), (2.2) and (3.6), $Y^{*\prime}(b) > 0$ for all $b \in [0, \bar{\beta}]$.*

The proof is given in Appendix B. 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. □

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, however, 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. eq. (4.14)). Once β is known, the regulator can calculate the production cost $C(y^{*\lambda}, \beta)$ and deduce the abatement cost from the (observed) total cost $C + a$.[7]

When $\lambda = 0$ (zero social cost of transfers), the $[\hat{t}, \hat{a}]$ mechanism implements the complete information allocation (y^*, a^*), defined by (3.3a)-(3.3b). 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 (3.3a) and (4.9) is the same as (3.3b). Since the solution of (3.3a)-(3.3b) 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.

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

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

where, $q(a) = -(1 + \lambda)/(\tau g(a))$ is defined in (3.4). Likewise, from (3.3a),

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

[7]The use of total cost observation to identify abatement costs is similar in approach, though not in details, to Laffont and Tirole (1986).

Subtracting the latter from the former gives

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

The above inequality can be expressed as

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

In view of (3.6), the integrand (the term inside the square brackets) is positive, implying $a^{*\lambda} < a^*$, hence $y^{*\lambda} = q(a^{*\lambda}) < q(a^*) = y^*$. 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, complete-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 $g(\cdot)$ is decreasing, emission, $g(a^{*\lambda})y^{*\lambda}$, may exceed or fall short of its full information counterpart $(g(a^*)y^*)$, depending on the specifications of the underlying production and abatement technologies and the asymmetric information.

5 Concluding comments

We offer a mechanism to regulate nonpoint source pollution based on individual outputs rather than ambient or aggregate indicators. The mechanism, specified for each individual polluter (firm) separately, consists of two functions defined in terms of the firm's observable output: a transfer function and an abatement function. 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) parameter, and allows implementation of optimal abatement when the firm's total cost (production and abatement) is observable. If total cost is unobserved, additional device will be needed to ensure that the firm actually carries out the abatement cost for which it has been reimbursed. Such a device may well be the existing 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 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.

We consider the case in which emission is proportional to output and the proportionality factor depends on abatement. In actual practice one encounters a host of output-abatement-emission structures. There are many examples of GHG emission reduction possibilities in land use and agricultural production practices that change the relationship between production and emissions, such as irrigation and water management practices that reduce GHG emissions from crop production or nutrient management that reduces emissions from fertilizer application. 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). Applying the framework developed here to any particular case will require appropriate modifications and verification that the properties, established in the present case, continue to hold.

Appendix

A 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

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

Necessary conditions for an interior optimum include

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

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

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

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

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

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

$$-\mu(b) = \lambda[1 - F(b)]. \quad \text{(A.5)}$$

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

B Proof of Lemma 1

Totally differentiate (4.8) to obtain $Y^{*\prime}D_1 = D_2$, where

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

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

and use has been made of (4.9) to express $A^{*\prime} = -g'Y^{*\prime}/(g''Y^*)$. Since the hazard function $h(b) = f(b)/[1 - F(b)]$ is nondecreasing, and (from (2.1)) $C_{12} < 0$ and $C_{212} \geq 0$, we have $D_2 < 0$. We next show that $D_1 < 0$.

Notice ((2.1) again) that the right-most term of D_1 is non-positive, so we need

$$-C_{11} + \frac{\tau}{1+\lambda}\frac{(g')^2}{g''}\frac{1}{Y^*} < 0.$$

To show this, recalling (3.4), multiply the left-hand side of the inequality by the positive function

$$q'(a) = \frac{1+\lambda}{\tau}\frac{g''(a)}{g'(a)^2}$$

evaluated at $a = A^*$ to obtain

$$-C_{11}(Y^*, b)q'(A^*) + \frac{1}{Y^*}.$$

Invoking (A.2), the above can be expressed as

$$-C_{11}(q(A^*), b)q'(A^*) + \frac{-g'(A^*)\tau}{1+\lambda}, \tag{B.1}$$

which equals the left-hand side of (3.6) evaluated at $a = A^*$ and $\beta = b$, verifying the claim.

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