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Nonpoint Pollution Control: Inducing First-best Outcomes through the Use of Threats

Kathleen Segerson
University of Connecticut

JunJie Wu
Oregon State University

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341 Mansfield Road, Unit 1063
Storrs, CT 06269–1063
Phone: (860) 486–3022
Fax: (860) 486–4463
http://www.econ.uconn.edu/

Abstract

In this paper we develop a simple economic model to analyze the use of a policy that combines a voluntary approach to controlling nonpoint-source pollution with a background threat of an ambient tax if the voluntary approach is unsuccessful in meeting a pre-specified environmental goal. We first consider the case where the policy is applied to a single farmer, and then extend the analysis to the case where the policy is applied to a group of farmers. We show that in either case such a policy can induce cost-minimizing abatement without the need for farm-specific information. In this sense, the combined policy approach is not only more effective in protecting environmental quality than a pure voluntary approach (which does not ensure that water quality goals are met) but also less costly than a pure ambient tax approach (since it entails lower information costs). However, when the policy is applied to a group of farmers, we show that there is a potential tradeoff in the design of the policy. In this context, lowering the cutoff level of pollution used for determining total tax payments increases the likely effectiveness of the combined approach but also increases the potential for free riding. By setting the cutoff level equal to the target level of pollution, the regulator can eliminate free riding and ensure that cost-minimizing abatement is the unique Nash equilibrium under which the target is met voluntarily. However, this cutoff level also ensures that zero voluntary abatement is a Nash equilibrium. In addition, with this cutoff level the equilibrium under which the target is met voluntarily will not strictly dominate the equilibrium under which it is not. We show that all results still hold if the background threat instead takes the form of reducing government subsidies if a pre-specified environmental goal is not met.

Keywords: ambient taxes, nonpoint-source pollution control, cost-minimizing abatement, voluntary approach

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I. INTRODUCTION

While concerns about pollution control originally focused on point sources of pollution, attention has now turned to the control of diffuse or nonpoint-source pollution (NPP).[1] Control of NPP is hampered by the fact that emissions of pollutants are not readily observable given their diffuse nature, which implies that traditional policy instruments based on emissions (e.g., emissions taxes or regulation) cannot be used in this context. This has lead economists to consider alternative policy instruments for the control of NPP, including input taxes, input regulations, ambient taxes, random fines, direct revelation, and type-specific contracts (Griffin and Bromley 1982; Shortle and Dunn 1986; Segerson 1988, Xepapadeas 1991, 1992, 1995; Cabe and Herriges 1992; Herriges et al. 1994; Govindasamy et al. 1994; Laffont, 1994, and Shortle and Abler 1994). Instruments that provide flexible incentives (such as ambient taxes) can be used to induce first-best control of NPP (Segerson 1988), but information about farm-level charactertistics is needed to design these first-best policy instruments. They have thus been criticized as being likely to involve high information and/or transactions costs (e.g., Cabe and Herriges 1992; Batie and Ervin 1997). This has led some to suggest the use of second best policy instruments instead (Helfand and House 1995; Wu and Babcock 1995, 1996; Wu, et al. 1995). Use of these second best instruments involves a tradeoff. While transaction and information costs may be lower, these instruments do not achieve the targeted water quality level at the minimum abatement cost.

In contrast to the theoretical literature of NPP, water quality policy has historically been based on the use of "carrot" instruments designed to entice farmers to use environmentally-friendly practices voluntarily or to participate in voluntary programs aimed at improving water quality.[2] However, the varying success rates of voluntary programs have led some to question whether reliance on voluntary measures alone will adequately control agricultural pollution (Ribaudo and Caswell 1997), suggesting the need for mandatory controls or incentives to ensure adequate environmental protection. Yet, as noted above, mandatory controls[3] generally have drawbacks in terms of inflexibility (in the case of second-best instruments) or high transaction or information costs (for first-best instruments). Thus, neither purely voluntary programs nor mandatory approaches by themselves seem to offer a desirable "solution" to agricultural NPP.

There is, however, an alternative role for voluntary and mandatory approaches to NPP, namely, as complementary instruments to be used together rather than as substitutes to be used in isolation. As has become apparent in the context of point source pollution, the threat of the imposition of mandatory controls can be an effective mechanism for inducing firms to participate in voluntary agreements (Segerson and Miceli 1998), while voluntary approaches have the potential to provide greater flexibility in meeting environmental quality goals and hence lower compliance and transaction costs (Commission of the European Communities 1996).

A few states have experimented with the use of mandatory approaches as threats to be invoked if reliance on voluntary measures is insufficient to control nonpoint source pollution, and the threat of regulation has been shown to create an incentive for farmers to alter their production practices (Ribaudo and Caswell 1997). Yet to date the economic literature on NPP has not considered the possible use of both voluntary and mandatory approaches as complementary parts of a policy package. Segerson and Miceli (1998) develop a model of this type in the context of point source pollution, where the regulator negotiates with an individual firm (or an industry representative) over the level of abatement under the agreement. Their focus is on the negotiated level of abatement that emerges under the agreement. They do not consider an approach under which the regulator sets an environmental quality target and then seeks participation in a program to achieve that target, as is typical in the case of NPP. Dawson and Segerson (2002) examine the use of industry-wide threats to induce participation in voluntary approaches, but again the context is point source pollution where the threat is an emissions tax (a policy instrument that is not feasible in the context of NPP). Wu and Babcock (1999) compare the relative efficiency of voluntary and mandatory approaches to NPP, but they treat the two as alternatives and do not consider a policy package under which the two are combined.

In this paper we develop a simple economic model to analyze the use of a policy that combines a voluntary approach to controlling nonpoint-source pollution with a background threat of an ambient tax (or losing government subsidies) if the voluntary approach is unsuccessful in meeting a pre-specified environmental goal. We use the model to examine whether the regulator can use such a policy to induce cost-minimizing abatement decisions without the high transaction or information costs that can accompany the use of first-best instruments. We first consider how a single farmer would respond to such a combined policy and then extend the analysis to the case where the policy is applied to a group of farms. In this context, we ask whether cost-minimizing voluntary abatement is part of a subgame perfect Nash equilibrium.

We show that, in both the case where the policy is applied to a single farmer and where it is applied to a group of farmers, such a policy can induce cost-minimizing abatement without actually imposing the tax because the threat of imposition of the tax is sufficient to induce voluntary compliance. In this sense, the combined approach can be both more effective than a purely voluntary approach and involve lower information or transaction costs than a pure tax approach. However, depending on the specific design of the tax policy and whether the tax can be applied retroactively, the cost-minimizing equilibrium may not be unique. When it cannot be applied retroactively (the typical case for most taxes), equilibria under which the target is not met voluntarily can emerge. In addition, equilibria under which the target is met voluntarily but some farmers free ride on the abatement of others emerge. In fact, when applied to a group of heterogeneous farmers we show that the tax cannot be designed to both induce a cost-minimizing equilibrium and eliminate the potential for free riding. However, if the tax can be applied retroactively, then it can be designed to ensure that cost-minimizing abatement (and hence voluntary compliance with the standard) is the unique equilibrium. While we derive the results assuming the regulator threatens imposition of an ambient tax, all of our results still hold if the background threat instead takes the form of reducing government subsidies if a pre-specified environmental goal is not met.

II. THE BASIC MODEL

Consider n farmers whose agricultural activities pollute a nearby waterbody. Each farmer, indexed i, can engage in abatement practices, such as the use of reduced tillage, establishment of buffer strips, construction of manure storage facilities, and land retirement, to reduce water pollution, or, equivalently, to increase ambient water quality in the waterbody. Let $a_i=(a_{i1},a_{i2},\ldots, a_{im})$ denote farmer i's abatement vector. Farms are assumed to differ in their characteristics, including both physical land characteristics and other characteristics that affect firm operations and/or costs (e.g., managerial skill). For notational simplicity, we assume that the characteristics of each farm can be represented by a single parameter, denoted θ_i. Expected ambient pollution in the waterbody, denoted x, is a function of abatement vectors of the individual farms, $a \equiv (a_1, a_2, \ldots, a_n)$, and farm characteristics, $\theta \equiv (\theta_1, \theta_2, \ldots, \theta_n)$.[4] Thus, $x = x(a_1, a_2, \ldots, a_n; \theta_1, \theta_2, \ldots, \theta_n)$, where $\partial x/\partial a_{ij} \leq 0$ and $\partial x/\partial \theta_i \geq 0$.[5] The cost of abatement for a farm depends on both the abatement practices and the characteristics of the farm, i.e., $C_i=C(a_i, \theta_i)$, where $\partial C/\partial a_{ij} > 0$ and $\partial^2 C/\partial a_{ij}^2 \geq 0$ for all i and j, and $C(0, \theta_i)=0$. For example, the cost of establishing riparian buffer strips depends not only on the establishment cost (e.g., fencing cost) but also on the land quality, which determines the opportunity cost of the land taken out of production.[6] We assume that farmers are better informed about their own characteristics than are regulators. Hence, θ_i is private information. However, we assume that both the regulator and the farmers know the distribution of farm characteristics in the watershed.

We assume that there is some exogenously set target level of water quality determined by a criterion such as "fishable and swimmable" or by the level necessary to support some desirable activity (e.g., salmon spawning).[7] This requires that ambient pollution not exceed an exogenous standard, x^s, where $x^s < x(0,\ldots,0;\theta_1,\ldots,\theta_n)$. A good example is the Total Maximum Daily Loads (TMDLs), mandated by Section 303(d) of the Clean Water Act. A TMDL is a water quality standard that establishes the maximum amount of pollution that a watershed can assimilate without violating state water quality standards. Given the standard, the social objective is to minimize the cost of meeting it.

The cost-minimizing abatement choices $\{a_i^*(\theta_1, \theta_2, \ldots, \theta_n, x_s), i = 1, 2, \ldots, n\}$ solve[8]

(1a) $$\text{minimize} \quad C(a_1, \theta_1) + C(a_2, \theta_2) + \ldots + C(a_n, \theta_n)$$

(1b) $$\text{subject to} \quad x(a_1, a_2, \ldots, a_n; \theta_1, \theta_2, \ldots, \theta_n) \leq x^s \; .$$

(1c) $$a_{ij} \geq 0, \; i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots m.$$

The necessary first order conditions require that

(2) $$\partial C/\partial a_{ij} + \lambda^*(x^s, \theta)\cdot(\partial x/\partial a_{ij}) \geq 0, \text{ for all } i \text{ and } j,$$

where $\lambda^*(x_s, \theta) > 0$ is the optimal value of the Lagrangian multiplier. We assume that the solution to (1) is unique. The corresponding abatement cost for farmer i is $C_i^* \equiv C(a_i^*(\theta_1, \theta_2, \ldots, \theta_n, x^s), \theta_i)$.

We are interested in whether, or under what conditions, allowing farmers to choose their abatement levels voluntarily will lead to this cost-minimizing outcome. We assume that the regulator seeks to minimize the cost of meeting the target and designs the following policy scenario. The regulator agrees to give farmers a chance to meet the standard voluntarily. If the standard is met, no further policy is imposed. However, if the standard is not met, the regulator will spend the resources necessary to learn θ and impose a mandatory policy on farmers that is sufficient to induce the farmer to choose an abatement vector that ensures that the standard will be met. We limit consideration to a mandatory policy that is comprised of a linear tax on ambient water pollution.[9]

More specifically, the timing of the interaction between the regulator and the farmers is as follows. At $t = 0$, the regulator commits to a policy that states that, if the target is not met in $t = 1$, then at the end of period 1 he will incur the costs to learn θ and impose an ambient tax that minimizes the cost of meeting the standard.[10] In $t = 1$, farmers simultaneously choose and implement voluntary abatement vectors. We denote these vectors by $a^v = (a_1^v, a_2^v, ..., a_n^v)$. At the end of period 1, the regulator observes ambient water pollution, $x(a^v, \theta)$. If $x(a^v, \theta) \le x^s$, then the regulator takes no action (i.e., no tax is imposed). However, if $x(a^v, \theta) > x^s$, then the regulator incurs the information costs necessary to learn the vector θ and imposes a permanent ambient tax on the farmers. (The specific form of the tax is specified below.) In $t = 2$, farmers again simultaneously choose and implement abatement vectors, conditional on the regulator's action (or inaction) at the end of $t = 1$. Let $a^t = (a_1^t, a_2^t, ..., a_n^t)$ denote the abatement choices if the tax was imposed between periods 1 and 2. If the tax was not imposed because the target was met in $t = 1$, then the game starts over again and farmers face the exact same situation they faced in $t = 1$ (i.e., the threat of a permanent tax imposed in the subsequent period if the target is not met in the current period).[11] Given this, their optimal choices will be the same as those in t=1, and we therefore use a^v to denote these abatement decisions as well.[12] Hence, the strategy for farmer i (s_i) consists of a combination of a voluntary abatement vector and an abatement vector under the tax, i.e., $s_i = \{a_i^v, a_i^t\}$.

As noted above, we limit consideration to a linear ambient tax. We analyze both the case where the tax cannot be applied retroactively (Sections III and IV)) and where it can (Section V). In either case, tax payments at the end of each period are based on water quality during that period. Thus, at the end of period 2, farmer i faces the following tax payments, TP_i :

$$TP_i = \begin{cases} 0 & if \;\; x(a^v, \theta) \le x^s \\ \tau_i \cdot [x(a^t, \theta) - \bar{x}] & if \;\; x(a^v, \theta) > x^s \end{cases} \tag{3}$$

where τ_i is the ambient tax rate for farmer i [13], and $\bar{x} \le x^s$ is a "cutoff level" of pollution.[14] [15] Note that this policy is analytically similar to the pure ambient tax/subsidy policy considered in Segerson (1988).[16] Under both policies, if ambient pollution exceeds a given target, a tax is imposed on the amount by which the ambient level exceeds a given cutoff level. However, in Segerson (1988), the target level (x^s) and the cutoff level ($\bar{x}$) are the same. Under the voluntary approach proposed here, we allow the two to differ. The importance of this is discussed in detail below. Another difference between the two policies arises when pollution is below the target. The voluntary approach acts like a pure tax policy, in that the farmer receives (and pays) nothing when the target is met (i.e., when ambient pollution is at or below the target level). In contrast, under the ambient tax/subsidy policy, the farmer receives a subsidy proportional to the amount by which pollution is below the target.[17]

We seek to identify sub-game perfect Nash equilibria, with particular interest in the voluntary abatement choices, $a^v = (a_1^v, a_2^v, ..., a_n^v)$, that emerge under these equilibria. We focus on the strategies chosen by farmers since we assume that the threat made by the regulator in $t = 0$ is credible, i.e., that the cost of learning θ and imposing the tax is sufficiently small relative to the benefit of imposing the optimal tax at $t = 2$ when the regulator observes that the target has not been met.[18] To derive the SPNE, we solve backwards and derive the Nash equilibrium choices under the tax, since these ultimately determine the payoff from alternative voluntary abatement vectors.

The incentives created by a linear ambient tax are well-known (see Segerson, 1988; Spraggon, 2002). In particular, it is straightforward to show the following. (The proofs of all propositions are given in the Appendix.).

Proposition 1: If $\tau_i = \lambda^*(x_s, \theta) \equiv \tau^*$, then $a^t = a^* = (a_1^*, \ldots, a_n^*)$ is the unique Nash equilibrium for the tax subgame. ***.*** *At this tax rate, $x(a^t, \theta) = x^s$, and the corresponding (negative) payoff for farmer i from this subgame from t=2 onward is*

(4) $$\frac{1}{r}[C_i^* + \tau^*(x^s - \overline{x})],$$

where $r > 0$ is the discount rate.

Proposition 1 implies that the regulator can induce cost-minimizing abatement decisions by imposing an ambient tax on each farmer equal to τ^*. Thus, since the regulator seeks to minimize social costs, the threat in $t = 0$ to impose this tax if the target is not met is a credible threat (provided the cost of learning θ is sufficiently low). Note that the optimal tax is uniform for all farmers, even though the abatement levels and contributions of farmers can differ. In each case, the tax rate is set at the shadow cost of pollution, which at the cost-minimizing abatement levels equals the marginal cost of abatement for each firms (which are equated across firms when costs are minimized.)

Given the ability to meet the target in a least-cost way using the ambient tax, an obvious question is what can be gained by first giving the farmers the opportunity to meet the tax voluntarily, i.e., by coupling the possibility of the tax with a voluntary approach. Below we show that a policy that combines the voluntary approach with the ambient tax (i.e., treating them as complements in a policy package rather than as substitute policies) can be designed such that the water quality target is met voluntarily at minimum cost. The tax is never actually imposed because the threat of imposition of the tax is sufficient to induce voluntary compliance. As a result, the regulator does not incur the information and/or implementation costs associated with an ambient tax. Thus, the combined policy approach can not only be more effective in protecting environmental quality than a pure voluntary approach (which does not ensure that water quality goals are met) but it can also be less costly than a pure ambient tax approach (since it entails lower information or transaction costs).

III. VOLUNTARY ABATEMENT: SINGLE POLLUTER CASE

To establish a benchmark for the study of the combined policy, we first consider the single polluter case (i.e., n=1). In this case, there is no issue regarding the allocation of abatement across farmers; cost-minimization simply requires that the farmer choose the cost-minimizing combination of abatement practices. Throughout this and the following section, we assume that the ambient tax cannot be applied retroactively. We consider the case of a retroactive tax in Section V.

We begin by noting the following:

Lemma 1: (i) If $x(a^{v*},\theta) > x^s$*, then* $a^{v*}=0$*. (ii) If* $x(a^{v*},\theta) \leq x^s$*, then* $a^{v*}=a*$.

Part *(i)* states that, if the farmer chooses not to meet the target voluntarily, he will not invest in any abatement. Conversely, *(ii)* states that, if he chooses to meet the target voluntarily, he will do so in the cost-minimizing way since he will solve the problem in (1) (for n=1), which yields cost-minimizing abatement choices. This implies that, when considering optimal choices for a^v, we need only consider two possibilities: 0 and a^*. In addition, Proposition 1 implies that if the farmer's optimal choice in $t = 1$ is $a^{v*}=0$, the farmer will choose a^* for all $t \geq 2$ (in response to the tax). Likewise, if the farmer's optimal choice in $t = 1$ is $a^{v*}=a^*$, then this will also be the optimal choice for all $t \geq 2$. This implies the following:

Lemma 2: For any $\bar{x}$ *, the pollution standard will be met at minimum abatement cost at all* $t \geq 2$*.*

Given Lemma 2, the key question is whether the standard will be met at minimum abatement cost (through voluntary abatement) in $t = 1$ as well. Proposition 2 establishes the conditions under which this will be true.

Proposition 2: The strategy $\{a^v,a^t\}=\{a^*,a^*\}$ *is an optimal response to the regulator's policy if and only if*

$$\bar{x} \leq x^s - \frac{rC^*}{\tau^*} \equiv \bar{x}^c. \qquad (5)$$

Corollaries 1 and 2 follow immediately.

Corollary 1: If $\overline{x} = x^s$, then $\{a^v, a^t\}=\{0, a^*\}$ is an optimal response to the regulator's policy.

Corollary 2: If $\overline{x} < \overline{x}^c$, then $\{a^v, a^t\}=\{a^*, a^*\}$ is the unique optimal response to the regulator's policy.

The above results highlight the fact that, although $\overline{x}$ does not affect the social cost of meeting the standard if the tax is imposed, it plays an important role in determining abatement behavior. In the standard ambient tax model (see Segerson (1988)), the cutoff level of pollution $\overline{x}$ was one key parameter that the regulator could choose to ensure efficient exit/entry conditions and industry size, and it was assumed that $\overline{x} = x^s$. Here the role of $\overline{x}$ is quite different. In choosing his abatement vector in $t = 1$, the farmer weighs the additional cost in t=1 of voluntary abatement over zero abatement (C^*) against the present value of the stream of tax payments he will face if the standard is not met ($\tau^*(x^s - \overline{x})/r$). Clearly, it will never be optimal to meet the standard voluntarily if $\overline{x} = x^s$. In this case, even if the tax is subsequently imposed in response to failure to meet the target in the previous period, as long as the target is subsequently met, there will be no net tax payments under the tax. Thus, with $\overline{x} = x^s$ the farmer is effectively given a new opportunity to meet the standard in each period. This eliminates any opportunity to "punish" the farmer for failure to meet the standard in a previous period. Thus, with $\overline{x} = x^s$ it is optimal for the farmer to take advantage of the first period reprieve and then meet the standard in all subsequent periods. However, if $\overline{x}$ is sufficiently below x^s, i.e., $\overline{x} < \overline{x}^c$, so that the tax payments he will face if the tax is imposed are sufficiently high, the farmer will strictly prefer to meet the standard voluntarily in all periods. As a result, by setting $\overline{x} < \overline{x}^c$, the regulator can induce voluntary compliance in all periods.

IV. MULTIPLE POLLUTERS

While the single-farm case provides a benchmark for the study of the combined policy approach, in many contexts there are likely to be several farms whose activities contribute to ambient water pollution in a neighboring lake or stream. We show in this section that a voluntary program coupled with a background threat of an ambient tax can induce cost-minimizing abatement decisions in this context as well. More specifically, we show that under the appropriate design of the ambient tax cost-minimizing voluntary abatement by all farmers is a subgame perfect Nash equilibrium. However, consistent with the results from the single polluter case, whether this equilibrium emerges or not depends on the choice of $\bar{x}$. However, unlike in the single polluter case, when the policy is applied to a group of farmers, when the tax cannot be applied retroactively, there is a fundamental tradeoff in setting $\bar{x}$ between creating incentives for voluntary abatement and inducing free-riding by some farmers.

We have already characterized the Nash equilibrium in the tax subgame in Section II above. Given this, we examine the Nash equilibria at $t = 1$, i.e., the farmers' optimal decisions regarding voluntary abatement. For ease of notation, we treat abatement by each farmer as a scalar, i.e., we assume m=1.[19]

Let $a_i^{v*}(a_{-i}^v)$ denote farmer i's optimal response to the other farmers' voluntary abatement levels, $a_{-i}^v = (a_1^v,...,a_{i-1}^v,a_{i+1}^v,...,a_n^v)$. Furthermore, given a_{-i}^v, let $a_i^s(a_{-i}^v)$ be the abatement level that farmer i must undertake to ensure that the target is just met, i.e., $x(a_i^s, a_{-i}^v, \theta) \equiv x^s$. Then, analogous to Lemma 1, we have:

Lemma 3: (i) If $x(a^{v*}, a^v_{-i}, \theta) > x^s$, *then* $a_i^{v*} = 0$. *(ii) If* $x(a^{v*}, a^v_{-i}, \theta) \leq x^s$, *then* $a_i^{v*} = a_i^s(a_{-i}^v)$.

The interpretation is similar to the interpretation of Lemma 1. Given the abatement choices of other farmers, farmer *i* will choose either zero voluntary abatement or the level of abatement just sufficient to ensure that the target is met (with equality). Thus, we can limit consideration of the farmer's choice of voluntary abatement to these two alternatives. We now state the result for the multiple polluter case that is analogous to Proposition 2.

Proposition 3: The strategies $\{a_i^v, a_i^t\} = \{a_i^*, a_i^*\}$ *are a subgame perfect Nash equilibrium if and only if*

$$\bar{x} \le \min_{\theta_i} \left\{ x^s - \frac{rC_i^*}{\tau^*} \right\} = \min_{\theta_i} \{\bar{x}_i^c\}. \tag{7}$$

Note that condition (7) in Proposition 3 is analogous to (5). At this equilibrium the standard is met voluntarily at minimum cost. In addition, as in the single polluter case, in order for cost-minimizing voluntary abatement to be an equilibrium, the regulator must set $\bar{x}$ sufficiently low. Note that at the upper bound, i.e., if $\bar{x} = \min_{\theta_i} \{\bar{x}_i^c\}$, the farmer who would incur the highest cost under the tax, i.e., the farmer with the highest C_i^*, will be indifferent between meeting the target voluntarily in this way and facing the tax, while all other farmers (with lower C_i^*'s) will strictly prefer to meet the target voluntarily.

Proposition 3 shows that when appropriately designed, the combined policy can induce each farmer to undertake the cost-minimizing abatement, as long as he believes other farmers are doing so. In this case, as in the single farmer model, by providing farmers the opportunity to meet the target voluntarily, the regulator can achieve cost-minimizing abatement without incurring the information and implementation costs that would be associated with reliance solely on an ambient tax. However, unlike in the single polluter case, here it is not possible to set $\bar{x}$ to ensure that the cost-minimizing abatement choices are a unique equilibrium. To see this, first note that if $\bar{x} \leq \bar{x}_i^c$, then farmer *i* is at least as well off if he and all other farmers undertake cost-minimizing voluntary abatement as he would be if the tax is imposed. If $\bar{x} < \bar{x}_i^c$, he would be strictly better off. This implies that under this condition each farmer would actually be willing to undertake voluntarily a level of abatement that exceeds his a_i^* to ensure that the target is met and the tax is avoided. The *maximum* level of abatement that farmer *i* would be willing to undertake voluntarily each period to ensure that the target is met, $a_i^{\max}$, is implicitly defined by

$$(8) \qquad \left(1+\frac{1}{r}\right)C(a_i^{\max},\theta_i) \equiv \frac{1}{r}[C_i^* + \tau^*(x^s - \bar{x})],$$

where the left-hand side of (8) is the present value of abatement costs from t =1 to infinity under voluntary abatement, and the right-hand side is the present value of abatement costs plus tax payments from t =2 to infinity under the tax. Note that $a_i^{\max} > a_i^*$ when $\bar{x} < \bar{x}_i^c$ and $a_i^{\max} = a_i^*$ when $\bar{x} = \bar{x}_i^c$. Furthermore, $\partial a_i^{\max} / \partial \bar{x} < 0$ for all *i*, i.e., as $\bar{x}$ increases and hence tax payments decrease, the maximum amount of abatement that each farmer is willing to undertake voluntarily decreases.

Using this concept, we can now show the existence of other subgame perfect Nash equilibria.

Proposition 4: The strategies $\{a_i^v, a_i^t\} = \{a_i^v, a_i^*\}$ *are a subgame perfect Nash equilibrium if*

(i) $\quad x(a_1^v, a_2^v, \ldots, a_n^v; \theta_1, \theta_2, \ldots, \theta_n) = x_s$.

(ii) $\quad a_i^v \leq a_i^{\max}$ *for all i.*

Clearly, Proposition 3 above is a special case of Proposition 4, since the cost-minimizing abatement choices always satisfy *(i)* and they satisfy *(ii)* when (7) holds. However, Proposition 4 also allows for equilibria under which the target is met voluntarily but not at minimum cost. In particular, it allows for equilibria under which some farmers free-ride on the abatement of others. In fact, when C_i^* varies across farmers, it is not possible to set $\bar{x}$ to eliminate the existence of such equilibria.

Proposition 5: If (i) $\bar{x} \leq \bar{x}_i^c$ for all i and (ii) $\bar{x} < \bar{x}_i^c$ for some i, then there always exists a subgame perfect Nash equilibrium under which the target is met voluntarily (i.e., $x(a_1^v, a_2^v, ..., a_n^v; \theta_1, \theta_2, ..., \theta_n) = x_s$) and free-riding occurs (i.e., $a_i^v < a_i^*$ for some farmer i).

Proposition 5 shows that, if $\bar{x}$ is set so that cost-minimizing abatement is an equilibrium, then with heterogeneous farms, there will always exist equilibria under which the water quality target is met voluntarily but not at minimum cost because of free-riding behavior. In particular, with $\bar{x} < x_i^c$ for some farmer, that farmer is willing to undertake more abatement than is efficient in order to avoid the tax. Another farmer can take advantage of this by abating less, i.e., he can free-ride on the other farmers' willingness to abate more. It is even possible that in equilibrium some farmers do not abate at all and the target is met through the abatement efforts of a subset of farmers. Note that in this context free-riding does not imply under-provision of the public good (here, water quality) since the target level of water quality is met. Rather, it implies that the public good is not provided in an efficient way, i.e., at least cost, because pollution abatement is not allocated efficiently across farms. Thus, the regulator faces a fundamental tradeoff in setting

$\bar{x}$: if he sets $\bar{x}$ to ensure that voluntary cost-minimizing abatement is an equilibrium, then he cannot eliminate the potential for free-riding in meeting the target.[20]

Propositions 3-5 focus on equilibria under which the water quality target is met voluntarily. It is also possible to have a equilibria under which the water quality target is not met voluntarily. In this case, it is clear that in equilibrium no farmers will abate voluntarily. More formally, we have:

Lemma 4: If the strategies $\{a_i^{v*}, a_i^*\}$ *are a subgame perfect Nash equilibrium and* $x(a^{v*}, \theta) > x^s$*, then* $a_i^{v*} = 0$ *for all i.*

Thus, in examining equilibria under which the target is not met voluntarily, we only look at strategies under which $a_i^v = 0$ for all *i*. Proposition 6 characterizes these equilibria.

Proposition 6: The strategies $\{a_i^v, a_i^t\} = \{0, a_i^*\}$ *are a subgame perfect Nash equilibrium if and only if*

(9) $$a_i^s(0,0,...,0) \geq a_i^{\max} \text{ for all } i=1, 2, ..., n.$$

When (9) holds, no individual farmer is willing to undertake the level of abatement that would be necessary to meet the target on his own, since the cost of doing so would exceed the cost he would face under the tax. In this case, if all other farmers choose zero abatement, then the best response of the remaining farmer is to choose zero abatement as well.[21] Conversely, if for at least one farmer it is less costly to meet the target on his own, then in equilibrium the target will always be met voluntarily. The fact that $a_i^{\max}$ is a decreasing function of $\bar{x}$ implies that increasing $\overline{x}$ (which reduces tax payments) expands the range over which (9) holds and hence makes it less likely that the target will be met voluntarily.

Figure 1 illustrates the impact of the cut-off level of pollution on the possible equilibria for the case of $n = 2$ and a linear $x(a_1,a_2)$ function, where we assume $\overline{x}_1^c < \overline{x}_2^c$. In the top graph, $\overline{x}$ is set below $\overline{x}_1^c$, while in the lower graph $\overline{x}$ is set equal to $\overline{x}_1^c$ (i.e., the upper bound in Proposition 3). Since $\overline{x} < \overline{x}_2^c$ in both graphs, $a_2^{\max} > a_2^*$. In the top graph, $\overline{x} < \overline{x}_1^c$ implies $a_1^{\max} > a_1^*$, while in the lower graph $\overline{x} = \overline{x}_1^c$ implies that $a_1^{\max} = a_1^*$. The curved line is an iso-cost curve showing all combinations of (a_1, a_2) with a cost equal to $C_1^* + C_2^*$. The cost-minimizing point, (a_1^*, a_2^*), is shown as the tangency point between this curve and the water quality constraint curve, $x(a_1, a_2) = x$, which depicts all combination of (a_1, a_2) that meet the water quality target. Consider now the possible equilibrium outcomes. Proposition 4 implies that all (a_1, a_2) combinations that satisfy $a_1 \le a_1^{\max}, a_2 \le a_2^{\max}$, and $x(a_1, a_2) = x^s$ are equilibria choices under which the water quality standard is met voluntarily. These combinations are shown by the segment AB on the water quality constraint curve in Figure 1a. Among these combinations, only (a_1^*, a_2^*) minimizes the total abatement cost of meeting the standard. All other combinations represent free-riding equilibria where one firm abates less than its efficient amount while the other abates more. As a result, the allocation of abatement across firms is inefficient and hence the cost of meeting the water quality standard exceeds $C_1^* + C_2^*$.

To see the role of $\overline{x}$ in determining the possible equilibria, note that in the top graph either farmer can free-ride on the abatement of the other. However, as $\overline{x}$ increases, the set of possible equilibria as shown by line segment AB shrinks. As shown in the lower graph, by lowering $\overline{x}$ to the point where $\overline{x} = \overline{x}_1^c$, the potential for farmer 2 to free ride on farmer 1 is eliminated since farmer 1 is not willing to abate beyond a_1^*. However, equilibria under which farmer 1 free rides on farmer 2 still exist. With heterogeneous firms (i.e., $\bar{x}_1^c \neq \bar{x}_2^c$), it is not possible to set $\bar{x}$ to eliminate the free-riding equilibria completely (see Proposition 5).

Finally, note that in both cases depicted in Figure 1 zero voluntary abatement is also an equilibrium outcome since (9) holds for both farmers. However, all equilibria under which the target is met voluntarily dominate the zero abatement equilibrium. The cost each farmer would incur under voluntary abatement is less than or equal to the cost under the tax for both farmers and strictly less for one of the farmers, implying that no farmer is worse off and at least one is better off if the target is met voluntarily. Hence, both farmers would prefer (either strictly or weakly) to meet the target voluntarily, even though the resulting allocation of abatement is inefficient.

V. VOLUNTARY ABATEMENT WITH A RETROACTIVE TAX

In the last section we showed that a policy that combines a voluntary approach with a background threat of a tax can induce cost-minimizing voluntary abatement by all farmers. However, such a policy has two potential problems. First, the cost-minimizing abatement choices are not a unique equilibrium. With heterogeneous farms, there will always exist other subgame perfect Nash equilibria under which the water quality target is met voluntarily but not at minimum cost because of free-riding behavior. Although the regulator can limit the potential of free riding behavior by adjusting the cut-off level of pollution, he can never eliminate it completely. Second, zero abatement by all farmers is a subgame perfect Nash equilibria if no individual farmer is willing to meet the target on his own. In this section, we show that both the potential free-rider problem and the potential for zero voluntary abatement hinge on the assumption that the tax is not applied retroactively; both of these problems can be eliminated by applying the tax retroactively.

Specifically, the retroactive tax is applied in the following way. At the end of period 1, the regulator observes ambient water pollution , $x(a^v, \theta)$. If $x(a^v, \theta) \le x^s$, then the regulator takes no action (i.e., no tax is imposed). However, if $x(a^v, \theta) > x^s$, then the regulator incurs the information costs necessary to learn the vector θ and imposes the ambient tax on the farmers for water quality violation in t=1 as well as for all future water quality violations. Tax payments at the end of period 1 are based on the water quality level observed in period 1. With the retroactive tax, we can prove the following result.

Proposition 7: With the threat of the retroactive tax $\tau_i = \tau^* = \lambda^*(x^s, \theta)$ *and* $x^s = \overline{x}$*, the strategy* $\{a_i^v, a_i^t\} = \{a_i^*, a_i^*\}$ *is a unique subgame perfect Nash equilibrium.*

As discussed in the last section, the potential for free riding occurs when farmers must pay positive tax payments if the ambient tax is imposed but avoid these costs if the target is met voluntarily. This net gain (in the form of avoided tax payments) from meeting the target voluntarily is eliminated if the cutoff level of pollution is set equal to the water quality standard, since in equilibrium tax payments are zero. In addition, from the farmers' perspective, making the tax retroactive is effectively equivalent to imposing it in t=1, which will induce all farmers to choose the cost-minimizing abatement levels from t=1 onward (see Proposition 1). Thus, the threat of a retroactive tax eliminates not only free-riding but also the zero voluntary abatement equilibrium that can emerge when the tax is not retroactive.

While from the farmers' perspective the retroactive tax is equivalent to a pure ambient tax policy, from the regulator's perspective the voluntary approach with the threat of a retroactive tax has a clear advantage over simply imposing an ambient tax at $t = 0$, namely, the regulator does not have to incur the information costs associated with learning θ in order to impose the tax unless the water quality standard is not met voluntarily (so that the threat must be carried out). Since in equilibrium the target will be met (farmers will be induced to choose the cost-minimizing abatement levels voluntarily), the information costs associated with imposition of the tax will never be incurred.

VI. REDUCTION OF GOVERNMENT SUBSIDIES

The analysis above assumes that the background threat takes the form of an ambient tax. However, agricultural water quality policy in the United States has historically been based on the use of "carrot" approaches designed to entice farmers to use environmentally friendly practices voluntarily through the use of government subsidies.[22] Such a policy can also be used with a background threat to achieve environmental goals at minimum costs. Instead of imposing an ambient tax, the background threat could be a reduction in government subsidies if a pre-specified environmental standard is not met. Specifically, under such a policy, the regulator would agree to give the farmer a chance to meet the standard voluntarily. If the standard is met, a pre-specified level of government subsidy would be paid. However, if the standard is not met voluntarily, the regulator would reduce the subsidy, with the magnitude of the reduction set at the level sufficient to induce the farmer to choose an abatement vector that ensures that the standard would be met. Formally, under the above policy, farmer i would face the following policy-related benefits:

$$S_i = \begin{cases} S_0 & \text{if } x(a^v, \theta) \le x^s \\ S_0 - \tau_i \cdot [x(a^p, \theta) - \overline{x}] & \text{if } x(a^v, \theta) > x^s \end{cases}$$

where S_0 is the pre-specified fixed subsidy, and a^p is the abatement vector farmers choose under the reduced government subsidies. It can be shown that the results derived above under the assumption that the regulator threatens imposition of an ambient tax would hold as well if the regulator threatens instead to reduce government subsidies as specified above.[23]

VII. CONCLUSIONS

Although the economic literature of NPP has focused on mandatory or stick approaches (e.g., input use taxes or restrictions), water quality policies in the U.S. have historically been based on the use of carrot instruments designed to entice farmers to adopt conservation practices voluntarily. Both the mandatory and voluntary approaches have been criticized in the economic literature. Mandatory approaches generally have drawbacks in terms of inflexibility or high transaction or information costs, while voluntary approaches may fail to provide adequate environmental protection. Thus, neither a purely voluntary program nor a purely mandatory approach seems to offer a desirable solution to agricultural NPP.

In this paper we examine a policy that combines a voluntary approach to controlling nonpoint-source pollution with a background threat of an ambient tax if the voluntary approach is unsuccessful in meeting a pre-specified environmental goal. In particular, we use the model to examine whether the regulator can use such a policy to induce cost-minimizing abatement decisions without the need for farm-specific information about pollution-related characteristics. We first consider how a single farmer would respond to such a combined policy, and then extend the analysis to consider multiple farmers. In the context of multiple farmers, we ask whether cost-minimizing abatement decisions are a subgame perfect Nash equilibrium and whether the proposed approach leads to free-riding by some farmers. While we derive the results in the context where the background threat is a tax, the results would also hold if the background threat were instead a reduction in government subsidies.

The main results can be summarized as follows. Combining a voluntary approach with a background threat of an ambient tax (or a reduction in government subsidies) can induce cost-minimizing abatement without the need for farm-specific information about pollution-related characteristics. This policy can therefore be both more effective than a pure voluntary approach without a threat (which might not ensure adequate environmental protection) and involve lower information or transaction costs than a pure ambient tax policy (since the regulator does not actually impose the tax). However, whether the cost-minimizing choices are a unique equilibrium or not depends on the design of the tax policy and whether it can be applied retroactively.

In the single farmer case, if the tax is not applied retroactively, then voluntary cost-minimizing abatement is the unique optimal response to the policy if the cutoff level of pollution is set sufficiently low, i.e., at a level that ensures that the present value of the stream of tax payments the farmer would face if the tax is imposed exceeds the one-period cost savings he would enjoy by not meeting the target voluntarily. In contrast, if the tax is applied retroactively, then voluntary cost-minimizing abatement is the unique optimal response regardless of the cutoff level of pollution.

When the policy is applied to a group of heterogeneous farmers, it can be designed to ensure that cost-minimizing abatement is a subgame perfect Nash equilibrium where the target is met voluntarily. However, when the tax is not applied retroactively, this equilibrium is never unique. It is possible to have equilibria under which the target is not met voluntarily. In particular, if no farmer is willing to meet the target voluntarily on its own, then zero voluntary abatement by all farmers is an equilibrium.

In addition, equilibria emerge under which the target is met voluntarily but, because of free-riding behavior, it is not met at minimum cost. The potential for free riding occurs because, with heterogeneous farmers, in order to induce the highest cost farmer to adopt voluntary abatement, the tax must be set in such a way that other farmers realize a net gain from meeting the target voluntarily. This makes these firms willing to abate more under voluntary compliance than they would have abated under the tax, which in turn allows other firms to abate less, i.e., to free ride. While reducing the cutoff level reduces the potential for free-riding, it cannot eliminate the potential for free riding.

However, both the zero voluntary abatement equilibria and the free-riding equilibria can be eliminated by threatening imposition of a retroactive tax. Under this policy, failure to meet the target voluntarily triggers imposition of the tax, but the tax is applied retroactively. From the farmers' perspective, the threat of a retroactive ambient tax is equivalent to the imposition of a pure ambient tax policy. As a result, the equilibrium abatement choices are identical to those that would be made under a pure tax policy, i.e., all farmers choose cost-minimizing abatement. However, in contrast to the pure ambient tax policy, when the tax is coupled with an opportunity for farmers to meet the standard voluntarily, the tax is never actually imposed in equilibrium and hence the associated information costs are never actually incurred. Thus, combining a voluntary approach with the threat of a retroactive tax is more efficient than either a pure voluntary approach or a pure ambient tax. If the tax cannot be applied retroactively, this efficiency gain is possible but not guaranteed.

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Appendix

Proof of Proposition 1

If $\tau_i = \lambda^*(x_s, \theta) \equiv \tau^*$, farmer i will choose a_i^t to minimize $C(a_i^t, \theta) + \tau^*[x(a_i^t, a_{-i}^t, \theta) - \overline{x}]$, where $a_{-i}^t = (a_1^t, ..., a_{i-1}^t, a_{i+1}^t, ..., a_n)$. The first-order conditions for the minimization problem require that

(A1) $$\frac{\partial C(a_i^t, \theta)}{\partial a_{ij}} + \tau^* \frac{\partial x(a_i^t, a_{-i}^t, \theta)}{\partial a_{ij}} \geq 0, \text{ for } j = 1,\ 2,\ ...,\ m.$$

From (A1) and (2), it follows that the solution to the farmer's minimization problem is $a_i^* \equiv (a_{i1}^*, a_{i2}^*, ..., a_{im}^*)$ if $a_{-i}^t = a_{-i}^* \equiv (a_1^*, ..., a_{i-1}^*, a_{i+1}^*, ..., a_n^*)$. Thus, $a^t = a^* = (a_1^*, ..., a_n^*)$ is a Nash equilibrium. Uniqueness follows from the assumption regarding the uniqueness of the solution to (1). The second part of the proposition follows immediately from strong monotonicity of the cost function and the infinite stream of costs incurred from $t = 2$ to infinity under the tax.

Proof of Proposition 2

The optimality of $a^t = a^*$ follows directly from Proposition 1. Consider the farmer's choice of a^v. By Lemma 1, we can limit consideration to $a^v=0$ and $a^r = a^*$. If $a^v=0$, the present value of the stream of costs for the farmer will be given by (4). On the other hand, if $a^v = a^*$, the present value of the stream of costs for the farmer from making this choice optimally now and every time it arises in the future will be

(A3) $$C^*\left(1 + \frac{1}{r}\right).$$

Comparing (4) and (A3) implies that the farmer's costs with $a^v = a^*$ will be at least as low as his cost with $a^v=0$ if and only if (5) holds.

Proof of Proposition 3

The optimality of $a_i^t = a_i^*$ again follows directly from Proposition 1. Given $a_{-i} \equiv (a_1^*,...,a_{i-1}^*, a_{i+1}^*,...,a_n^*)$, Lemma 3 implies that farmer *i*'s optimal response to a_{-i} in $t = 1$ is either $a_i^v = 0$ or $a_i^v = a_i^s(a_{-i}^*) = a_i^*$. The present value of the stream of costs if $a_i^v = a_i^*$ is

(A3) $$C_i^*\left(1+\frac{1}{r}\right).$$

Alternatively, if $a_i^v = 0$, the present value of the stream of costs is given by (4). Thus, $a_i^v = a_i^*$ is an optimal response for farmer *i* to $a_{-i} \equiv (a_1^*,...,a_{i-1}^*, a_{i+1}^*,...,a_n^*)$ if and only if $\bar{x} \le x^s - r\left(C_i^*/\tau^*\right)$, and $a_i^v = a_i^*$ is an optimal response for all *i* if and only if (7) holds.

Proof of Proposition 4

Consider a vector $(a_i^{v'}, a_{-i}^{v'})$ satisfying *(i)* and *(ii).* By *(i)*, $a_i^{v'} = a_i^s(a_{-i}^{v'})$. By Lemma 3, farmer *i*'s best response to $a_{-i}^{v'}$ is either $a_i^v = 0$ or $a_i^v = a_i^s(a_{-i}^{v'}) = a_i^{v'}$. By *(ii)* and the definition of $a_i^{\max}$, the cost farmer *i* incurs by choosing $a_i^{v'}$ is less than or equal to the cost incurred by choosing $a_i^v = 0$. Hence, $a_i^{v'}$ is a best response to $a_{-i}^{v'}$ for all *i*.

Proof of Proposition 5

Condition *(i)* ensures that $a_i^* \le a_i^{\max}$ for all i. By *(ii),* there exists at least one farmer for which $a_i^* < a_i^{\max}$. Call this farmer 1. Define ε >0 such that

$x(a_1^{\max}, a_2^* - \varepsilon, a_3^*, ..., a_n^*; \theta_1, \theta_2, ..., \theta_n) = x_s$. Then, by Proposition 4, $\{a_1^v, a_1^t\} = \{a_1^{\max}, a_1^*\}$, $\{a_2^v, a_2^t\} = \{a_2^* - \varepsilon, a_2^*\}$, and $\{a_i^v, a_i^t\} = \{a_i^*, a_i^*\}$ for all i = 3,…,*n* is a subgame perfect Nash equilibrium.

Proof of Proposition 6

The result regarding $a_i^t = a_i^*$ follows directly from Proposition 1. For the result regarding a_i^v, suppose $a_{-i}^v = (0,...,0)$. By Lemma's 3 and 4, either $a_i^{v*} = 0$ or $a_i^{v*} = a_i^s(0,0,...,0)$. The choice $a_i^v = 0$ yields a cost given by (4). The choice $a_i^v = a_i^s(0,0,...,0)$ yields a cost equal to $C(a_i^s(0,0,...,0), \theta_i)[1+(1/r)]$. Given these choices and the corresponding costs, $a_i^{v*} = 0$ is a best response to $a_{-i}^v = (0,...,0)$ for all *i* if and only if the former cost is no greater than the latter one. Given the monotonicity of *C*, this is true if and only if (9) holds.

Proof of Proposition 7

The optimality of $a_i^t = a_i^*$ again follows directly from Proposition 1. Given this and $a_{-i}^v \equiv (a_1^*, ..., a_{i-1}^*, a_{i+1}^*, ..., a_n^*)$, farmer i will choose a_i^v to minimize

$$\tilde{C}_i(a_i^v) = \begin{cases} C(a_i^v, \theta_i)\left(1 + \dfrac{1}{r}\right) & \text{if } x(a_i^v, a_{-i}^*, \theta) \le x^s \\ C(a_i^v, \theta_i) + \tau^*[x(a_i^v, a_{-i}^*, \theta) - x^s] + \dfrac{C_i^*}{r} & \text{if } x(a_i^v, a_{-i}^*, \theta) > x^s \end{cases}$$

By Lemma 3, the minimizing choice for the top line is $a_i^v = a_i^s(a_{-i}^*) = a_i^*$. Likewise, by Proposition 1, the minimizing choice for the bottom line is $a_i^v = a_i^*$.Thus, the strategy $\{a_i^v,$

$a_i^t\}=\{a_i^*, a_i^*\}$ is a subgame perfect Nash equilibrium. To prove the equilibrium is unique, note that under a retroactive tax with $\tau_i = \tau^*$ and $\bar{x} = x^s$, $a_i^{\max}$ is implicitly defined by $C(a_i^{\max})[1+(1/r)] = C_i^*[1+(1/r)]$, which implies that $a_i^{\max} = a_i^*$. Hence, free-rider equilibria under which the target is met voluntarily do not exist. To show that there are no equilibria under which the target is not met voluntarily, suppose otherwise. Let a^{v0} denote the voluntary abatement vector at this equilibrium. Then, given a_{-i}^{v0}, a_i^{v0} minimizes $C(a_i^{v0}, \theta_i) + \tau^*[x(a_i^{v0}, a_{-i}^{v0}, \theta) - x^s]$ for all i. By Proposition 1, the unique solution is $a^{v0} = a^*$. However, with this voluntary abatement vector, the target is met voluntarily.

Footnotes

[1] Recent discussions of reauthorization of the Clean Water Act, for example, have focused on the control of NPP. A notable example of nonpoint source pollution (NPP) is the contamination of surface water from the runoff of agricultural chemicals. In many locations agriculture has been identified as the largest source of NPP. Hence, much of the literature on NPP is in the context of agricultural water pollution. For an overview of issues relating to nonpoint source pollution from agriculture, see Braden and Segerson (1993) and Tomasi, Segerson and Braden (1994).

[2] For discussions of the use of subsidies to reduce agricultural sources of water pollution, see Braden and Lovejoy (1990), Norton et al. (1994), Lohr and Park (1995), Bosch et al. (1995), Wu and Babcock (1995), Hardie and Parks (1996), Wiebe et al. (1996), Wu and Babcock (1996), Babcock et al. (1996), Cooper and Keim (1996), Ribaudo and Caswell (1997), Ogg and Kuch (1997).

[3] Henceforth, we use the term "mandatory controls" to refer both to mandatory regulations or restrictions and tax-based policies such as ambient taxes or input taxes.

[4] Some characteristics may affect costs but not pollution, or vice versa. Our general specification allows for any given characteristics to affect only one or both.

[5] It is well-recognized that actual water quality will depend on a and θ as well as on other random variables such as weather (e.g., Segerson, 1988). The expected level of water quality then depends on the distribution of the weather variable. However, since we state the policy goal as one of meeting a water quality standard on average over some period rather than at every instant in time, the daily variability attributable to weather is not a key part of the analysis. Thus, for simplicity of notation, we suppress the weather variable. Note, however, that when compliance with the target is determined on a continuing basis, i.e., at every point in time, rather than on average over a period of time, the existence of weather variability affects the efficiency properties of alternative policy instruments. For example, with weather variability and continual determination of compliance, a pure ambient tax would not induce first-best abatement. See Spraggon (2002) for a useful summary.

[6] For some abatement practices such as installation of manure storage facilities, the abatement cost may depend on only the abatement practice.

[7] This is in contrast to the model in Segerson and Miceli (1998), where the level of environmental quality under the voluntary approach is determined endogenously as a result of bargaining between the regulator and the firm.

[8] We do not model the interactions among pollutants and externalities among farmers in this paper.

[9] Alternatively, we could consider a forcing contract, under which each farmer faces a sufficiently severe fixed penalty whenever ambient pollution exceeds the target. The efficiency properties of such contracts are well-known (e.g., Holmstrom, 1982; Laffont and Martimort, 2002). However, this solution suffers from a multiple-equilibrium problem because many combinations of agents' actions are best responses to this contract. A number of recent attempts to implement forcing contracts in laboratory settings have produced poor results (Nalbantian and Schotter, 1997; Spraggon, 2002). In addition, punishing each team member arbitrarily severely seems to be an unrealistically dramatic way of solving the moral hazard problem (McAfee and McMillan, 1991).

[10] Although the regulator cannot commit to a specific tax rate for each farmer before he knows θ, he can commit to setting the tax rate at a level sufficient to ensure that the target is met. In addition, he can commit to parameters of the tax policy that do not depend on θ, such as the cut-off level of pollution.

[11] If the regulator does not impose the tax after $t=1$ and there is no threat of imposition of a tax in the future, then farmers have no incentive to invest in abatement in $t=2$. If abatement decisions are reversible (i.e., last for only one period) and the tax threat is not on-going, then, when they have met the target in $t=1$, farmers will always choose zero abatement in $t=2$. Given this, the regulator's commitment not to impose the tax if the target is met may not be credible. For these reasons, we assume the threat is on-going. This implies that the regulator uses a form of a "trigger" strategy, where failure to meet the standard in one period triggers permanent imposition of the tax in all subsequent periods.

[12] Alternatively, this represents a case where abatement decisions in t=1 are irreversible and the voluntary abatement levels chosen do not exceed the levels that would have been chosen under the tax (implying that imposition of the tax would induce additional abatement).

[13] While the specification in (3) allows the tax rate to vary across farms, we show below that the tax rate chosen by the regulator will actually be uniform across farmers.

[14] We do not consider the case where $\overline{x} > x^s$, which would imply that the farmer receives net payments for meeting the standard. In this case, the farmer would never find it optimal to meet the standard voluntarily.

[15] If the tax is applied retroactively, then, if $x(a^v, \theta) > x^s$ in period 1, the farmer would also make a tax payment of $\tau_i \cdot (x(a^v, \theta) - \overline{x})$ at the end of period 1. See further discussion in Section V below.

[16] It is also similar to a negligence rule in tort law, under which an injurer is liable for damages if the level of care he undertook in conducting an activity is below the "due standard of care" but not liable if he met the standard of care. See Shavell (1987) for a discussion of the economics of negligence rules.

[17] Given that the tax/subsidy policy in Segerson (1988) is based on actual pollution at each

point in time, which fluctuates as a result of random factors such as weather, the use of the subsidy when pollution is below the target ensures efficient incentives. However, depending on the value of $\bar{x}$, it is possible that under the pure tax/subsidy approach, in equilibrium the farmer will choose an abatement vector such that on average the target is just met. In this case, on average no tax/subsidy payments occur in equilibrium and the equilibrium outcome under the pure tax/subsidy policy is identical to the outcome under a successful voluntary approach.

[18] Note that credibility is not a problem for the specific tax rate(s) or for the cut-off level of pollution. Threatening to impose the cost minimizing tax ensures that the cost-minimizing regulator will want to impose these particular tax rates. Furthermore, since the choice of a cut-off level of pollution does not affect the social cost of meeting the target (it only affects total tax payments), the regulator has no incentive to want to deviate from the cut-off level announced in t=0.

[19] In this case, we can interpret a_i as the abatement index for farm i. Farmers will have an incentive to minimize the cost of achieving any given level of the index.

[20] A similar free rider problem arises in the model of point source pollution developed by Dawson and Segerson (2002), where the regulator threatens to impose an emissions tax on an industry if it does not meet an exogenous emissions target. As in the model here, free riding generates an inefficiency because abatement is allocated inefficiently across firms. However, Segerson and Dawson (2001) show that, despite this inefficiency, the voluntary approach will still be more efficient if the regulator threatens imposition of a costly (inefficient) regulation rather than an emissions tax. Even under the threat of a tax, the voluntary approach may still be more efficient, if the welfare loss associated with the inefficient allocation of abatement across firms is less than the information or other transaction costs required for implementation of the tax.

[21] A special case of Proposition 6 is when no farmer would realize a net gain by meeting the target voluntarily. Suppose, for example, that all farmers were homogeneous and hence the regulator could set the level of $\bar{x}$ such that $a_i^{\max} = a_i^*$ for all i. Since $a_i^S(0,...,0) > a_i^*$ by the monotonicity of $x(a,\theta)$, (9) holds, implying that zero voluntary abatement is a possible equilibrium outcome.

[22] See references in footnote 2.

[23] Proofs are analogous and will be provided upon request.

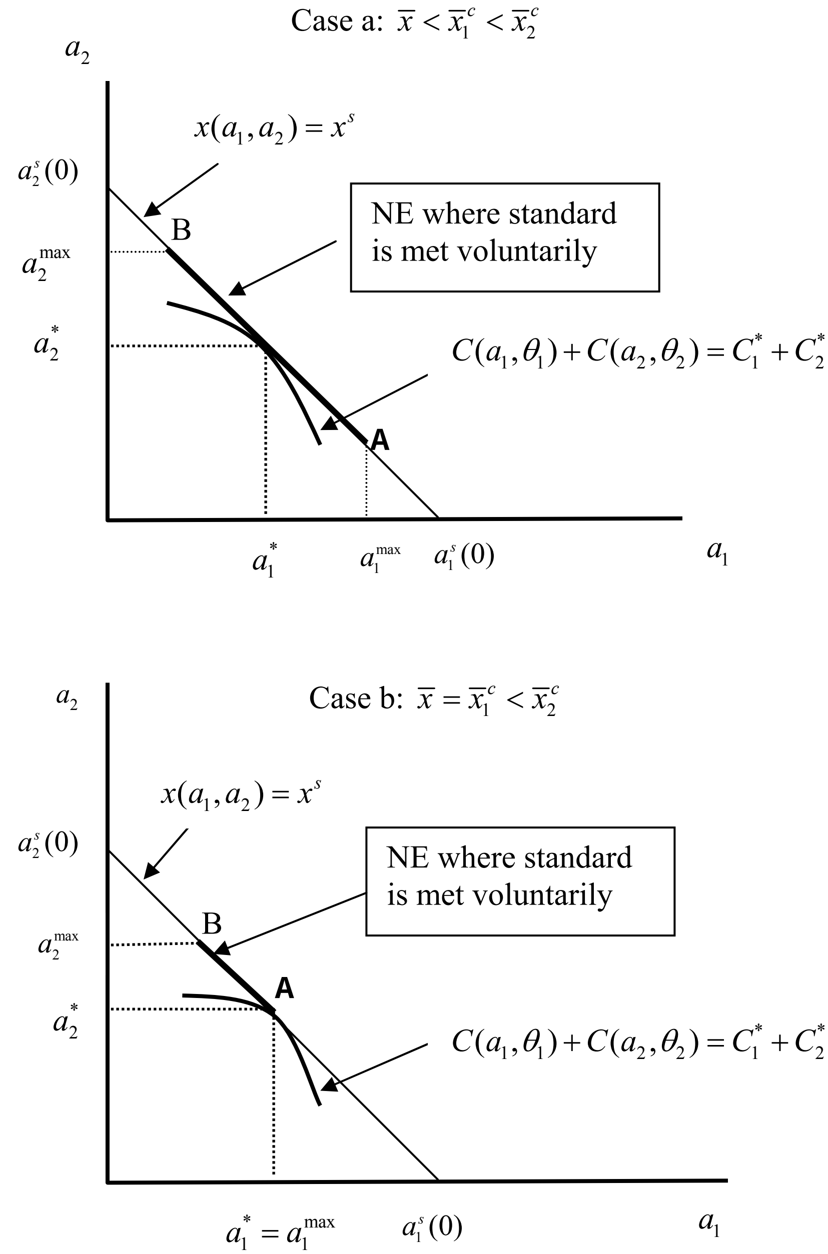

Fig. 1. The cut-off level of pollution and the tradeoff between creating incentives for voluntary abatement and inducing free-rider problems