The Regulation of Heterogenous Non-Point Sources of Pollution Under Imperfect Information

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ABSTRACT

This paper discusses the role of information structure (i.e., information cost, reliability, and distribution among agents) in the design of a regulatory mechanism for controlling non-point source pollution. An ambient concentration tax mechanism is examined for a non-point source pollutant with spatial transport among multiple zones. Imposition of the tax requires costly measurement of ambient concentrations in selected zones, and the selection of zones for measurement must be undertaken without perfect information regarding several parameters of the problem. Potentially crucial information issues in this context include: (a) the cost of measuring ambient concentration may exceed the benefits from imposing the tax, though these costs can be substantially reduced by carefully targeting monitoring sites; (b) producers' responses to the tax depend on prior beliefs regarding the fate and transport mechanism, and the efficacy of the ambient tax will depend upon the regulator's ability to ascertain and, perhaps, modify those beliefs; and (c) without regard to the extent to which the ambient concentration tax is imposed, it may be optimal for the regulator to acquire additional information regarding the fate and transport mechanism, either for the entire region or for specified "problem" zones.

I. INTRODUCTION

As progress is made in controlling point-sources of pollution, non-point source problems command greater attention. The rising concern with off-site consequences of agricultural chemical application provides a prominent example. But the design of regulatory mechanisms to control non-point source pollutants raises a different set of issues than those which arise in controlling point source pollutants. The new issues concern the cost and reliability of information about the linkages between control costs and the fate and transport of the pollutant. Answers to the question "What information is available at what cost" should be expected to play a crucial role in determining the structure and parameters of the best regulatory mechanism for the problem at hand. Indeed, the useful distinction between point and non-point source pollution problems is in the differing cost structures for the acquisition of information regarding important parameters of the problem. In the case of point source pollution, emissions, or effluent loadings, created by individual polluters are regarded as "measurable". Such magnitudes are not regarded as "measurable" in cases of non-point source pollutants, or measurable only at a cost which is automatically prohibitive. More generally, there may be several variables which describe important dimensions of a pollution problem: levels of inputs used and technology applied in polluting activities, effort applied and technology available for pollution abatement, and parameters of the biogeophysical process that transform a regime of polluting activities into a geographic distribution of ambient concentrations which cause harm. Rather than being "measurable" or "unmeasurable", these magnitudes are almost always subject to measurement, but at a cost and with varying reliability.

While considerations of the cost of information and informational asymmetries between polluters and regulators have been raised in the discussion of proposed regulatory mechanisms, such considerations have rarely played an explicit role in formal models designing and comparing mechanisms for pollution control. The purpose of this paper is to examine the role of information structure (i.e., cost, reliability, and distribution among agents) in the context of the ambient concentration tax mechanism recently proposed by Segerson [10]. Therein, the author develops a novel control mechanism for non-point source pollutants in which firms pay a tax based upon the ambient concentration of a pollutant. The linkage between production and ambient concentrations (i.e., the fate and transport mechanism) is assumed to be uncertain, but with a known and commonly held prior distribution. In this paper, Segerson's tax mechanism is extended in three directions. First, the symmetry between the producers' and regulator's beliefs regarding the fate and transport mechanism is relaxed. Second, the Segerson tax is extended to allow for multiple damage sites. Third, the cost of acquiring information and the reliability of that information is explicitly incorporated into the design of the optimal tax. This information can characterize the production and control practices of the regulated firms, reduce uncertainty regarding the fate and transport mechanism, or reveal ambient concentrations at additional sites.

II. BACKGROUND

The economic literature of pollution control has considered a wide range of regulatory mechanisms, and implementation of any of these mechanisms requires the acquisition of certain information concerning the pollution problem at hand. The large number of geographically dispersed polluters in the case of non-point source pollution raises the importance of information requirements in mechanism design. The U.S. Department of Agriculture's current effort to implement the Conservation Compliance provisions of the Food Security Act of 1985 is a case in point. This effort requires processing information on essentially all farms which participate in federal farm programs.

Regulatory incentive mechanisms use devices such as direct imposition of standards, prescriptions of technology in the polluting activity, charges, subsidies, or transferable permits. In turn, standards, subsidies, or charges can be based on effluent characteristics, ambient concentrations, input use, or technology choice. Further, design of any mechanism must address the issue of how much the mechanism will recognize the many sources of heterogeneity among polluters, or the extent to which these sources of heterogeneity will be ignored by lumping together polluters which differ in some more or less important respect. The extent to which the mechanism is tailored to heterogenous polluters will have important implications for the information burden imposed by the regulation.

Regulatory mechanisms always rely on information about the important parameters of the problem at hand, but the nature of information which must be acquired varies widely among mechanisms. For example, the traditional form of government intervention directed to reducing agricultural erosion has required observation of the individual farmer's cultural practices; taxes on agricultural chemicals, as in the state of Iowa, only require information on usage of the chemicals concerned; the novel system of charges proposed in Segerson [10] would require information on ambient concentrations of pollutants. Mechanisms can also vary in the nature of the information requirement, as distinguished from the nature of information required. Information requirements may be dictated by initial implementation of the regulation, routine administration of the mechanism, or enforcement of compliance.

While considerations of costly acquisition of information and informational asymmetries between the polluter and the regulator have often been raised in discussion of proposed regulatory mechanisms, such considerations have rarely played an explicit part in formal models comparing regulatory mechanisms for pollution control. Despite the absence of well developed formal analysis of mechanism design treating the trade-offs between information costs and allocative efficiency, at least two branches of the economic literature of pollution control mechanisms bear on the issue.[1] First, some progress has been made concerning the optimal geographic scale for the regulation of a single pollutant. While it is generally recognized that information costs vary with the level of aggregation at which a mechanism is to be applied,[2] and that these costs must be balanced against the allocative benefits of more finely tailored regulatory mechanisms, these considerations have not been thoroughly treated.[3]

In addition to the burden of information costs implied by the level of detail, or degree of specificity of the mechanism, choice of regulatory mechanism will imply certain information costs associated with enforcement. There is a literature which examines the trade-offs between enforcement effort and compliance with the regulatory mechanism, and compares mechanisms on these grounds. A program of enforcement associated with a particular mechanism implies information requirements, and the cost of enforcement obviously will depend on the information structure of the pollution problem at hand. Thus, enforcement considerations also imply a dependance of mechanism design on information structure, a problem which is likely to be particularly important for regulation of non-point source pollution.

III. A SPATIAL MODEL OF NON-POINT SOURCE POLLUTION

A. Notation

Consider a geographical region consisting of N zones. The region is determined by the jurisdiction of the regulator. The zones divide this jurisdiction according to the nature of damage from the pollutant under consideration and production and pollutant transport attributes of the region.[4] Specifically, from the damage perspective, zones are defined to be small enough so that the presence of a given level of the pollutant within the zone implies a given damage to society. Thus, a single measurement of ambient pollution level within the zone is sufficient to determine the damage to society. From the pollution creation perspective, areas must be small enough so that the fate of a pollutant entering the environment from within the zone can be treated as the same, without regard to the precise location of release of the pollutant. This division is based upon the mechanics of transport, including hydrologic characteristics, prevailing winds, etc.[5] Finally, the initial zone divisions are specified so that opportunity cost of pollution abatement is uniform within the zone. For agricultural non-point source pollution, for example, this division will depend upon the productivity attributes of the soil.

The non-point source pollutant of interest originates within the region as a by-product of a single production process that can be undertaken in any of the zones, with y_i denoting the level of production in zone i and $y. = (y_1,\ldots,y_N)'$. Individual firms can reduce the level of pollutant entering the environment from within their zone through abatement effort, denoted by a_i, with $a. = (a_1,\ldots,a_N)'$. In general, there need not be a one-to-one correspondence between the abatement effort, a_i, and abatement level. For example, in an agricultural context, a_i may represent alternative tillage or rotation practices, a_i and y_i can then be viewed as joint outputs of the farm. The cost of producing y_i with abatement effort a_i is denoted by $C_i(y_i,a_i)$, where C_i is assumed to be a strictly convex function of y_i and a_i.

The combination of $y.$ and $a.$ determines the ambient level of pollution in each zone through a transport mechanism. Specifically, let X_i denote the ambient level of pollution in zone i, with $X. = (X_1,\ldots,X_N)'$. These pollution concentrations are determined by the transformation $X. = T(y.,a.,\epsilon)$ (i.e., $T:\Re^N \times \Re^N \times \Re^M \rightarrow \Re^N$) where ϵ is an $M \times 1$ vector of stochastic transport effects.[6] The random component reflects the uncertainty on the part of both regulators and firms regarding the exact nature of the transport mechanism, due to such factors as weather and imperfect knowledge of relevant physical processes. The regulator is assumed to have a prior on the distribution of these unknown factors, denoted by $f_r(\epsilon)$, while producers are assumed to share a potentially different prior, denoted by $f_p(\epsilon)$. The priors on ϵ in turn generate priors on the ambient conditions that result from a given level of production activity and abatement level within the region.

Finally, the damage to society from the pollutant in question is assumed to be a nondecreasing function of the vector of ambient pollution levels and is represented by the function $D(X.)$, where $D_i = \partial D/\partial X_i \geq 0$, $i=1,\ldots,N$. A convenient simplification of this function considered below assumes that $D(X.) = \sum_{i=1}^{N} d_i(X_i)$, where $\partial d_i(x)/\partial x \geq 0\ \forall\ i$.

B. Taxes on Ambient Pollution Levels Under Uncertainty

Segerson [10] proposed a pollution control mechanism in which firms pay a tax based upon an uncertain ambient level of pollution with a known distribution. Firms and regulators were assumed to share a common prior on the transport mechanism. In this section, a multizone version of Segerson's tax is considered. Specifically, a tax on the producers in zone j is considered where the tax is calculated as the product of the tax rate, t_{jk}, and the ambient level of pollution in zone k. Unlike Segerson, however, a distinction is made between the regulator and producer priors regarding the transport mechanism. Initially, the administrative costs associated with the tax, including the cost measuring the ambient pollution level, are ignored.

The regulator's problem is one of choosing the optimal level for each t_{jk}. First, however, the producer's problem of choosing output and abatement effort is dealt with.

1. *The Producer's Problem*

The producer in zone j faces a vector of taxes, denoted by $t_{j.} = (t_{j1},\ldots,t_{jN})$, and uncertainty regarding the transport mechanism, T. Each firm is assumed to be a price taker and risk neutral, maximizing its expected profits and taking the level of production and abatement in other zones as given. Thus, the firm in zone j solves:

$$\pi_j(t_{j.}) = \max_{y_j, a_j} E_p\{py_j - C_j(y_j,a_j) - t_{j.}.X.\} \tag{1}$$

$$= \max_{y_j, a_j} \{py_j - C_j(y_j,a_j) - E_p[t_{j.}.X.]\}$$

where p denotes the price for the producer's output and $E_p()$ denotes the expectation operator given the producer's prior distribution on ϵ, $f_p(\epsilon)$. Assuming that an interior solution exists satisfying the usual second order conditions, firm j's optimal output and abatement levels $y_j^*(t_j.)$ and $a_j^*(t_j.)$ will solve:[7]

$$0 = p - \partial C_j/\partial y_j - \sum_{k=1}^{N} t_{jk} E_p(T_{jk}^y) \qquad (2a)$$

$$= p - \partial C_j/\partial y_j - \sum_{k=1}^{N} t_{jk} \hat{T}_{jk}^y$$

$$0 = -\partial C_j/\partial a_j - \sum_{k=1}^{N} t_{jk} E_p(T_{jk}^a) \qquad (2b)$$

$$= -\partial C_j/\partial a_j - \sum_{k=1}^{N} t_{jk} \hat{T}_{jk}^a$$

where $T_{jk}^y = \partial X_k/\partial y_j$ and $T_{jk}^a = \partial X_k/\partial a_j$ denote, respectively, the marginal impact of production and abatement effort in zone j on the ambient pollution level in zone k and

$$\hat{T}_{jk}^y = E_p(T_{jk}^y) \qquad (3a)$$

$$\hat{T}_{jk}^a = E_p(T_{jk}^a) \qquad (3b)$$

denote the prior means producer's form regarding these marginal effects. In general, $T(y.,a.)$ is a nonlinear function of its arguments. However, if T is linear, or approximately so near the optimal levels for $y.$ and $a.$, then the concentration taxes (i.e., the t_{jk}'s) influence production and abatement effort only through the tax indices:

$$\hat{T}_j^y = \sum_{k=1}^{N} t_{jk}\ \hat{T}_{jk}^y$$

$$\hat{T}_j^a = \sum_{k=1}^{N} t_{jk}\ \hat{T}_{jk}^a$$

This suggests that the optimal concentration tax matrix, developed in the next section, need not be unique in the multizone setting.

2. *Specification of the Optimal Tax*

The regulator's problem is then to set the optimal level of the tax rates (i.e., the t_{jk}'s) so as to maximize the expected sum of producer and consumer surplus, less the damages resulting from the ambient pollution levels generated by producers; i.e., $X.$. Specifically, the regulator solves:

$$W^* = \max_{t..} E_r\{\int_0^{Y(t..)} p(y)dy - \sum_{j=1}^{N} C_j[y_j^*(t_j.),a_j^*(t_j.)] - D(X.)\} \qquad (4)$$

$$\text{s.t.}\quad t_{ij} \geq 0 \qquad i,j=1,\ldots,N$$

$$= \max_{t..} W(t..)$$

$$\text{s.t.}\quad t_{ij} \geq 0 \qquad i,j=1,\ldots,N$$

where $E_r()$ denotes the expectation operator given the regulator's prior distribution on ϵ (i.e., $f_r(\epsilon)$), $t.. = (t_1.',\ldots,t_N.')'$ denotes the N × N matrix of taxes, p(y) denotes the demand for the output produced and $Y(t..) = \sum_{j=1}^{N} y_j^*(t_j.)$ denotes system-wide production of y given taxes of $t..$. The corresponding first order necessary conditions are as follows:

$$0 \geq \partial W(t..)/\partial t_{jk} \qquad (5a)$$

$$= \Big[(p(Y) - [\partial C_j/\partial y_j])\partial y_j^*/\partial t_{jk} - [\partial C_j/\partial a_j]\partial a_j^*/\partial t_{jk}$$

$$- \sum_{n=1}^{N} E_r\{[\partial D/\partial X_n][(\partial X_n/\partial y_j)(\partial y_j^*/\partial t_{jk}) + (\partial X_n/\partial a_j)(\partial a_j^*/\partial t_{jk})]\}\Big]$$

$$= \Big[(p(Y) - [\partial C_j/\partial y_j])\partial y_j^*/\partial t_{jk} - [\partial C_j/\partial a_j]\partial a_j^*/\partial t_{jk}$$

$$- (\partial y_j^*/\partial t_{jk})\overline{D}_j^y - (\partial a_j^*/\partial t_{jk})\overline{D}_j^a\Big] \qquad j,k=1,\ldots,N$$

$$t_{jk}[\partial W/t_{jk}] = 0 \qquad j,k=1,\ldots,N \tag{5b}$$

and

$$t_{jk} \geq 0 \qquad j,k=1,\ldots,N \tag{5c}$$

where

$$\overline{D}_j^y = \sum_{n=1}^{N} E_r[(\partial D/\partial X_n)T_{jn}^y] \tag{6a}$$

and

$$\overline{D}_j^a = \sum_{n=1}^{N} E_r[(\partial D/\partial X_n)T_{jn}^a] \tag{6b}$$

denote the regulator's expectations regarding the system-wide damage resulting from a marginal change in output and ambient levels in zone j, respectively. Substituting the firm's first order conditions into (5b) yields:

$$0 = t_{jk}[(\sum_{n=1}^{N} t_{jn}\ \hat{T}_{jn}^y - \overline{D}_j^y)\partial y_j^*/\partial t_{jk} + (\sum_{n=1}^{N} t_{jn}\ \hat{T}_{jn}^a - \overline{D}_j^a)\partial a_j^*/\partial t_{jk}] \tag{7}$$

For $t_{jk} > 0$, this is equivalent to

$$(\sum_{n=1}^{N} t_{jn}\ \hat{T}^{y}_{jn})(\partial y^*_j/\partial t_{jk}) + (\sum_{n=1}^{N} t_{jn}\ \hat{T}^{a}_{jn})(\partial a^*_j/\partial t_{jk}) = \bar{D}^{y}_j(\partial y^*_j/\partial t_{jk}) + \bar{D}^{a}_j(\partial a^*_j/\partial t_{jk}) \tag{7'}$$

The left hand-side of equation (7') indicates the changes in marginal tax burden producers expect to be generated by a change in the tax rate t_{jk}, while the right hand-side measures the marginal benefit of the tax rate in terms of reducing pollution damages.

A number of special cases of the above problem are of interest. In particular, suppose that a_i is measured in terms of the effluent emissions level controlled. Then $(-T^{a}_{jk})$ can be interpreted as a generalized transfer coefficient, depending upon both the level of production and abatement effort in zone j. If, in addition, it is assumed that the level of output does not directly influence the transport mechanism (i.e., $T^{y}_{jk} = 0$), then equation (7') reduces to:[8]

$$\sum_{n=1}^{N} t_{jn}\ \hat{T}^{a}_{jn} = \bar{D}^{a}_j \qquad j=1,\ldots,N \tag{8}$$

Equation (8) provides a system of only N equations with N^2 unknowns (i.e., the t_{jk}'s). With no direct relationship between the level of production and ambient pollution levels, the level of production (y_j) becomes an implicit function of abatement effort (a_j) through equation (2a). The tax now induces change in the concentration of pollution in each zone only through its impact on the level of abatement. The optimal level of abatement can be achieved through an infinite number of combinations of t_{jk}'s, with no impact on the corresponding level of y_j.

Case 1: The Single Polluter/Single Damage Site. In the case of a single polluter and a single damage site (i.e., N = 1), the optimal tax, t, becomes:

$$t = \bar{D}^{a} / \hat{T}^{a} \tag{8'}$$

$$= E_r[(\partial D/\partial X)(\partial X/\partial a)]/E_p[\partial X/\partial a] \quad .$$

This is equivalent to Segerson's [10] equation (5a) when the regulator and producers have the same prior on the transport mechanism. However, if the producers do not perceive that they have a significant influence on ambient concentration at the damage site (i.e., $E_p[\partial X/\partial a]$ is small relative to $E_r(\partial X/\partial a)$), then t will have to be large in order to efficiently reduce the level of pollution damage.[9]

Case 2: Linear Damage Function, Multiple Zones. Suppose D() is linear in the X_j's, with $\partial D/\partial X_j = \alpha_j$. Then the optimal tax rates for the multiple zone model are defined by:

$$\sum_{n=1}^{N} t_{jn} \hat{T}^{a}_{jn} = \bar{D}^{a}_{j} \tag{9}$$

$$= \sum_{n=1}^{N} \alpha_n \bar{T}^{a}_{jn} \qquad j=1,\ldots,N$$

where $\bar{T}^{a}_{jk} = E_r\{T^{a}_{jk}\}$ denotes the regulator's expectation regarding the generalized transfer coefficient. While the matrix of t_{jk}'s solving (9) need not be unique, one solution can be found by noting that equation (9) identifies the diagonal elements in the matrix relationship:

$$t_{..}(\hat{T}^{a}_{..})' = A(\bar{T}^{a}_{..})' ,$$

where $\hat{T}^{a}_{..} = \{\hat{T}^{a}_{jn}\}$, $\bar{T}^{a}_{..} = \{\bar{T}^{a}_{jn}\}$, and $A = \alpha_{.} \otimes i_N$, with i_N being an $N \times 1$ vector of ones and $\alpha_{.} = (\alpha_1, \ldots, \alpha_N)$. If $\hat{T}^{a}_{..}$ is invertible, then[10]

$$t_{..} = A[(\hat{T}^{a}_{..})^{-1}\bar{T}^{a}_{..}]' ,$$

If producers and regulators have the same prior means with regards to the transfer coefficients (i.e., $\hat{T}^{a}_{..} = \bar{T}^{a}_{..}$), then equation (10) reduces to $t_{jk} = \alpha_k$. That is, the marginal tax rate for all zones with respect to concentration impacts on zone k is simply the marginal damage cost from the increased concentration (α_k).

IV. INFORMATION

In general, the burden of information required to implement the tax derived in Section III is significant. The regulator must know the nature of the firm's costs, the nature of demand, the ambient level of pollution in each zone, and the nature of the damages in area k from the ambient level of pollution. In addition, the regulator must be able to evaluate the expectations defined by the producer's prior distribution on the transport mechanism, as well as evaluate the expectations defined by its own prior distribution on the transport mechanism. In this section, consideration is given to impact of information costs and structure on the ambient tax mechanism developed above.

A. Education Costs

As illustrated in the case of a single polluter and single damage site (Case 1), the discrepancy between the prior beliefs of the regulator and the the producer can have a significant impact on the optimal tax policy. In the extreme, if producers in a given zone, say j, believe they are completely helpless to control concentration levels, the tax becomes a discrete policy tool. With $T^y_{j\cdot} = 0$ and $T^a_{j\cdot} = 0$, the first order conditions in equations (2a) and (2b) are independent of the ambient taxes. The policymaker must then choose between enduring the damage caused by the pollution emanating from zone j (i.e., by setting $t_{j\cdot} = 0$) or driving the producers out of the market entirely by setting taxes at a level $t_{j\cdot}$ such that $\pi(t_{j\cdot}) < 0$.

This problem is illustrated graphically in Figure 1 for the single zone case. For ease of exposition, abatement effort is assumed to be zero (i.e., a = 0), so that the firm influences concentration levels within the zone only through changes in the level of production. Total societal net benefits, W, can then be written as a function of output, y^*, with

$$W(y^*) = E_r(\int_0^{y^*} p(y)dy - C(y^*,0) - D[T(y^*,0,\epsilon)]) \tag{10}$$

with $W(0) = 0$. This relationship is illustrated in the upper quadrant of Figure 1.

The lower quadrant of Figure 1 depicts y^* as a function of the ambient tax level, t. If $\hat{T}^y = 0$, then the firm perceives its tax burden to be independent of its production level and $y^*(t)$ is determined by the solid line in the lower half of Figure 1. That is, $y^*(t)$ remains at a constant level (i.e., $y^*(t) = y_0$) for $t \leq t_0 = \{ t \mid py^*(t) - C(y^*(t),0) = tX\}$. Once t exceeds t_0, the tax burden becomes sufficient to drive the firm out of the market (i.e., $y^*(t) = 0$, $t > t_0$). Under these circumstances, the ambient tax mechanism becomes a crude policy tool, only allowing the regulator to choose between (a) continued production and pollution (with $W^* = W(y_0)$) and (b) the termination of production (with $W^* = W(0) = 0$). The former will be chosen as long as $y_0 < B$ in Figure 1, while the latter will be preferred if $y_0 > B$.[11]

A similar problem emerges when $\hat{T}^y_{jn}$ and $\hat{T}^a_{jn}$ are small relative to their true values or those perceived by the regulating agency. Again, Figure 1 illustrates the situation for the single zone scenario. If $\hat{T}^y$ is small, $y^*(t)$ will change little as the tax level is increased, as with the dashed line in Figure 1. Eventually, however, the taxes will reach a level t_0' that will drive the firm from the market. In this case, the optimal policy will again be to raise taxes beyond t_0', forcing the firm out of operation. If $\hat{T}^y$ is larger, as in the case of the dotted line, then continued operation may be optimal, with output reduced from y_0 to y_0'' using an ambient tax level of t_0''. The range of policy alternatives, however, remains narrow and the optimal tax policy achieves a social welfare level, W_0'', substantially below the global maximum for W, W^*.

The above arguments suggest that the regulator's ability to ascertain and alter the firm's prior beliefs about the transport mechanism is likely to be crucial to the success in designing and implementing the ambient tax mechanism. If these education costs are high, emission standards or restrictions on technology, typically viewed as less efficient policy tools, may prove to be the more cost-effective policy mechanisms.

B. Monitoring Costs

The analysis presented in Section III assumes that information on the true level of X. is known without cost to the regulator. In fact, "...determining groundwater pollution and monitoring groundwater quality are extremely difficult and expensive." (Ng [8], p. 777). The decision to impose an ambient tax must be considered jointly with the cost of obtaining the necessary measures of pollution concentration within each zone. Thus, equation (4) needs to be extended to include the cost of measuring ambient pollution in every area, k, on which a tax will be based.

Let $\delta_k = 1$ if the regulator chooses to measure the pollutant's concentration in zone k, with $\delta_k = 0$ otherwise. Furthermore, let χ_k denote the cost of measuring ambient concentration in area k. The regulator's problem is then to solve:

$$W^{**} = \underset{t..,\delta.}{\text{Max}} \; E_r\{\int_0^{Y(t..\Delta)} p(y)dy - \sum_{j=1}^{N} C_j[y_j^*(t_j.\Delta), a_j^*(t_j.\Delta)] - D(X.)\} - \delta.\chi.$$

$$\text{s.t.} \quad t_{ij} \geq 0 \qquad i,j=1,\ldots,N \tag{11}$$

$$= \underset{t..,\delta.}{\text{Max}} \; W(t..,\delta.)$$

$$\text{s.t.} \quad t_{ij} \geq 0 \qquad i,j=1,\ldots,N$$

where $\chi. = (\chi_1,\ldots,\chi_N)'$, $\delta. = (\delta_1,\ldots,\delta_N)$, and $\Delta = \text{diag}\{\delta_k\}$. Equation (11) can be written equivalently as a two stage maximization process, with

$$W^{**} = \underset{\delta.}{\text{Max}} \; W^*(\delta.) \tag{12}$$

where

$$W^*(\delta.) \equiv \underset{t..}{\mathrm{Max}}\ W(t..,\delta.) \quad . \tag{13}$$

Once monitoring costs are included, the regulator must decide which receptor sites should be monitored. This decision will be based, in part, on the regulator's priors on ambient concentration levels, $X..$ These priors could be formed on the basis of two sorts of information. First, if the regulator has knowledge of $y.$ and $a.$, then priors on the transport mechanism induce a prior distribution on concentration levels. Second, whether $y.$ and $a.$ are known or not, the regulator may believe that ambient concentration levels are correlated in a way related to their spatial relationships. If so, then measurement at a given site will cause the regulator to revise priors on nearby concentrations. The possibility of spatial correlation casts the regulator's problem as one of optimal search.[12] The initial choice of sites to measure is based on priors about what will be found in the measurements, and subsequent measurement decisions are based on priors informed by the results of earlier measurement.

The choice of $\delta.$ in (13) will also depend upon the priors held by producers. The measurement of a given site has two benefits to the regulator. First, it increases the flexibility of the tax policy by allowing $t._k > 0$ once site k is measured. Second, it provides information with which priors on the transport mechanism can be updated. Depending upon the structure of producer priors, however, the former benefit may quickly become zero. For example, if T is linear in $y.$ and $a.$, then, as indicated in Section III.B.1, the taxes influence firm behavior only through the tax indices $\hat{T}^y_j$ and $\hat{T}^a_j$. As long as

$\hat{T}^y_{\cdot k}$ and $\hat{T}^a_{\cdot k}$ are non-zero for two k's, two sites will exhaust all flexibility benefits from monitoring additional sites. The corresponding $t_{\cdot k}$'s can be set so as to achieve the levels of $\hat{T}^y_j$ and $\hat{T}^a_j$ that will induce the optimal $y.$ and $a.$.

C. **Knowledge of Pollutant Fate and Transport**

For a given source area, j, imposition of the tax for transfer to receptor area k will involve monitoring and education costs discussed above, as well as a reduction in the sum of producer and consumer surplus generated by production in area j. Since T is not known with certainty, imposition of the tax may result in too much or too little pollution reduction at the receptor site, even when the producer's abatement response to the tax is perfectly anticipated by the regulator. Thus, the regulator's prior distribution on ϵ, which determines the transport mechanism, induces a prior distribution on the net social value of extending the tax to account for transport from area j to area k.

Let

$$V(t..,\delta.,\epsilon) = \int_0^{Y(t..\Delta)} p(y)dy - \sum_{j=1}^{N} C_j[y_j^*(t_j.\Delta),a_j^*(t_j.\Delta)] - D(X.) - \delta.\chi. \quad (14)$$

The $W(t..,\delta.)$ of equation (11) is then given by

$$W(t..,\delta.) = \int_\Omega V(t..,\delta.,\epsilon)f_r(\epsilon)d\epsilon,$$

where Ω denotes the state space of ϵ. Equation (11) describes the "no data" problem of choosing an action, $(t..,\delta.)$, to maximize the expected value of

V(). Regardless of this initial choice of $(t_{..},\delta_{.})$ based on current beliefs regarding ϵ, it may be desirable to acquire additional information about the transport mechanism to better inform subsequent regulatory decisions.[13] Suppose the regulator has the option to undertake a research project at a cost of ψ with outcome $z \in Z$, related to ϵ by the conditional distribution $h(z \mid \epsilon)$. Using the outcome of the research project, the posterior expectation of V, conditional on z, is given by:

$$W_p(t_{..},\delta_{.},z) = \int_{\Omega} V(t_{..},\delta_{.},\epsilon) f_r(\epsilon \mid z) d\epsilon \quad .$$

The regulator should fund the research project if

$$\psi < \int_Z \underset{t_{..},\delta_{.}}{\text{Max}} \; W(t_{..},\delta_{.},z) g(z) dz - \underset{t_{..},\delta_{.}}{\text{Max}} \; W(t_{..},\delta_{.}) \quad ,$$

where

$$g(z) = \int_{\Omega} h(z \mid \epsilon) f_r(\epsilon) d\epsilon \quad .$$

This simple formulation of the regulator's problem of information acquisition in support of the Segerson tax neglects the multiperiod duration of the benefit of new information, and considers a single research project of fixed size and scope. In fact, acquisition of information on the physical processes influencing fate and transport of pollutants is best regarded as a long term investment, with benefits enduring over several periods. This suggests that the regulator's discount rate could be crucial to decisions regarding the desirability of research projects. Furthermore, the scope of research is clearly endogenous. Not only is there flexibility in the total budget, ψ, to be devoted to research on fate and transport, but there is a trade-off between the quality of information generated by the project and its geographic coverage. Thus, one project's information, characterized by $h(z \mid \epsilon)$, could offer low variance of z given ϵ for a restricted set of components of the vector of z. An alternative project with the same budget could offer an $h(z \mid \epsilon)$ with higher variance for a less restricted set of components of z.

V. SUMMARY AND CONCLUSIONS

This paper has examined the role of information structure in the design of a particular mechanism for controlling non-point source pollution. The tax mechanism considered is based on ambient concentration of pollutants, and therefore must rely on the acquisition of information regarding concentrations at appropriately designated sites. The mechanism avoids routine acquisition of information concerning production and abatement practices of individual firms, but requires at least some information on fate and transport of the pollutant, as would any likely regulatory scheme. Information issues discussed in the context of this tax mechanism include the selection of sites for monitoring, the importance of ascertaining and perhaps influencing the beliefs of firms regarding the mechanism of pollutant transport, and the possibility of acquiring new information regarding the fate and transport of pollutants.

The larger issue, and a clear next step in investigating the role of information in the design of regulatory mechanisms, is consideration of the choice among alternative regulatory mechanisms. Since regulatory mechanisms differ in their information requirements, and costs of acquiring and processing information differ among the different contexts in which regulation may be considered, it should be expected that the balancing of information costs against allocative merits of mechanisms will not lead to the superiority of any single structure of mechanism for all contexts. The economics of regulation under imperfect information should provide a framework within which to consider the suitability of various mechanisms for regulatory contexts with differing information structures. Especially in the information intensive business of regulating non-point source pollutants, comparisons of alternative mechanism must be undertaken within this framework.

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VI. FOOTNOTES

1. There is also relevant literature, unrelated to environmental regulation, recently surveyed in Besanko and Sappington [2].

2. "In general, the more categories (markets) that units are divided into, the greater the administrative costs." Mendelsohn [6]. The application in the final section of Mendelsohn's paper does not incorporate this consideration, but to do so would be a fairly straightforward extension.

3. Typical of the literature's treatment of this admittedly difficult issue is the following. In the introduction to Kolstad [5, pp. 386-7], the author notes that: "The administrative costs of implementing firm-by-firm controls may be great. It is often difficult to obtain information regarding firm costs, the eventual fate of pollutants, and pollution damage. ... That uniform regulations balance gains in administrative and informational efficiency with losses in allocational efficiency is obvious." In describing the formal model it is stated that: "Perfect information is assumed on the part of everyone." Kolstad [5, p. 388].

4. This notion of zones is similar to the one employed by Tietenberg [13].

5. Delineation of the zones within a given region is itself a difficult task. Recent work by Gold *et al.* [4], Young *et al.* [14], and Anderson, Opaluch and Sullivan [1] provide potential tools for this process.

6. In general, one would expect $\partial X_k/\partial y_j \geq 0$, $\partial X_k/\partial a_j \leq 0$, $\partial^2 X_k/\partial y_j^2 \geq 0$, $\partial^2 X_k/\partial a_j^2 \leq 0$, and $\partial^2 X_k/\partial a_j \partial y_j \leq 0$. That is, X_k is convex in y_j and $(-a_j)$.

7. In general, the solution to the maximization process in (1) need not be an interior one. First, the necessary second order conditions may not hold when equations (2a) and (2b) are satisfied because T is not a convex function of y_j and a_j. Second, with the imposition of the ambient tax, the farm may no longer be profitable, leading to exit from the market and a discontinuity in the objective function at points (y_j, a_j) such that profits are zero for a given t_j. . This problem is discussed further in Section IV.

8. Segerson [10] uses this restriction in deriving an optimal tax rate. However, the fate and transport of agricultural pollutants will generally depend upon the intensity of production, with $T^{y_j}_k$ typically being positive.

9. This assumes that the tax does not become so large as to drive the producer out of the market. This potential problem is discussed further in Section IV.

10. If $\hat{T}^{*}_{\cdot\cdot}$ is singular, this suggests that all of the farmers perceive a fixed relationship between the generalized transfer coefficients for two or more of the zones. For example, $\hat{T}^{*}_{\cdot k} = \theta \hat{T}^{*}_{\cdot j}$. In this case the zones j and k can be combined for the purposes of imposing the ambient tax.

11. Given the usual curvature assumptions for D and T, y_0 will lie to the right of A in Figure 1.

12. Whether the search will be sequential (i.e., measuring ambient concentrations one site at a time), fixed-sample-size (i.e., a one-time choice for δ.) or variable-sample-size (i.e., sequentially choosing the number of sites to measure) will depend upon the degree of perceived correlation between the X_j's and the discount factor with respect to time. The higher the perceived correlation, the greater will be the attraction for sequential search. See Morgan and Manning [7], Cressie and Morgan [3], and Olson [9].

13. In the case of agricultural non-point source pollution of groundwater, substantial resources are now being devoted to such an acquisition of information. Olson [9] analyzes the similar problem of information acquisition on the carcinogenicity to inform regulatory decisions.

Figure 1
The Impact of Producer Priors and Yield Discontinuities on Tax Program Flexibility