Politics, public bads, and private information

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October 20, 2005

Abstract

Preferential treatment for politically influential sectors often has undesired consequences such as increasing pollution or ecosystem degradation. Private information on firm productivity constrains the government's ability both to redistribute income and regulate public bad production. Given political economy and information constraints, this article characterizes a social-welfare maximizing policy. The optimal policy uses a single instrument to achieve both goals, making income-support subsidies contingent upon reduction of bad outputs. Output price uncertainty works to the advantage of the government, potentially eliminating some firms' information advantage.

JEL Classification: D82, H23, Q52

Key words: Mechanism design, environmental policy, political economy, countervailing incentives

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1 Introduction

It is a widely bemoaned fact that government subsidies often encourage the creation of public "bads" (e.g., Green Scissors Campaign (2004) and Myers and Kent (2001)). This type of policy is frequently encountered in environmental and natural resource intensive sectors. Examples range from below-market timber concessions, to subsidized credit to fishing fleets, to price supports for agricultural producers. These subsidies are especially pernicious since the usual welfare loss from market distortions is compounded by the anti-Pigouvian effect of increasing negative externalities. Their continued existence in spite of high social costs is a testament to the political influence of the beneficiaries.

To the palpable frustration of public interest groups, simply making policy-makers aware of possibilities for simultaneously cutting budget deficits while reducing environmental degradation is not sufficient to ensure remedial action. Policy recommendations that do not satisfy implicit political economy constraints are likely to be non-starters.

In practice, when governments do try to reduce public damages caused by a politically influential sector, income subsidies are often completely "decoupled" from the action an individual firm might take to reduce its share of undesirable outputs. Take United States' agricultural policy, for example. Agricultural income support is popularly perceived as providing a safety net for economically vulnerable farmers. In this spirit, most direct payments are countercyclical in nature, providing lump-sum transfers that vary inversely with output prices. Income support is generally not contingent upon reducing environmental damage. The largest agro-environmental program, the Conservation Reserve Program, is administered independently as an auction in which farmers competitively bid for rental payments to take environmentally-sensitive cropland out of production.

At first glance, the approach of using two policy instruments to achieve the two policy targets of income redistribution and public bad reduction seems economically efficient. Lump-sum transfers redistribute income in a non-distortionary way. Why use an auction for the environmental component? In principle, a linear subsidy could efficiently allocate public bad reductions. It is often reasonable, however, to suppose that individual firms know the true opportunity cost of reducing damages better than the government. If public funds are limited, mechanism design theory suggests that auctions can be an effective means of reducing the rents firms gain from their private information.

Upon further reflection it becomes evident that there should be a way of doing even better. Suppose a firm's opportunity cost of reducing public bads (for expository purposes henceforth referred to as pollution emissions) depends upon its overall profitability. Then, a firm's participation in an emissions auction reveals information that can be useful in determining how much of an income subsidy that firm should receive. This observation suggests that under asymmetric information, the two-instruments-for-two-targets approach may not perform as well as killing two birds with one stone: using one integrated instrument to achieve both objectives.

Previous research has characterized optimal policies under asymmetric information using the framework of Baron and Myerson (1982). These studies model a policy as a system of contracts to which the government and the regulated sector commit. Private information can give firms an incentive to misrepresent their true characteristics (referred to as a firm's **type**) by choosing a contract intended for another firm. In order to overcome these incentives some firms must receive surplus payments. By making payments vary non-linearly with observable actions, the government can impose costs to a firm for misrepresenting its type. This result can make it suboptimal to decouple income redistribution payments from production decisions in a politically powerful sector (Lewis et al., 1989).

Private information frequently gives firms an incentive to misrepresent their type in one direction. In an income support program for example, firms have an incentive to claim that they are relatively less profitable in order to receive a larger subsidy. If the government can introduce incentives that operate in the opposite direction, social welfare can be further improved (Lewis and Sappington, 1989). This insight has led a number of authors to look for means of introducing such "countervailing" incentives in environmental policy. If relatively few firms have political clout, countervailing incentives may be created by allocating tradable emissions permits first to preferred firms, then to the rest (Lewis and Sappington, 1995). Alternatively, if the government can commit to a lottery over whether to monitor an input or an output in a polluting industry, this contract introduces uncertainty into the firms' incentives thereby reducing surplus payments and increasing social welfare (Bontems and Bourgeon, 2000; Khalil and Lawarrée, 2001).

This article builds on earlier work in a number of ways. In previous articles, the government is in a relatively strong position vis a vis the regulated sector. Regulated firms can be made worse off by the policy than they were without it, as long as they earn a minimum level of profit. Here, I examine regulation of more powerful sectors where not only must a profit target be met, but participation in the program must be voluntary. Unlike Lewis and Sappington (1995), I consider cases where the entire regulated sector has political clout, so I cannot rely on unprivileged firms to generate countervailing incentives. Also, unlike Bontems and Bourgeon (2000) or Khalil and Lawarrée (2001), the government does not need to have the capacity to monitor more than one action.

This last element is important in many sectors. In agriculture, for example, it would be costly to monitor variable input and output use since these tend to be commodities that can be bought or sold in many outlets. Moreover, some can be procured or consumed on the operation itself (e.g., fertilizer obtained from manure or crops fed to livestock). A single quasi-fixed input like land cultivation, in contrast, is relatively easy to observe.

Finally, unlike earlier research I examine the effect of random price variation. The literature commonly assumes prices to be either non-stochastic or non-contractible. In reality of course, neither is true. Not only do prices fluctuate, but contracts contingent on future prices are common in both the private and public sectors. Firms' welfare and incentives can depend upon the realized price level. If so, the government can gain by forcing agents to commit to a price-contingent contract before prices become known. The gains to the government occur even if firms are risk neutral.

The two political constraints of a minimum profit level and voluntary participation can of themselves create countervailing incentives. Private information works to the advantage of firms and to the disadvantage of society both in terms of providing income support and voluntarily reducing emissions. Consider a pure income support program. Due to the social cost of income transfers, the government would ideally give each firm the minimum payment necessary to attain the income target. Firms have an underlying incentive to under-state profitability in order to receive a higher subsidy. For a voluntary program to reduce emissions, private information also gives firms a means of increasing payments from the government. In this case, the higher a firm's profitability, the higher its "return" to polluting, and the greater the compensatory payment necessary to induce it to reduce emissions. Consequently, firms have an incentive to over-state profit.

This intuition underlies the result that linking income support to emissions reduction can outperform a combination of lump-sum transfers with either a cap-and-trade emissions scheme or a mechanism such as an emissions-reduction auction. If the two policy targets are linked to the same instrument a firm cannot simultaneously over-state and under-state its type.

These countervailing incentives are not strong enough, however, to cancel each other out completely. The degree of countervailing incentives depends on prices and contract timing. For any given output price level, one incentive always dominates. The effect of the two political constraints varies with output price. If price is relatively high, the income support constraint binds for fewer firms, but the voluntary participation constraint binds for more firms. If price is low, the opposite is true.

If commitment takes place ex post (after output price is known), all firms know with certainty whether they should over-state or under-state type. If commitment takes place ex ante, the benefit from over-stating type should output price be high must be balanced with the cost if it ends up being low. Thus, an ex ante contract serves to strengthen countervailing incentives by reducing the expected benefit of misrepresenting type. In some cases these countervailing incentives can be strong enough to eliminate entirely any incentive to misrepresent type for a wide range of firm types.

In the next section, I present the formal model and assumptions, explicitly specifying the political economy constraints and the government's social welfare function. In Section 3, I establish a baseline by obtaining the allocation of emissions and payments that would maximize social welfare if the government could observe firm type. In this full-information case, standard policy approaches such as a cap-and-trade permit system can achieve the social optimum. The remaining sections relax the full-information assumption. In Section 4, I examine the case where contract commitment takes place before the resolution of price uncertainty. In Section 5, I examine the case where contract commitment occurs after price is known. The model makes it clear that the set of the government's feasible options becomes gradually more constrained as the analysis progresses from Sections 3 to 5. As such, the ex ante policy dominates the ex post policy. I offer concluding remarks in Section 6, and present proofs in the Appendix.

2 The Model

Risk-neutral firms are identical except for the productivity of emission permits. The scalar parameter $\theta \in \Theta \equiv [\underline{\theta}, \overline{\theta}]$ represents a firm's **type**. Type is a measure of productivity known only to the individual firm. The probability distribution of types for the entire sector is common knowledge, however. The functions $f(\theta)$ and $F(\theta)$ denote the probability density and cumulative distribution, where $dF(\theta) \equiv f(\theta)\,d\theta$, and $f(\theta) > 0$ for all θ.

Firms use input x to create good q and emissions e. The government can monitor e, but not x or q.[1] The government regulates emissions by requiring a permit for each unit of e. Each firm has the initial right to a maximum of $\overline{e}$ permits, and must be compensated for relinquishing any.

Input price is normalized to unity, and p denotes output price. Market profit earned by a firm type θ at price p with $e \in [0, \overline{e}]$ permits is a thrice continuously differentiable function $\pi(p, e, \theta) \equiv \sup_{x,q} \{pq - x\colon x \text{ can produce } q \text{ given } e, \theta\}$. Output price is random, having a Bernoulli distribution with outcomes "low" (p_ℓ) with probability $\rho \in [0, 1]$, and "high" (p_h) with probability $1 - \rho$. Production takes place after resolution of price uncertainty. Expected market profit (before p is known) is $\Pi(e, \theta) \equiv \rho\pi(p_\ell, e, \theta) + [1 - \rho]\,\pi(p_h, e, \theta)$.

The following regularity conditions restrict the production technology and distribution of types:

[1] Alternatively, the model could easily be adapted to cases in which the government can monitor a single input or output, but not emissions.

R1. $\pi(p, 0, \theta) = 0$

R2. $\pi_e(p, e, \theta) > 0$;

R3. $\pi_{ee}(p, e, \theta) < 0$;

R4. $\pi(p, e, \theta) = g(\theta)\tilde{\pi}(p, e)$, where $\tilde{\pi}(p, e) \equiv \pi\left(p, e, \bar{\theta}\right)$;

R5. $g'(\theta) > 0$;

R6. a. $\frac{d}{d\theta}\left[\frac{F-\phi}{f}\right] > 0$, for $\phi \in \{0, 1\}$;

b. $\frac{[1+\lambda]}{\lambda}g'(\theta) + \frac{F-\phi}{f}g''(\theta) \geq 0$, for $\phi \in \{0, 1\}, \lambda > 0$;

c. $\frac{[1+\lambda]}{\lambda}g(\theta) + \frac{F-1}{f}g'(\theta) \geq 0$, for $\lambda > 0$.

The first two conditions state that a firm cannot profitably operate if it eliminates all emissions (R1) and that there is always a positive opportunity cost to reducing emissions (R2). By R3 this cost increases as a firm reduces emissions. Condition R4 states that θ behaves as a profit-neutral technical change parameter (Chambers, 1988). This restriction simplifies the analysis by allowing a focus on this particular class of technologies.[2] Combined with R4, condition R5 indicates that a higher value of θ is desirable: profit is always increasing in type. Combined with R2, it ensures that the Spence-Mirrlees condition is satisfied such that the foregone profit of higher types from a marginal reduction in e is higher than that of lower types. Variations on the three parts of condition R6 are commonly used in the literature to prevent pooling equilibria arising from purely technical characteristics of the distribution of types and the production technology (Fudenberg and Tirole, 1991).[3]

The government's problem is to design a one-time allocation of transfers and emissions reduction to each type of firm.[4] Let $t(p, \theta)$ denote the transfer to firm type θ in price

[2] Maggi and Rodríguez-Clare (1995) and Jullien (2000) characterize solutions to problems where R4 is not satisfied.

[3] For a detailed treatment of how to solve problems where R5 is violated consult Guesnerie and Laffont (1984).

[4] Alternatively, this interaction can be viewed as a repeated game in which the government can commit not to use information learned in one iteration in later repititions, thus avoiding the "ratchet effect" (Laffont

state p. Expected transfers are $T(\theta) \equiv \rho t(p_\ell, \theta) + [1-\rho] t(p_h, \theta)$. The allocation of emission permits to a firm of type θ is $e(\theta)$. Reflecting possible transition costs of altering the production process to reduce pollution, the allocation $e(\theta)$ does not vary with price fluctuations.[5] The amount of emissions from the entire sector is $E = \int_\Theta e(\theta)\, dF(\theta)$. The amount of environmental damage caused by the sector is $D(E)$, where $D'(E) > 0$, and $D''(E) > 0$.

The optimal allocation maximizes the average (across firms) of expected (across price states) net social benefits. To simplify the analysis, I assume that output demand is perfectly elastic. Let $\lambda > 0$ denote the social cost of raising one dollar of public funds. Average expected welfare, $\tilde{W}(\cdot)$, from a given policy is then the sum of producer profit less the cost of public funds and the damage caused by emissions:

$$\tilde{W} \equiv \int_\Theta \{\Pi(e(\theta), \theta) - \lambda T(\theta) - D(E)\}\, dF(\theta). \tag{1}$$

In designing an allocation of transfers and permits, the government must satisfy two political economy constraints: i) all firms must attain a minimum profit threshold, m; and ii) participation in the program must be voluntary. The first constraint is modeled as a requirement that all firms earn at least minimum profit m in each price state:

$$\pi(p, e(\theta), \theta) + t(p, \theta) \geq m, \quad \text{for all } \theta, p. \tag{2}$$

To ensure the program is voluntary, firms must be compensated for the ex post cost of emissions reductions. After price becomes known, no firm can have an incentive to cancel the contract (i.e., decline both to reduce emissions and receive a payment). This participation

and Tirole, 1993).

[5] In agriculture, for example, most environmental benefits accrue from taking a unit of land out of production for an extended period of time (OECD, 1993).

constraint is:

$$\pi\left(p,e\left(\theta\right),\theta\right)+t\left(p,\theta\right)\geq\pi\left(p,\overline{e},\theta\right),\quad\text{for all }\theta,p. \tag{3}$$

I assume that in the absence of any government program all types earn below the minimum income threshold when price is low and above the threshold when price is high: $\pi\left(p_{\ell},\overline{e},\theta\right)<m<\pi\left(p_{h},\overline{e},\theta\right)$. Thus, satisfaction of the income constraint implies the participation constraint is satisfied when output price is low, and satisfaction of the participation constraint implies that the income constraint is satisfied when output price is high.

Denote surplus payments received by a firm in excess of the minimum necessary to satisfy (2) and (3) by:

$$s\left(p,\theta\right)\equiv\pi\left(p,e\left(\theta\right),\theta\right)+t\left(p,\theta\right)-\max\left\{m,\pi\left(p,\overline{e},\theta\right)\right\}. \tag{4}$$

Constraints (2) and (3) can then be replaced by the following surplus constraint:

$$s\left(p,\theta\right)\geq0\text{ for all }\theta,p. \tag{5}$$

Ex ante surplus is $S\left(\theta\right)\equiv\rho s\left(p_{\ell},\theta\right)+\left[1-\rho\right]s\left(p_{h},\theta\right)$.

It is convenient to redefine net welfare $\tilde{W}\left(e\left(\theta\right),t\left(p,\theta\right)\right)$ as a function $W\left(e\left(\theta\right),s\left(p,\theta\right)\right)$ of surplus rather than transfers. Using Eq. (4) to change the variables, $\tilde{W}$ can be rewritten as:

$$W\equiv\int_{\Theta}\left\{\left[1+\lambda\right]\Pi\left(e\left(\theta\right),\theta\right)-D\left(E\right)-\lambda\left[S\left(\theta\right)+\rho m+\left[1-\rho\right]\pi\left(p_{h},\overline{e},\theta\right)\right]\right\}dF\left(\theta\right) \tag{6}$$

The government's problem is to choose an allocation $\left\langle e\left(\theta\right),s\left(p,\theta\right)\right\rangle$ that maximizes W. The differences between the three mechanisms (full information, ex ante, and ex post) are essentially differences in the set of feasible allocations from which the government can choose. In the next section, I examine the full information mechanism.

3 Full Information Mechanism

Suppose type is observable and contractible. In this case, the regulator's problem is simply one of allocating emissions and transfer payments to each type such that social welfare is maximized subject to the political economy constraints summarized by (5). Let $\psi(p,\theta) \geq 0$ be the Lagrange multiplier for (5), and $\mu(\theta)$ be the Lagrange multiplier for the constraint that a firm's maximum emissions cannot exceed $\overline{e}$. The government's problem is to maximize the full-information Lagrangian:

$$\begin{aligned} L^{FI} &= W(e(\theta), s(p,\theta)) + \int_{\Theta} \mu(\theta) [\overline{e} - e(\theta)] \, d\theta \\ &\quad + \lambda \int_{\Theta} \{\rho\psi(p_\ell,\theta) s(p_\ell,\theta) + [1-\rho] \psi(p_h,\theta) s(p_h,\theta)\} \, d\theta. \end{aligned} \tag{7}$$

Proposition 1 characterizes an interior solution to this problem.

Proposition 1 An interior solution for a maximum of L^{FI} satisfies:

$$e(\theta) = \{e : [1+\lambda] \Pi_e(e,\theta) = D'(E)\}; \tag{8}$$

$$s(p,\theta) = 0. \tag{9}$$

Eq. (8) defines the optimal emissions allocation. Intuitively, allocation of an additional emission permit to a firm of a given type has social benefits and costs. The benefits arise from increasing the firm's profit. The increase in profit has two welfare implications. First, it increases firm welfare by Π_e. Second, this increase in profit reduces the social cost of satisfying the political constraints by $\lambda \Pi_e$. Increasing e also creates a social cost by increasing environmental damage by $D'(E)$. At the optimum, the marginal benefits equal the marginal cost for each firm. Since $D'(E)$ has the same value for all types, a second implication is that at the optimum the marginal profit earned from an additional emission permit is equal for all firms. Eq. (8) also indicates that pooling is not optimal. The allocation of emissions permits is optimally strictly increasing in type. This result follows directly from the curvatures of π and D.

If the government can directly observe a firm's type, no surplus payment is necessary to induce it to tell the truth. Since surplus payments are socially costly, they are optimally zero, hence Eq. (9).

Under full information, the two policy targets of redistributing income and obtaining a socially optimal amount of pollution can be achieved by a traditional two-instrument set of policies. For example, the efficient emission allocation can be achieved by either a Pigouvian tax or an emission trading scheme. These policies cause all firms to equate the marginal profit of an emissions permit to the emissions tax or the market price of an permit. The political economy constraints can then be satisfied by lump-sum transfers, where the size of the transfer depends upon the firm's type. By Eq. (8), a policy such as a common emissions standard that applies to more than one type of firm is not optimal for a full information mechanism. Moreover, since the government can replicate any ex post allocation with a state-contingent ex ante allocation, timing has no influence on the full information mechanism.

4 Ex Ante Mechanism

Having confirmed the optimality of conventional policy prescriptions under full information, I now relax this assumption. The government cannot force a firm to accept the contract intended for it. Rather, a firm only accepts a contract that maximizes expected welfare compared to all other available contracts.[6] Hence, the government's problem is more constrained than under full information. With this additional constraint, conventional policies such as cap-and-trade or a Pigouvian subsidy are no longer optimal. In general, it is optimal to link payments to emissions in a non-linear way. In addition, it may be optimal to enforce a common emissions standard for a non-degenerate range of types.

For the ex ante revelation mechanism to be truthful, incentive compatibility requires that expected firm income be maximized by reporting the true type θ:

$$\theta \in \arg\max_{\tilde{\theta}} \left\{ \Pi\left(e\left(\tilde{\theta}\right), \theta\right) + T\left(\tilde{\theta}\right) \right\}, \text{ for all } \left(\theta, \tilde{\theta}\right) \in \Theta^2. \tag{10}$$

Lemmas 1 and 2 state the constraints that incentive compatibility imposes on the ex ante mechanism.

Lemma 1 A truthful ex ante mechanism requires the permit allocation to be monotonically non-decreasing in type:

$$e'(\theta) \geq 0. \tag{11}$$

Lemma 2 A truthful ex ante mechanism requires the change in expected surplus over type to follow:

$$S'(\theta) = \Pi_\theta(e(\theta), \theta) - [1-\rho]\, \pi_\theta(p_h, \overline{e}, \theta) \tag{12}$$

Note the shape of $S(\theta)$ as described in Eq. (12). Expected surplus may be increasing or decreasing in type. For any given value of ρ, the incentive to over or under-state type depends on the emissions allocation $e(\theta)$. To understand the intuition behind this result,

[6] I do assume that if a firm is indifferent between two contracts, it will choose the one intended for it by the government.

consider the extreme allocations $e = 0$ and $e = \overline{e}$. If a firm is required to shut down completely, to satisfy income and participation constraints it must receive minimum expected payment of $\rho m + [1-\rho]\,\pi(p_h, \overline{e}, \theta)$. Since this payment is increasing in type, lower types need to receive expected surplus to induce them to tell the truth.

If a firm is not required to reduce emissions at all, then the situation is reversed. The minimum expected payment that satisfies income and participation constraints is $\rho\,[m - \pi(p_\ell, \overline{e}, \theta)]$. Since this payment is decreasing in type, it is higher types that require expected surplus to induce them to tell the truth.

By conditions R2, R4, and R5, there is only one emissions allocation that makes $S'(\theta) = 0$ for a given type. Let $\hat{e}$ denote this allocation:

$$\hat{e} \equiv \left\{ e : \tilde{\Pi}(e) = [1-\rho]\,\tilde{\pi}(p_h, \overline{e}) \right\}. \tag{13}$$

Expected surplus is decreasing for $e(\theta) < \hat{e}$, and increasing for $e(\theta) > \hat{e}$. By imposing structure on the way type interacts with the production technology, R4 allows this precise characterization of the optimal contract mechanism. Specifically, this condition makes $\hat{e}$ constant for all θ.

Since Lemma 1 requires that the permit allocation be non-decreasing in type, $S(\theta)$ has the possible shapes depicted in the lower panels of Figure 1. The support Θ can be divided into three possible intervals depending on the emissions allocation. For Θ_1, $e(\theta) < \hat{e}$ and $S(\theta)$ is decreasing, for Θ_2, $e(\theta) = \hat{e}$ and $S(\theta)$ is constant, and for Θ_3, $e(\theta) > \hat{e}$ and $S(\theta)$ is increasing. Let θ_1 denote the upper bound of Θ_1, and θ_2 denote the lower bound of Θ_3.

Let $\Gamma(\theta)$ be the Lagrange multiplier for constraint (12) in Lemma 2. The government's Lagrangian for the ex ante mechanism is the full information Lagrangian (7) with the additional constraints implied by ex ante incentive compatibility:

$$L^{XA} = L^{FI} + \lambda \int_{\Theta} \Gamma(\theta) \left[\Pi_{\theta}(e(\theta), \theta) - (1-\rho) \pi_{\theta}(p_h, \overline{e}, \theta) - S'(\theta) \right] d\theta \tag{14}$$

subject to (11).

To solve this problem, I employ the standard practice of temporarily ignoring (11), and later checking to ensure that this condition is satisfied by the solution to this relaxed problem. After integrating the objective function (14) by parts, the first-order condition for an interior solution to the optimal emissions allocation is:

$$[1+\lambda] \Pi_e(e(\theta), \theta) = D'(E) - \frac{\Gamma(\theta)}{f(\theta)} \lambda \Pi_{e\theta}(e(\theta), \theta). \tag{15}$$

Let $e^*(\Gamma(\theta), \theta)$ denote the optimal allocation that implicitly solves Eq. (15). Proposition 2 characterizes an interior solution to this problem.

Proposition 2 An interior solution for a maximum of L^{XA} satisfies:

$$e(\theta) = \begin{cases} e^*(F(\theta), \theta), & e^*(F(\theta), \theta) < \hat{e} \\ \hat{e}, & e^*(F(\theta) - 1, \theta) < \hat{e} < e^*(F(\theta), \theta) \\ e^*(F(\theta) - 1, \theta), & \hat{e} < e^*(F(\theta) - 1, \theta); \end{cases} \tag{16}$$

$$S(\theta) = \begin{cases} \int_{\theta}^{\theta_1} \{[1-\rho] \pi_{\theta}(p_h, \overline{e}, z) - \Pi_{\theta}(e(z), z)\} dz, & e(\theta) = e^*(F(\theta), \theta) \\ 0, & e(\theta) = \hat{e} \\ \int_{\theta_2}^{\theta} \{\Pi_{\theta}(e(z), z) - [1-\rho] \pi_{\theta}(p_h, \overline{e}, z)\} dz, & e(\theta) = e^*(F(\theta) - 1, \theta). \end{cases} \tag{17}$$

Figure 1 depicts the three categories of solution to the ex ante problem depending on parameter values, specifications of profit and damage functions, and the distribution of types.

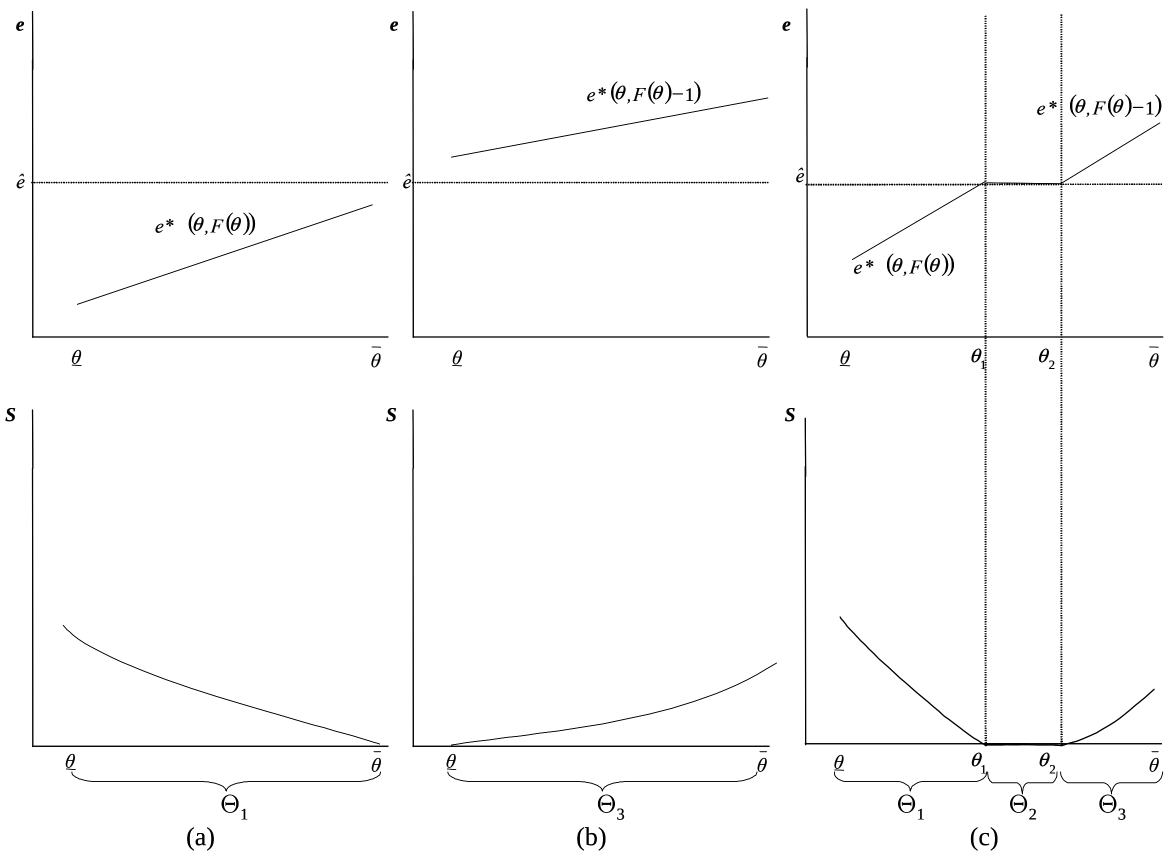

Figure 1: Ex ante contract allocations

Since output price is unknown at the time contract commitment takes place, misrepresenting one's type has an opportunity cost. Namely, declaring a type that maximizes utility when price is high will be suboptimal if price turns out to be low. If $e^*(F(\theta), \theta) < \hat{e}$ for all θ, then all types belong to Θ_1, and all types except $\bar{\theta}$ receive strictly positive expected surplus. For this solution, depicted in panel (a) of Figure 1, emissions reductions are so large that the dominant incentive is always to over-state type. The probability of a low price state occurring is low enough and foregone profit in the high price state is high enough, such that for all θ, the expected net benefit of over-stating type is positive for all types. Therefore, the expected surplus required to induce truth-telling is decreasing in type. Type $\bar{\theta}$ requires no expected surplus since it cannot credibly over-state type.

If $\hat{e} < e^*(F(\theta) - 1, \theta)$ for all θ, as depicted in panel (b), then the previous situation is reversed, with all types belonging to Θ_2, and having the dominant incentive to under-state type. In this case, expected surplus is increasing, with $\underline{\theta}$ receiving zero expected surplus.

If $e^*(F(\theta) - 1, \theta) < \hat{e} < e^*(F(\theta), \theta)$ for some interior types, then those types belong to Θ_2, as depicted in panel (c). This interval of types must be non-degenerate since by the strict concavity of π in θ (condition R3), $e^*(F(\theta) - 1, \theta) < e^*(F(\theta), \theta)$ for all types. For Θ_2 the expected net benefit from either over-stating or under-stating type is zero. That is to say, the incentive for over-stating type exactly countervails the incentive to understate type. Therefore, no expected surplus payments are required to induce truth-telling. All types lower than θ_1 face the dominant incentive to over-state type, and all types greater than θ_2 face the dominant incentive to under-state type.

Either $\bar{\theta}$ or $\underline{\theta}$ could possibly belong to Θ_2, but not both simultaneously. Note from Eqs. (8) and (15) that $e^*(F(\underline{\theta}), \underline{\theta}) = e^*(0, \underline{\theta})$ is the full-information emissions allocation for $\underline{\theta}$ and that $e^*\left(F\left(\bar{\theta}\right) - 1, \bar{\theta}\right) = e^*\left(0, \bar{\theta}\right)$ is the full-information allocation for $\bar{\theta}$. For both extreme types to belong to Θ_2 it would have to be true that $e^*(0,\underline{\theta}) > \hat{e} > e^*(0,\bar{\theta})$. This cannot be so, however, since under full information emissions are optimally increasing in θ.

Which of the three categories is the solution cannot be determined a priori. However, all solutions share the characteristic that at least one type always receives zero expected surplus.

Combined with first-order condition (15), Eq. (16) indicates that for all three categories, there is a distortion such that the marginal net social benefit of an additional permit is not equated across all types. Unlike the full information case, since right-hand-side of Eq. (15) varies across types, the linear emission price obtained by a Pigouvian tax or emission trading scheme is not optimal here.

With asymmetric information, the selected contract is the only information the government can use to distinguish between different types of firms. Thus, the permit allocation must effectively perform two roles: reduce pollution damages and reduce the cost of income support. Eq. (15) reflects this trade-off. The marginal cost of increasing permits to a given firm includes not only the environmental damage, but the net cost of additional payments made to all other firms.

In summary, the only difference between the government's problem for the ex ante mechanism and the full information mechanism is that for the ex ante mechanism the set of feasible contract allocations is limited by the incentive compatibility requirement (10). This small difference has profound implications for the characteristics of the optimal mechanisms for the two information settings. With full information there is only one class of solutions: emissions steadily increase with type, and no type receives any surplus payment. With the ex ante contract, there are three classes of solutions.[7] One exhibits pooling, such

[7] There would be more without R4.

that optimal emissions levels remain constant over a range of types. In each class some types receive strictly positive expected surplus and at least one type receives zero expected surplus. Unlike the full information mechanism, the marginal profit from an additional unit of emission is never equated across types for the optimal ex ante mechanism. As a result, a policy instrument such as tradable permits is not optimal with asymmetric information. If pooling is optimal, uniform standards may be appropriate for a non-degenerate range of firms. Otherwise, the optimal mechanism is characterized by a menu of contracts linking transfers to emissions in a non-linear manner.

5 Ex Post Mechanism

The ex post mechanism differs from the ex ante mechanism in that firms commit to contracts after output price is known. Permitting firms to contract ex post results in a more restrictive incentive compatibility constraint than in the ex ante case.

For the ex post revelation mechanism to be truthful, incentive compatibility requires that a firm's income (profit plus transfer) be maximized by reporting its true type:

$$\theta \in \arg\max_{\tilde{\theta}} \left\{ \pi\left(p, e\left(\tilde{\theta}\right), \theta\right) + t\left(p, \tilde{\theta}\right) \right\}, \text{ for all } \left(\theta, \tilde{\theta}\right) \in \Theta^2, p. \tag{18}$$

This requirement implies two constraints that a feasible ex post mechanism must satisfy, summarized in Lemmas 3 and 4.

Lemma 3 A truthful ex post mechanism requires the permit allocation to be monotonically non-decreasing in type:

$$e'(\theta) \geq 0. \tag{19}$$

Lemma 4 A truthful ex post mechanism requires that the change in surplus over type follow:

$$
\begin{aligned}
s_\theta(p_\ell,\theta) &= \pi_\theta(p_\ell, e(\theta), \theta) && (20)\\
s_\theta(p_h,\theta) &= \pi_\theta(p_h, e(\theta), \theta) - \pi_\theta(p_h, \overline{e}, \theta) && (21)
\end{aligned}
$$

Lemma 3 is identical to its counterpart for the ex ante case, Lemma 1. The fundamental difference between the two mechanisms lies in Lemmas 2 and 4. Note that any contract schedule that satisfies Eqs. (20) and (21) necessarily satisfies Eq. (12), but that the converse is not true. Since the ex post incentive compatibility constraints are more restrictive than the ex ante constraints, it follows that the ex post mechanism cannot achieve higher expected welfare than the ex ante mechanism.

To see the precise effect of this stronger constraint, note the shape of surplus in each state indicated by Lemma 4. Surplus is increasing if price is low and increasing if price is high. Thus, when the income constraint is binding surplus is increasing in type. The opposite is true when the participation constraint binds.

Let $\gamma(p,\theta)$ denote the Lagrange multipliers for ex post constraints (20) and (21). Since satisfaction of (20) and (21) implies satisfaction of the ex ante incentive compatibility constraint (12), the ex post Lagrangian can be expressed as the ex ante Lagrangian (14) with the additional constraints:

$$
\begin{aligned}
L^{XP} &= L^{XA} + \lambda \int_\Theta \left\{ \rho\gamma(p_\ell,\theta)\left[\pi_\theta(p_\ell, e(\theta), \theta) - s_\theta(p_\ell,\theta)\right] \right. && (22)\\
&\quad \left. + [1-\rho]\,\gamma(p_h,\theta)\left[\pi_\theta(p_h, e(\theta), \theta) - \pi_\theta(p_h, \overline{e}, \theta) - s_\theta(p_h,\theta)\right] \right\} d\theta
\end{aligned}
$$

subject to (19).To solve this problem, I again temporarily ignore (19). After integrating the objective function (22) by parts, the first-order condition for an interior solution for the ex post emissions allocation is:

$$\begin{aligned}[1+\lambda]\,\Pi_e\left(e\left(\theta\right),\theta\right) &= D'\left(E\right) - \\ &\quad \lambda\left[\tfrac{\rho\gamma(p_\ell,\theta)}{f(\theta)}\pi_{e\theta}\left(p_\ell,e\left(\theta\right),\theta\right)+\tfrac{[1-\rho]\gamma(p_h,\theta)}{f(\theta)}\pi_{e\theta}\left(p_h,e\left(\theta\right),\theta\right)\right].\end{aligned} \tag{23}$$

Let $e^{**}\left(\gamma\left(p_\ell,\theta\right),\gamma\left(p_h,\theta\right),\theta\right)$ denote the optimal allocation that implicitly solves (23). Proposition 3 characterizes the optimal allocation for an interior solution to the ex post problem.

Proposition 3 An interior solution for a maximum for L^{XP} satisfies:

$$e\left(\theta\right) = e^{**}\left(F\left(\theta\right)-1,F\left(\theta\right),\theta\right); \tag{24}$$

$$S\left(\theta\right) = \rho\int_{\underline{\theta}}^{\theta}\pi_\theta\left(p_\ell,e\left(z\right),z\right)dz-[1-\rho]\int_{\theta}^{\bar{\theta}}\left[\pi_\theta\left(p_h,e\left(z\right),z\right)-\pi_\theta\left(p_h,\overline{e},z\right)\right]dz. \tag{25}$$

As in the ex ante mechanism, there is a distortion in the optimal ex post emission allocation from the optimal full information allocation. Combining Eqs. (23) and (24) shows that the marginal net benefit of an additional emission is not equal for all types. Since at the optimum the second term on the right-hand-side of Eq. (23) varies across types, the linear emission price obtained by a Pigouvian tax or emission trading scheme is not optimal here. Note, however, that the emission allocation for the ex post mechanism is not generally equivalent to that of the optimal ex ante mechanism. Condition (24) indicates that absent a corner solution, the optimal permit allocation is strictly increasing in type. In other words, unlike the ex ante case uniform standards are never optimal.

Ex post, one extreme type receives zero surplus in each price state. If price is low, all types have a dominant incentive to under-state type. In this case, the lowest type receives zero surplus. Since the reverse occurs when price is high, then the highest type receives zero surplus in that price state. In contrast with the ex ante mechanism, however, by Eq. (25)

all types receive strictly positive **expected** surplus.

Since the government's ex post problem is more constrained than the optimal ex ante mechanism, it cannot be superior. In addition, a permit allocation that satisfies the necessary conditions for the ex post contract cannot satisfy the necessary conditions for an optimal ex ante contract. As a result, an optimally designed ex post mechanism must generate lower social welfare than an optimally designed ex ante mechanism.

6 Conclusion

Under full information, standard policy instruments can optimally reduce the production of public bads while satisfying political economy constraints. A cap-and-trade scheme, for example, ensures that the socially optimal amount of emissions are produced at the least possible cost to society. Income distribution targets can then be achieved by lump-sum transfers. If firm productivity is private information, however, it is no longer optimal to use two policy instruments to achieve the two policy targets.

The loss in welfare caused by information asymmetry relative to the full information case can be ameliorated if countervailing incentives are present. For the problem of reducing public bads in politically sensitive sectors potential countervailing incentives exist if high productivity is correlated with high losses in profit from reduced emissions. Firms with higher productivity then require higher compensatory payments for pollution reduction. As a result, firms have an incentive to over-state productivity. For an income support program, however, high productivity implies a lower need for subsidies. Therefore, firms have an incentive to under-state productivity for income support.

With asymmetric information, in the absence of price uncertainty, employing a decoupled program with two policy instruments generally results in lower social welfare than using one instrument to attain both income distribution and environmental quality goals. A program linking income transfers to environmental performance helps overcome information problems since firms cannot simultaneously over and under-state productivity. For any given level of output prices, the optimal linked program cannot be implemented by tradable permits, an emissions fee, or uniform emissions standards. Instead, payments must vary non-linearly with pollution reduction.

Social welfare actually increases if output prices fluctuate randomly. If firms are obliged to commit to an emissions reduction contract before output price is known, this uncertainty reduces the incentive to misrepresent their true productivity. If a firm overstates productivity, this may help it if output price is high, but hurt it if the price turns out to be low. Unlike contracts signed when price is known, this uncertainty can completely eliminate the advantage of private information for an entire range of firms. For this case, an inflexible standard is optimal for those firms.

This analysis implies that information can have a negative social value. Specifically, suppose the government enacted an optimal policy under conditions of price uncertainty. Any research done to give firms reliable information about future prices before contract commitment would effectively transform the optimal mechanism from an ex ante one to an ex post one. This research would be beneficial to the firms since it would allow them to reap more benefits from their private information regarding profitability. However, the net social welfare effect would be negative since the ex post mechanism is generally inferior to the ex ante mechanism.

Although the discussion in this article focused on a case where pollution can be monitored and regulated with emissions permits, the results can be easily extended to other cases. In cases where public damages are a function of observable inputs or outputs these may be regulated in a similar way. In agriculture, for example, the government may pay farmers to take land out of production. Fishermen may be offered payments to reduce their catch or to reduce their fishing capacity. Timber companies may be paid to reduce their output or reduce the acres harvested. For influential sectors such as these, the mechanism described in this paper is likely to be politically feasible since public damages are reduced voluntarily and firms are able to maintain previous levels of preferential treatment.

Appendix

Proof of Proposition 1. Necessary conditions obtained by maximizing (7) with respect to $s(p, \theta)$ are:

$$\psi(p, \theta) = f(\theta); \tag{26}$$

$$\psi(p, \theta) \geq 0; s(p, \theta) \geq 0; \psi(p, \theta) s(p, \theta) = 0. \tag{27}$$

Eq. (26) implies that $\psi(p, \theta) > 0$. Eq. (9) then follows directly from (27). A necessary condition for an interior solution maximizing (7) is $W_e = 0$. Combined with Eq. (9), this condition implies Eq. (8).

Proof of Lemmas 1 and 2. Standard results, see for example Fudenberg and Tirole (1991).

Proof of Proposition 2. First, note that for the ex ante mechanism there is no loss in generality in replacing surplus constraint (5) with expected surplus constraint $S(\theta) \geq 0$ since risk neutrality ensures that the government and firms are indifferent between contracts that yield the same expected surplus with different combinations of ex post surplus. Thus, any contract with non-negative expected surplus can be implemented with payouts such that ex post surplus is weakly positive in each state. Let $\Psi(\theta)$ be the Lagrange multiplier for the expected surplus constraint $S(\theta) \geq 0$. The Lagrangian is then:

$$W + \int_{\Theta} \Big\{ \mu(\theta)\left[\overline{e} - e(\theta)\right] + \lambda\{\Psi(\theta) S(\theta) \tag{28}$$

$$+\Gamma(\theta)\left[\Pi_{\theta}(e(\theta), \theta) - S'(\theta) - [1-\rho]\,\pi_{\theta}(p_h, \overline{e}, \theta)\right]\} \Big\}\, d\theta,$$

with control variables $e(\theta)$ and $S(\theta)$.

Integration of (28) by parts yields:

$$W + \int_{\Theta} \mu(\theta)\left[\overline{e} - e(\theta)\right] d\theta + \lambda\left[\Gamma(\underline{\theta}) S(\underline{\theta}) - \Gamma(\bar{\theta}) S(\bar{\theta})\right] + \tag{29}$$

$$\lambda \int_{\Theta} \left\{ \left[\Gamma'(\theta) + \Psi(\theta)\right] S(\theta) + \Gamma(\theta)\left[\Pi_{\theta}(e(\theta), \theta) - [1-\rho]\,\pi_{\theta}(p_h, \overline{e}, \theta)\right] \right\} d\theta.$$

By point-wise optimization, a necessary conditions for an interior solution for $e(\theta)$ is:

$$W_e = -\frac{\Gamma(\theta)}{f(\theta)} \lambda \Pi_{e\theta}(e(\theta), \theta). \tag{30}$$

Necessary conditions for $S(\theta)$ are:

$$\Psi(\theta) = f(\theta) - \Gamma'(\theta) \tag{31}$$

$$\Psi(\theta) \geq 0; S(\theta) \geq 0; \Psi(\theta) S(\theta) = 0 \tag{32}$$

Eq. (31) indicates that $\Psi(\theta)$ may not be strictly positive for all types. Consequently some types may receive positive expected surplus. Necessary conditions for the optimal endpoints of $S(\theta)$ are:

$$-\Gamma(\underline{\theta}) \geq 0; S(\underline{\theta})\,\Gamma(\underline{\theta}) = 0 \tag{33}$$

$$\Gamma\left(\overline{\theta}\right) \geq 0; S\left(\overline{\theta}\right)\Gamma\left(\overline{\theta}\right) = 0 \tag{34}$$

Since $\underline{\theta}$, $\bar{\theta}$, and Θ_2 are the three potential minima of $S(\theta)$, if it is optimal for any type(s) to receive zero expected surplus it will be one of these. To see that it is optimal for at least one of these to receive zero expected surplus, consider the contrary. Integration of (31) implies:

$$\int_{\underline{\theta}}^{\overline{\theta}} \Gamma'(\theta)\, d\theta = \int_{\underline{\theta}}^{\overline{\theta}} f(\theta)\, d\theta - \int_{\underline{\theta}}^{\overline{\theta}} \Psi(\theta)\, d\theta \tag{35}$$

$$\Gamma\left(\overline{\theta}\right) - \Gamma(\underline{\theta}) = 1 - \int_{\underline{\theta}}^{\overline{\theta}} \Psi(\theta)\, d\theta \tag{36}$$

If all types strictly positive expected surplus, then $\Psi(\theta) = 0\ \forall\ \theta$. In addition, (33) and (34) imply $\Gamma(\underline{\theta}) = \Gamma\left(\overline{\theta}\right) = 0$. Consequently, (36) implies $0 = 1$, clearly a contradiction.

For an interior solution, the optimal contract schedule can take one of three different forms depending upon which types receive the minimum expected surplus. Which case applies cannot be determined a priori since it depends in turn upon the particular specifications of π, D, and F. The three candidate solutions are described below.

Case 1: $S\left(\overline{\theta}\right) = 0$ and $\bar{\theta} = \theta_1$. In this case, $e\left(\overline{\theta}\right) < \hat{e}$. To satisfy monotonicity condition (11) then, $e(\theta) < \hat{e}\ \forall\ \theta$. By definition (13), this in turn implies that $S'(\theta) < 0\ \forall\ \theta \in \left(\underline{\theta}, \overline{\theta}\right)$. Since expected surplus is decreasing in θ, then the constraint $S(\theta) \geq 0$ is nonbinding for $\theta < \bar{\theta}$. Consequently, $\int_{\underline{\theta}}^{\theta} \Psi(\theta)\, d\theta = 0$, $\forall\ \theta$. Also, by (33), it must be the case that $\Gamma(\underline{\theta}) = 0$. Integration of (31) from $\underline{\theta}$ to θ then yields the result that $\Gamma(\theta) = F(\theta)$, $\forall\ \theta$. Plugging this expression into Eq. (30) implicitly defines the allocation schedule $e^*(F(\theta), \theta)$. The regularity conditions ensure that this schedule satisfies (11). If $e^*\left(1, \bar{\theta}\right) < \hat{e}$ then this schedule confirms the initial hypothesis that $S\left(\bar{\theta}\right) = 0$ and $\bar{\theta} < \theta_1$. If, however, $e^*\left(1, \bar{\theta}\right) \geq \hat{e}$ then Case 1 is not a solution.

Case 2: $S(\underline{\theta}) = 0$ and $\underline{\theta} = \theta_2$. In this case, $e(\underline{\theta}) > \hat{e}$. To satisfy monotonicity condition (11) then, $e(\theta) > \hat{e}\ \forall\ \theta$. By definition (13), this in turn implies that $S'(\theta) > 0\ \forall\ \theta \in \left(\underline{\theta}, \bar{\theta}\right)$. Since expected surplus is increasing in θ, then the constraint $S(\theta) \geq 0$ is nonbinding. Consequently, $\int_{\theta}^{\overline{\theta}} \Psi(\theta)\, d\theta = 0,\ \forall\ \theta$. Also, by Eq. (34), it must be the case that $\Gamma\left(\overline{\theta}\right) = 0$. Integration of (31) from θ to $\overline{\theta}$ then yields the result that $\Gamma(\theta) = F(\theta) - 1,\ \forall\ \theta$. Plugging this expression into first-order condition (30) implicitly defines the allocation schedule $e^*(F(\theta) - 1, \theta)$. The regularity conditions ensure that this schedule satisfies (11). If $e^*(-1, \underline{\theta}) > \hat{e}$ then this schedule confirms the initial hypothesis that $S(\underline{\theta}) = 0$ and $\underline{\theta} > \theta_2$. If, however, $e^*(-1, \underline{\theta}) \leq \hat{e}$ then Case 2 is not a solution.

Case 3: $S(\theta) = 0$ for $\theta \in \Theta_2$. For all $\theta \leq \theta_1$, $e(\theta) < \hat{e}$ and for all $\theta \geq \theta_2$, $e(\theta) > \hat{e}$. This in turn implies that $S'(\theta) < 0\ \forall\ \theta \in (\underline{\theta}, \theta_1)$ and $S'(\theta) > 0\ \forall\ \theta \in \left(\theta_2, \bar{\theta}\right)$. Since expected surplus is decreasing in Θ_1, and increasing in Θ_3 then the constraint $S(\theta) \geq 0$ is nonbinding for these intervals. Consequently, $\int_{\underline{\theta}}^{\theta} \Psi(\theta)\, d\theta = 0,\ \forall\ \theta \in \Theta_1$ and $\int_{\theta}^{\overline{\theta}} \Psi(\theta)\, d\theta = 0,\ \forall\ \theta \in \Theta_3$. Also, by (33) and (34), it must be the case that $\Gamma(\underline{\theta}) = \Gamma\left(\overline{\theta}\right) = 0$. Integration of (31) over the intervals Θ_1 and Θ_3 yields:

$$\Gamma(\theta) = \begin{cases} F(\theta), & \theta \in \Theta_1 \\ F(\theta) - 1, & \theta \in \Theta_3 \end{cases}. \tag{37}$$

Plugging this expression into first-order condition (30) implicitly defines the allocation schedule

$$e(\theta) = \begin{cases} e^*(F(\theta), \theta), & \theta \in \Theta_1 \\ \hat{e}, & \theta \in \Theta_2 \\ e^*(F(\theta) - 1, \theta), & \theta \in \Theta_3 \end{cases}. \tag{38}$$

The regularity conditions ensure that this schedule satisfies (11). If $e^*\left(F\left(\bar{\theta}\right), \bar{\theta}\right) < \hat{e}$ or $e^*\left(F\left(\underline{\theta}\right) - 1, \underline{\theta}\right) > \hat{e}$ then this schedule contradicts the initial hypothesis that $S(\theta) = 0$ for $\theta \in \Theta_2$, and the solution falls into Case 1 or Case 2 respectively.

Proof of Lemmas 3 and 4. Standard results, see for example Fudenberg and Tirole (1991).

Proof of Proposition 3. First, remove the redundant expected surplus motion constraint (12) and its multiplier $\Gamma(\theta)$, since its satisfaction is implied by the ex post surplus motion constraints (20) and (21). The resulting Lagrangian is:

$$\begin{aligned} W + \int_\Theta & \left\{ \mu(\theta)\left[\overline{e} - e(\theta)\right] + \lambda\{\rho\gamma(p_\ell, \theta)\left[\pi_\theta(p_\ell, e(\theta), \theta) - s_\theta(p_\ell, \theta)\right]\right. \\ & \left. + [1-\rho]\gamma(p_h, \theta)\left[\pi_\theta(p_h, e(\theta), \theta) - \pi_\theta(p_h, \overline{e}, \theta) - s_\theta(p_h, \theta)\right]\}\right\} d\theta \end{aligned} \tag{39}$$

with control variables $e(\theta)$ and $s(p, \theta)$.

Integration of (39) by parts yields:

$$\begin{aligned} & W + \int_\Theta \Big\{ \lambda \left\{ \rho \left[\left[\gamma_\theta(p_\ell, \theta) + \psi(p_\ell, \theta) \right] s(p_\ell, \theta) + \gamma(p_\ell, \theta)\pi_\theta(p_\ell, e(\theta), \theta) \right] \right. \\ & \left. + [1-\rho]\left[\left[\gamma_\theta(p_h, \theta) + \psi(p_h, \theta) \right] s(p_h, \theta) + \gamma(p_h, \theta)\left[\pi_\theta(p_h, e(\theta), \theta) - \pi_\theta(p_h, \overline{e}, \theta) \right] \right] \right\} \\ & + \mu(\theta)\left[\overline{e} - e(\theta)\right] \Big\} d\theta \\ & + \lambda\rho\left[\gamma(p_\ell, \underline{\theta}) s(p_\ell, \underline{\theta}) - \gamma\left(p_\ell, \bar{\theta}\right) s\left(p_\ell, \bar{\theta}\right) \right] \\ & + \lambda[1-\rho]\left[\gamma(p_h, \underline{\theta}) s(p_h, \underline{\theta}) - \gamma\left(p_h, \bar{\theta}\right) s\left(p_h, \bar{\theta}\right) \right]. \end{aligned} \tag{40}$$

By point-wise optimization, a necessary conditions for an interior solution for the emission allocation $e(\theta)$ is:

$$W_e + \lambda \left[\rho \gamma (p_\ell, \theta) \pi_{e\theta} (p_\ell, e(\theta), \theta) + [1 - \rho] \gamma (p_h, \theta) \pi_{e\theta} (p_h, e(\theta), \theta) \right] = 0 \tag{41}$$

Necessary conditions for surplus allocations are:

$$\psi (p, \theta) = f(\theta) - \gamma_\theta (p, \theta); \tag{42}$$

$$\psi (p, \theta) \geq 0; s(p, \theta) \geq 0; \psi (p, \theta) s(p, \theta) = 0. \tag{43}$$

Necessary conditions for optimal endpoints $s(p, \underline{\theta})$ and $s(p, \bar{\theta})$ are:

$$-\gamma (p, \underline{\theta}) \geq 0; \gamma (p, \underline{\theta}) s(p, \underline{\theta}) = 0; \tag{44}$$

$$\gamma (p, \overline{\theta}) \geq 0; \gamma (p, \overline{\theta}) s(p, \overline{\theta}) = 0. \tag{45}$$

Integration of (42) from $\underline{\theta}$ to θ yields:

$$\gamma (p, \theta) = F(\theta) - \int_{\underline{\theta}}^{\theta} \psi (p, z) dz + \gamma (p, \underline{\theta}). \tag{46}$$

Since $s(p, \theta)$ is increasing when price is low and decreasing when price is high, if it is optimal for any type to receive zero surplus ex post it will be $\underline{\theta}$ or $\bar{\theta}$, respectively. For all other types surplus is strictly positive and $\psi (p, \theta) = 0$. Next, observe that if one endpoint optimally receives strictly positive surplus, the other must optimally receive zero surplus. To see this, consider the contrary. If both endpoints receive strictly positive surplus, then $\psi (p, \theta) = 0$ for all types. In addition, (44) and (45) imply $\gamma (p, \underline{\theta}) = \gamma (p, \overline{\theta}) = 0$. Consequently, when evaluated at $\theta = \bar{\theta}$, Eq. (46) implies the contradiction $0 = 1$.

Since $s(p_h, \underline{\theta}) > 0$, (44) and (46) imply $\gamma(p_h, \theta) = F(\theta)$. Since $s\left(p_\ell, \bar{\theta}\right) > 0$, integration of (42) from θ to $\bar{\theta}$, combined with (45) yields $\gamma(p_\ell, \theta) = F(\theta) - 1$. The regularity conditions guarantee that $e^{**}(F(\theta) - 1, F(\theta), \theta)$ satisfies monotonicity condition (19).

Acknowledgements. Robert G. Chambers, Valerie A. Mueller, François Salanié, and Arthur A. Small III provided valuable comments and suggestions.

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