Watershed Nutrient Trading Under Asymmetric Information

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This study evaluates first- and second-best trading policies for regulating watershed phosphorus under asymmetric information. The trading policies are differentiated on the degree to which regulators observe point and nonpoint source abatement efforts. The efficiency losses attributable to these informational asymmetries and those of the second-best policies can be measured in social welfare, and provide regulators the shadow value of foregoing first-best measures. Given representative monitoring costs from national water monitoring programs, it is shown that under asymmetric information, the chosen second-best trading policies outperform first-best policies by 11% in the control of watershed nutrient pollution.

Key Words: nonpoint source, permit trading, phosphorus, pollution, watershed

That agricultural pollution adversely affects national water resources to a significant degree is no longer questioned. In its 1998 report to Congress on the state of the nation's water, the U.S. Environmental Protection Agency (EPA) reported that agricultural pollution contributed to 60% of impaired river areas, 30% of impaired lake areas, 15% of the impaired estuarine areas, and 15% of the impaired coastal shoreline assessed (U.S. EPA, 2000).

While the EPA has moved to exert increased control over pollution generated at larger livestock and poultry facilities (U.S. EPA, 2001a), there exists no similar provision under the Clean Water Act allowing federal control of agricultural pollution arriving from nonpoint sources (NPSs) such as cropland. Reductions in agricultural NPS pollution have historically been achieved via voluntary conservation programs, typically practice-based, which pay farmers to adopt "best" management practices (BMPs) or retire environmentally sensitive cropland (Ribaudo, Horan, and Smith, 1999).

Modest environmental successes from these programs have been realized (Ribaudo, Osborn, and Konyar, 1994; Feather and Hellerstein, 1997; Hansen, Feather, and Shank, 1999). Nevertheless, as evidenced by more than 37 effluent trading and offset programs for NPS water pollution (Environomics, 1999), the promise of performance-based trading policies to achieve water quality goals at least cost remains tempting (Heimlich and Claassen, 1998).

The performance and appropriateness of these policies for NPS pollution, however, continue to be challenged for a number of reasons—e.g., noncompliance (Malik, 1990), market power (Van Egteren and Weber, 1996), transactions costs (Stavins, 1995), uncertainty (Taff and Senjem, 1996), and trading ratios (Hoag and Hughes-Popp, 1997).

This study focuses on one persistent criticism of performance-based policies for agricultural nonpoint sources: informational asymmetries and the associated problem of moral hazard and noncompliance. Specifically, farmers may misrepresent abatement efforts when imperfect monitoring exists, which erodes the cost-effectiveness of such policies. This possibility has been extensively noted in the nonpoint source literature (Shortle and Dunn, 1986; Smith and Tomasi, 1999; Moledina, Coggins, and Polasky, 2002), and many analysts have modeled optimal monitoring and enforcement efforts to address this problem in theory.

These theoretic policy models have generally fallen into two categories: (*a*) those that base monitoring and enforcement on observations of ambient environmental quality (e.g., Segerson, 1988;

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Xepapadeas, 1991; Horan, Shortle, and Abler, 1998), and (*b*) those that focus monitoring and enforcement on individual firms (e.g., Malik, 1993; Garvie and Keeler, 1994; Stranlund and Dhanda, 1999).

This analysis follows the latter framework, which arguably better reflects current regulatory practices. While much of this literature has addressed non-stochastic, point source (PS) pollution, three recent studies are more applicable to agricultural, NPS trading programs. Malik (1993) examines incentive-compatible auditing and enforcement by the regulator when firms must self-report abatement compliance. Garvie and Keeler (1994) extend this analysis to heterogeneous firms which strategically interact with the regulator. Finally, Stranlund and Dhanda (1999) explicitly consider noncompliance in dynamic trading policies under asymmetric information. They establish, in such a case, that optimal monitoring and enforcement need not be differentiated across heterogeneous firms as advocated earlier by Malik (1993) and Garvie and Keeler (1994).[1]

These theoretical models illustrate how noncompliance and costly monitoring and enforcement can erode the efficiency of market-based policies to control pollution. However, the extent of these efficiency losses and how they compare to those under conventional uniform performance standards or other second-best policies remains in question.

This study is the first to empirically examine watershed nutrient trading policies for PS and NPS pollution and the welfare losses due to asymmetric information. These losses are examined for a phosphorus-impaired watershed in southern Minnesota. The objective is to evaluate trade-based policies in the presence of asymmetric information assuming moral hazard and noncompliance when watershed sources are required to invest in and report abatement efforts.

In the following section, several watershed trading programs for point and nonpoint sources are developed. These programs are based on the extent to which the regulator can observe abatement efforts[2] and on investments in monitoring. To evaluate these policies, watershed data are then used to estimate cost and benefit functions for restricting phosphorus discharges into area surface waters. Assuming farmers act on the asymmetric information and moral hazard present, the policies are evaluated based on realized social welfare (i.e., the net of expected benefits, compliance costs, and monitoring investments). The results section establishes that second-best polices can outperform first-best policies by as much as 11% given costly monitoring. Both first- and second-best trading programs are observed to generally outperform uniform performance standards by more than 29%. Concluding remarks are provided in the final section.

Theoretical Model

There are n sources ($i = 1, ..., n$) that discharge phosphorus into a watershed: j point sources ($i = 1, ..., j$), and $n - j$ nonpoint sources ($i = j + 1, ..., n$). The regulator has observed past discharges by sources and expects aggregate phosphorus discharge in the absence of regulation (ex ante) to be $\bar{E} = \sum_{i=1}^{n} \bar{e}_i$ for expected weather patterns (where overbars represent expected values). Let total discharges in the presence of regulation (ex post) be $E = \sum_{i=1}^{n} e_i$, and aggregate abatement be $A = \sum_{i=1}^{n} a_i$, where abatement effort (a_i) for source i is the difference between expected discharge ($\bar{e}_i$) and actual discharge (e_i).[3]

The cost for PSs to abate quantity a_i is given as $C(a_i)$ for $i = 1, ..., j$, where $C(a_i)$ maps the cost-minimizing choice of abatement effort to achieve the desired abatement level. For NPSs, abatement is a function of two parameters: observable abatement effort (r) and unobservable abatement effort (z). For this analysis, observable abatement efforts include crop choice and tillage practice; unobservable efforts include the rate and method of fertilizer applications. These efforts can be loosely thought of as abatement effort on the observable extensive margin and abatement effort on the unobservable intensive margin, respectively (Yiridoe and Weersink, 1998).

NPS abatement can then be written as $C(a_i(r_i, z_i))$ $\forall\, i = j + 1, ..., n$. These cost functions exhibit the typical properties one might expect from constraining discharge:

$$\frac{\partial C(a_i)}{\partial a_i} > 0 \quad \text{and} \quad \frac{\partial^2 C(a_i)}{\partial a_i^2} > 0, \quad \forall\, i = 1, ..., n.$$

[1] As noted above, Van Egteren and Weber (1996) explore trading programs and noncompliance. However, the main thrust of their paper is the extent to which market power and noncompliance interact and how permit endowments may be catered to remedy this issue.

[2] Basing permit trades on the degree to which BMPs are directly observable is similar to recent developments in EPA-sponsored offset programs (Environomics, 1999).

[3] The theoretical development and empirical analysis herein are based on expected values; hence, the uncertain nature of nonpoint sources is manifest only in the self-reporting of unobservable abatement efforts. Whether or not nonpoint sources can be treated as uncertain point sources is often debated in the literature. However, such discussion would not add to or subtract from the results of this analysis.

This abatement is increasing in abatement effort:

$$\frac{\partial a_i(r_i, z_i)}{\partial r_i} > 0 \;\text{ and }\; \frac{\partial a_i(r_i, z_i)}{\partial z_i} > 0,$$

which implies

$$\frac{\partial C(a_i(r_i, z_i))}{\partial r_i} > 0 \;\text{ and }\; \frac{\partial C(a_i(r_i, z_i))}{\partial z_i} > 0,$$
$$\forall\, i = j + 1, \ldots, n.$$

Perfect Information

Because individual costs are convex in abatement, it must be that aggregate abatement costs for the watershed are also convex:

$$\frac{\partial C(A)}{\partial A} > 0 \;\text{ and }\; \frac{\partial^2 C(A)}{\partial A^2} > 0.$$

The function $B(A)$ maps the benefits to society of restricting phosphorus from entering area surface water. Benefits are strictly concave in abatement:[4]

$$\frac{\partial B(A)}{\partial A} > 0 \;\text{ and }\; \frac{\partial^2 B(A)}{\partial A^2} < 0.$$

With perfect information, the regulator's problem (RP^0) is to choose aggregate abatement to maximize social welfare (SW):

(1) $$RP^0 \equiv \max_A SW(A) = \max_A B(A) - C(A).$$

The first-order condition characterizing a solution to (1) is necessary and sufficient given the assumptions on the benefit and cost functions. This is specified as:

(1a) $$\frac{\partial B(A)}{\partial A} = \frac{\partial C(A)}{\partial A}.$$

The regulator can achieve optimal abatement, A^* (where the superscript asterisk represents optimal levels), by employing a number of regulatory mechanisms, generally a price (e.g., Pigouvian tax) or quantity (e.g., quota or permit) instrument. These mechanisms have different advantages and disadvantages, but under full information either achieves *Pareto optimality* (Weitzman, 1974).

In the case of phosphorus discharges and tradable permits, the regulator may distribute permits, R_i, such that

$$\sum_{i=1}^{n} R_i = \bar{E} - A^*,$$

where each permit represents the right to discharge one pound of phosphorus into the river in the year the permit was issued.[5] Under this trading program, each source will buy and sell permits (x_i) and choose abatement (a_i) to solve the source problem (SP):

(2) $$SP_i \equiv \min_{a_i, x_i} C(a_i) - P_R x_i,$$

where $x_i = \bar{e}_i - R_i - a_i$, and P_R is the equilibrium permit price. The corresponding necessary and sufficient $n + 1$ first-order conditions are:

(2a) $$\frac{\partial C(a_i^*)}{\partial a_i} \geq P_R \;\text{ and }\; a_i^*\left(\frac{\partial C(a_i^*)}{\partial a_i} - P_R\right) = 0,$$
$$\forall\, i = 1, \ldots, n,$$

and

(2b) $$\sum_{i=1}^{n} a_i^* = A^*.$$

The least-cost solution to (2) is characterized by the vector of optimal abatement levels, $\mathbf{a}^* = \mathbf{a}(\mathbf{r}^*, \mathbf{z}^*)$, such that marginal abatement costs are equalized across sources.

Asymmetric Information

Suppose the regulator has determined $\mathbf{A}^*$ and $\mathbf{a}^*$, given known costs and benefits, but cannot directly observe the NPS choice vector $\mathbf{z}$. There now exists the incentive for NPSs to misrepresent abatement efforts. This noncompliance, if it occurs, will be of the following form. First, there is no possibility for PSs to misrepresent abatement efforts or for NPSs to misrepresent adoption of r_i, both of which are freely observed.[6] However, NPSs can mislead the regulator by reporting and adopting different levels of unobservable abatement efforts.

To distinguish between reported abatement efforts and adopted efforts, let reported values be denoted by a prime symbol ($'$), and adopted values be denoted by a double prime ($''$). Then if NPSs were to fully exploit the unobservable $\mathbf{z}$ (the vector of all possible unobservable abatement choices), they would simply report $\mathbf{a}' = \mathbf{a}(\mathbf{0}, \mathbf{z}')$, where $\mathbf{z}' = \max(\mathbf{z})$, and would adopt $\mathbf{a}'' = \mathbf{a}(0, 0) = 0$. However, because the

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[4] Assume that $\partial B(0)/\partial A > \partial C(0)/\partial A = 0$, and that, for A sufficiently large, $\partial B(A)/\partial A < \partial C(0)/\partial A$.

[5] This analysis assumes sources receive an endowment of permits proportional to their ex ante emission levels. Alternative distribution mechanisms will not affect the outcome of the trading market, as perfect competition is assumed.

[6] The term "freely observed" is used to distinguish those practices that are "easily" observed. While such monitoring would entail some costs, it is assumed these costs are negligible compared to the costs of monitoring fertilizer application rates and methods.

regulator knows $C(a_i(r_i, z_i))\ \forall\ i = j+1, ..., n$, and because $\mathbf{r}$ is observable,[7] the NPSs must report, at the least, $\mathbf{a}' = \mathbf{a}(\mathbf{r}', \mathbf{z}') \geq \mathbf{a}(\mathbf{r}^*, \mathbf{z}^*)$, resulting in the abatement vector $\tilde{\mathbf{a}} = \mathbf{a}(\mathbf{r}', \mathbf{0}) \leq \mathbf{a}^*$. This notion of strategic noncompliance is dissimilar to that found in Stranlund and Dhanda (1999), but is intuitively more realistic given the nature of agricultural production.

Given this behavioral assumption, the regulator can do one or more things depending on the extent to which adopted and reported values diverge. The regulator can simply accept the resulting aggregate abatement,

$$\tilde{A} = \sum_{i=1}^{j} a_i^* + \sum_{i=j+1}^{n} \tilde{a}_i,$$

where the full range of $\mathbf{z}$ is available to NPSs. Let this most flexible trading program be denoted ETS-2. The regulator could also restrict $\mathbf{z}$ and eliminate abatement credits for certain unobservable abatement choices. Let these trading programs be denoted ETS-1 and ETS-0, where ETS-1 does not allow credit for fertilizer application rate changes, and ETS-0 does not allow credit for fertilizer application method or rate changes. The range of trading programs, m, is then $m \in (0, 1, 2)$.

In addition to restricting credits for unobservable practices, the regulator may also invest in monitoring efforts to reveal nonpoint choices of $\mathbf{z}$. Let there be three levels of monitoring effort, d, which have different per acre costs, $CC(d)$.[8] The regulator can choose not to monitor unobservable abatement practices ($d = 0$), where $CC(0) = 0$. The regulator can purchase monitoring devices which allow monitoring of fertilizer application methods ($d = 1$). The regulator may also purchase monitoring devices which allow monitoring of fertilizer application methods and rates ($d = 2$), where $0 < CC(1) < CC(2)$. The range of investment choices available to the regulator is then $d \in (0, 1, 2)$.

For each trading program there is an abatement level, A_m^*, which solves (1a) for ETS-0, ETS-1, and ETS-2. The regulator distributes tradable permits,

$$\sum_{i=1}^{n} R_i = \bar{E} - A_m^*,$$

and invests in monitoring devices (d) to maximize expected social welfare. Given d, m, and behavioral assumptions, the expected ex post abatement levels will be $\tilde{A}_{dm}$. The costs and benefits will be $C(\tilde{A}_{dm})$ and $B(\tilde{A}_{dm})$, respectively. If the regulator has an exogenous budget ($\$B$) to spend on monitoring, the regulator's problem is RP^1:

$$\text{(3)} \qquad RP^1|_{\$B} \equiv \max_{d,m} SW(\tilde{A}_{dm}) = \max_{d,m} B(\tilde{A}_{dm}) - C(\tilde{A}_{dm}),$$
$$\text{s.t.:}\ (n-j)CC(d) \leq \$B.$$

For each trading program, the first-order conditions are:

$$\text{(3a)} \qquad \frac{\partial B(\tilde{A}_{dm})}{\partial d} - \frac{\partial C(\tilde{A}_{dm})}{\partial d} - \lambda \geq 0, \quad d^*\left[\frac{\partial B(\tilde{A}_{dm})}{\partial d} - \frac{\partial C(\tilde{A}_{dm})}{\partial d} - \lambda\right] = 0;$$

$$\text{(3b)} \qquad \$B - (n-j)CC(d^*) \geq 0, \quad \lambda^*\left[\$B - (n-j)CC(d^*)\right] = 0;$$

and

$$\text{(3c)} \qquad \sum_{i=1}^{n} \tilde{a}_i = \tilde{A}_{dm}.$$

Here, λ can be interpreted as the shadow value of increasing the budget to allow increasing investments in monitoring efforts. Optimal investment is characterized by equating the marginal net benefits of increased abatement due to monitoring efforts with λ. Given the discrete nature of monitoring investments and relative effects on the cost function, the optimal choice of $\tilde{A}_{dm}$ will always be the maximum allowable under $\$B$.

Empirically estimating (3) is important in and of itself. However, the optimization required by the regulator in this sense has no explicit incentive to weigh the marginal welfare gains from increasing investments in monitoring efforts. By endogenizing the budget, it is possible to better illustrate the tradeoffs between social welfare and environmental quality (Horan, Shortle, and Abler, 1998; Farzin and Kaplan, 1999; Stranlund and Dhanda, 1999).

Therefore, suppose the regulator now levies a lump-sum tax (T) on the $(n-j)$ nonpoint sources to

[7] The regulator has observed (via surveys or direct observation) farm choices of **r** and **z** in the past, and has mapped discharge levels and profits as a function of weather, soil characteristics, **r**, and **z** using a biophysical soils model. Furthermore, given observable data (i.e., weather and soil characteristics) and correctly reported data (i.e., **r** and **z**), the regulator can accurately estimate how much phosphorus is discharged from nonpoint sources. As mentioned, the regulator can readily observe actual **r**-abatement efforts. The only parameters the regulator cannot observe are the farm choices of **z**.

[8] Assume that control costs are not a function of abatement levels, but are simply fixed costs required each year to monitor the relevant NPS management practice (e.g., the purchase of LandSat imagery of the region to determine timing or type of tillage practice).

pay for monitoring devices.[9] Such a tax might resemble a per acre fee assessed by a monitoring agency to pay for farm visits or to purchase water quality kits.[10] The regulator facing an endogenous budget constraint will solve RP^2:

$$(4)\qquad RP^2 \equiv \max_{d,m} SW(\bar{A}_{dm}) = \max_{d,m} B(\bar{A}_{dm}) - C(\bar{A}_{dm}) - (n-j)T,$$

$$\text{s.t.:}\ (n-j)CC(d) \leq (n-j)T.$$

For each trading program, the first-order conditions are:

$$(4a)\qquad \frac{\partial B(\bar{A}_{dm})}{\partial d} - \frac{\partial C(\bar{A}_{dm})}{\partial d} - \lambda \geq 0,$$

$$d^*\left[\frac{\partial B(\bar{A}_{dm})}{\partial d} - \frac{\partial C(\bar{A}_{dm})}{\partial d} - \lambda\right] = 0;$$

$$(4b)\qquad (n-j)T - (n-j)CC(d) \geq 0,$$

$$\lambda^*\left[(n-j)T - (n-j)CC(d)\right] = 0;$$

and

$$(4c)\qquad \sum_{i=1}^{n} \bar{a}_i = \bar{A}_{dm}.$$

The regulator will levy taxes to purchase monitoring equipment such that the net benefits including the costs of monitoring are maximized. Specifically, the regulator will invest in monitoring devices so long as the gains in social welfare achievable under the monitored regime exceed the cost of purchasing the devices.

Empirical Application

To illustrate the changes in social welfare across policies, this analysis utilizes data gathered from the Sand Creek watershed of the Lower Minnesota Basin. The Lower Minnesota is the largest source of the 1,000+ tons of phosphorus deposited by the Minnesota River (Faeth, 2000; Mulla, 1998) into the Mississippi River. The Sand Creek is one of the largest sub-basins in the Lower Minnesota, draining 148,394 acres of agricultural land and contributing on average 115,000 pounds/year of phosphorus to the Minnesota River (Johansson, 2000). These are substantial and important quantities, particularly since the Minnesota Pollution Control Agency (MPCA) has targeted the Minnesota River for more than a 40% reduction in aggregate phosphorus discharges (MPCA, 1999).

Nonpoint Source Abatement Costs

Following Montgomery's (1972) general framework, the abatement cost function maps the cost-minimizing choice of abatement effort for each NPS necessary to achieve any desired abatement level. The restricted profits and phosphorus discharge values needed to estimate these abatement cost functions were simulated using the Agricultural Drainage and Pesticide Transport (*ADAPT*) model. *ADAPT* is a field-scale, water table management model, which estimates nutrient and pesticide loads in addition to crop yields (Chung, Ward, and Schalk, 1992). This model was selected because it has the ability to account for major surface and subsurface hydrologic processes including agricultural subsurface tile drainage systems, useful for the tile-drained soils of the Upper Midwest.

The watershed modeling approach used to predict nutrient discharges and crop yields was developed by Gowda et al. (1999). This approach uses geographically referenced data to separate the region into distinct representative farm areas. These data layers include land uses, slopes, tillage practices, soil groups, and distance to water channel. These distinct farm areas, termed Transformed Hydrologic Response Units (THRUs), can be thought of as the $n-j$ nonpoint sources on a per acre basis corresponding to the 148,394 acres in the watershed. THRUs are used with the watershed model *ADAPT* to simulate crop yields and nutrient movement in the watershed as a function of crop, tillage, and fertilizer management practices.

To estimate the NPS cost functions, ordinary least squares (OLS) was used first to map abatement costs to abatement levels and to identify the appropriate functional form of the cost function. However, because OLS estimations minimize the squared deviation of observations from the fit of the abatement cost function, it may be biased upward due to redundant combinations of intensive and extensive

[9] Note that this tax is not an effluent fee or a penalty per se designed explicitly as a disincentive to pollute (Horan, Shortle, and Abler, 1998; Smith and Tomasi, 1999). Rather, this tax is used to invest in monitoring efforts, which will reveal farmers' adoption of unobservable abatement practices. For the purposes of exposition, the penalty for noncompliance is assumed to be sufficiently high to induce truth telling.

[10] The lump-sum tax is assumed to be small enough that it does not affect the firm's entry or exit decisions, and therefore the per acre representation is used to illustrate how potential ranges of monitoring costs might affect the regulator's monitoring investment and program decisions. The per acre fee could also be levied on point sources; under many EPA point-nonpoint source offset programs, it is the point source that is responsible for the monitoring costs to ensure the offset contract is being met (Ross and Associates Consulting, 2000).

Table 1. Abatement Costs for Sand Creek Point and Nonpoint Sources

POINT SOURCES [a]	Discharge (lbs./year)	No. Operations	Abatement Cost	R^2
WWTF-J	2,285	1	$0.033166(a)^2$	0.94
WWTF-N	8,445	1	$0.004903(a)^2$	0.92
Feedlots	29,180	92	$0.839657(a)^2$	0.81
NONPOINT SOURCES [b]	Discharge (lbs./year)	Acres	Abatement Cost	R^2
MN079A (> 300')	20,161	59,014	$136.56(a)^2$	0.63
MN080A (> 300')	4,777	11,673	$230.90(a)^2$	0.70
MN081A (> 300')	3,452	8,476	$87.73(a)^2$	0.63
MN163A (> 300')	2,180	8,300	$350.76(a)^2$	0.56
MN165A (> 300')	3,070	2,525	$14.85(a)^2$	0.89
MN169A (> 300') [c]	1,685	1,433	$!2.69(a)^2$	0.03
MN171A (> 300')	243	508	$155.69(a)^2$	0.66
MN178A (> 300')	155	549	$593.47(a)^2$	0.96
MN196A (> 300')	16,648	34,953	$131.74(a)^2$	0.74
MN079B (< 300')	8,188	9,219	$20.20(a)^2$	0.63
MN080B (< 300')	1,922	1,806	$34.16(a)^2$	0.70
MN081B (< 300')	1,453	1,373	$12.98(a)^2$	0.63
MN163B (< 300')	1,317	1,928	$51.89(a)^2$	0.56
MN165B (< 300')	1,579	499	$2.20(a)^2$	0.89
MN169B (< 300') [c]	1,118	366	$!0.40(a)^2$	0.03
MN171B (< 300')	41	33	$23.03(a)^2$	0.66
MN178B (< 300')	54	73	$87.97(a)^2$	0.96
MN196B (< 300')	7,016	5,665	$19.49(a)^2$	0.74

Source: Johansson (2000).

Notes: Reported R^2 values conform to OLS estimates of quadratic abatement costs. For nonpoint source estimates, the R^2s conform to the initial OLS estimation of functional form. The abatement cost functions reported conform to the second-stage frontier estimation.

[a] WWTF-J and WWTF-N are wastewater treatment facilities in Jordan and New Prague, respectively.

[b] Nonpoint sources are distinguished by Minnesota soil association (MN----) and distance to a water transport channel corresponding to Transformed Hydrologic Response Units (THRUs) (Gowda et al., 1999; Sharpley et al., 1999).

[c] The nonpoint source abatement cost functions are estimated over the intensive management margin. In certain instances over this range, the estimation indicates that the constrained profit exceeds the unconstrained profit (i.e., negative abatement costs). This phenomenon is reflected in actuality via the adoption of conservation tillage regimes (Conservation Technology Information Center, 1998), but does revert to the expected convex form when extensive management practices are necessary for high levels of abatement.

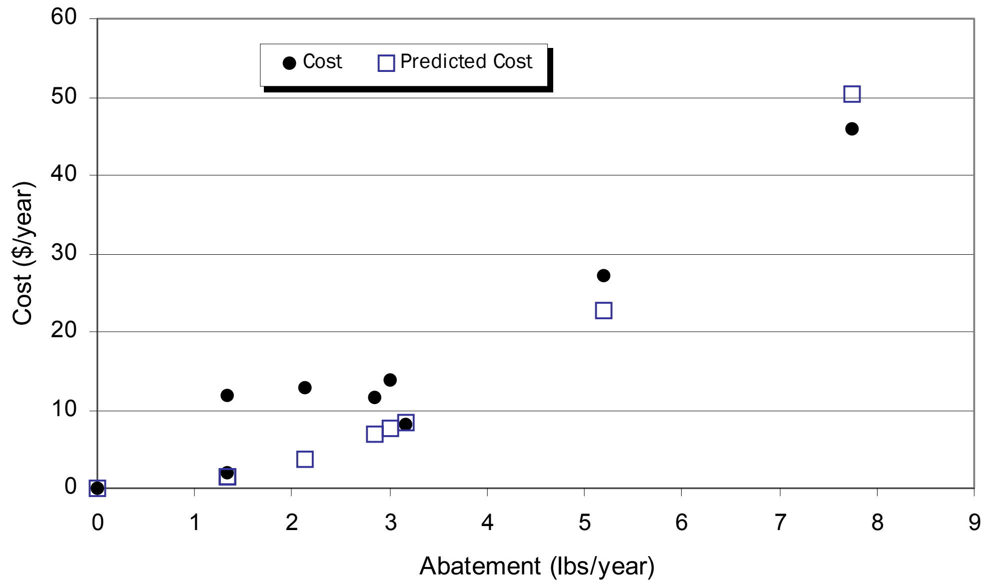
abatement efforts used in the simulations. These redundancies arise from topographical features and may not be consistent with cost-minimizing behavior. Therefore, frontier analysis was used to estimate the actual cost function (Battese, 1992; Coelli, 1995; Johansson, 2000). The convex frontier will represent the cost-minimizing shell of all best management practices (table 1).[11]

[11] A simple quadratic function describing the convex relationship between abatement levels and costs is justified with the exception of two nonpoint sources: MN169A and MN169B. These correspond to marginally productive soils and account for only 2.4% of the aggregate phosphorus discharge. As noted by an anonymous reviewer, because these soils have negative abatement costs, they will manifest in excessive abatement if there is a market for permit sales. However, these functions conform to convexity at high levels of abatement effort (Johansson, 2000). Consequently, these sources will immediately adopt abatement efforts that yield positive returns (e.g., conservation tillage), but will weigh further efforts that are costly (i.e., once the cost curve becomes convex) against potential revenue from permit sales.

Point Source Abatement Costs

The main point source contributors of phosphorus to the Sand Creek are the wastewater treatment facilities in Jordan and New Prague (WWTF-J and WWTF-N) and 92 feedlots. Using observations from 10 comparable wastewater facilities (Senjem, 1997) having different flow rates and influent concentrations, the marginal effects of these variables on average abatement costs were first estimated using OLS. These estimates were then used to construct abatement cost functions for WWTF-J and WWTF-N, given the flow rates and influent concentrations at those facilities (table 1).

To estimate abatement costs for the feedlots, it was necessary to compare livestock producers' willingness to accept contracts for abatement of manure nutrients in this region (Tiffany, 1999). Under this



Source: Johansson (2000).

Figure 1. Feedlot abatement costs

program, livestock producers applied for financial assistance when adopting better phosphorus management practices requiring a detailed explanation of costs and benefits resulting from the adoption of these practices (figure 1). Using OLS, the costs of reducing the discharge of phosphorus into surrounding waters was estimated for a representative feedlot (table 1).

Aggregate Abatement

To estimate the aggregate abatement costs and benefits for the Sand Creek watershed for the trading programs, several assumptions were necessary. Using the individual abatement cost functions, the aggregate costs for different levels of abatement were simulated for the three trading programs (ETS-2, ETS-1, and ETS-0) assuming full-information. The resulting costs for each program were used to estimate an aggregate cost function. As expected, when nonpoint sources are allowed to base trades on the complete set of management practices, aggregate costs are lower than those for the more restrictive trading programs (table 2).

To calculate social welfare (SW) under these policies, an estimate of the marginal benefit function for phosphorus abatement in the Sand Creek was required. Combining revealed and stated preferences, Mathews, Homans, and Easter (1999) estimate a random-effects probit model for phosphorus abatement in the Minnesota River similar to a model developed by Loomis (1997). This study allows an estimation of the marginal effects of water quality on the willingness to pay for phosphorus abatement calibrated to the Sand Creek region. This estimate requires that marginal willingness to pay approaches zero as abatement approaches 100%—i.e., the benefits to abatement level off as total abatement is realized, consistent with traditional assumptions of benefits functions. Given this assumption and the relevant literature (Deaton and Muellbauer, 1980), the form of the inverse demand function for phosphorus abatement is assumed to be semi-log (table 2).

Results

To generate the potential for noncompliance on the unobservable margin, the efficient level of abatement given the permit constraint was first estimated for each PS and NPS. All possible combinations of r and z yielding the same level of abatement were then generated for the NPSs. The cost-minimizing levels of observable and unobservable abatement choices were selected for analysis given the relationship $C(a_i(r_i', z_i')) \geq C(a_i(r_i^*, z_i^*)) \geq C(a_i(a_i'', 0))$ $\forall\, i = j + 1, ..., n$.

Evaluating the first-order conditions, (4a)–(4c), for all $m \in (0, 1, 2)$, it is possible to derive solutions to RP^2 given the costs of investing in monitoring

Table 2. Aggregate Costs and Benefits of Abatement for Trading Programs

Trading Program	Aggregate Costs	Aggregate Benefits
ETS-2	$C(A') = 0.000441(A')$	$B(A) = 635.2024(A) - 50.2024(A \times \ln(A))$
ETS-1	$C(A') = 0.000461(A')$	$B(A) = 635.2024(A) - 50.2024(A \times \ln(A))$
ETS-0	$C(A') = 0.001242(A')$	$B(A) = 635.2024(A) - 50.2024(A \times \ln(A))$

Sources: Mathews, Homans, and Easter (2000); Johansson (2000).

Table 3. Abatement and Social Welfare for Monitoring and Trading Programs

Trading Program	Device	Abatement [a]	Social Welfare
ETS-2	2	48,800	$3,500,029 $-$ (148,394 × $CC(2)$)
	1	41,690	$3,154,926 $-$ (148,394 × $CC(1)$)
	0	30,801	$3,079,450
ETS-1	1	47,804	$3,453,394 $-$ (148,394 × $CC(1)$)
	0	31,094	$3,083,220
ETS-0	0	28,323	$2,418,186

[a] Abatement levels correspond to the expected level of aggregate abatement given the regulator's choice of [*d*, *m*] and source choice of actual abatement given the presence of moral hazard.

Table 4. Effects of Monitoring Costs on Social Welfare

Monitoring Costs ($/acre)	Device	Trading Program	Social Welfare, $SW(\tilde{A}_{dm})$
$2.83 > $CC(1)$ + $0.31 > $CC(2)$	2	ETS-2	$SW(\tilde{A}_{22})$ = $3,500,029 $-$ (148,394 × $CC(2)$)
$2.49 > $CC(2)$ + $0.31 > $CC(1)$	1	ETS-1	$SW(\tilde{A}_{11})$ = $3,453,394 $-$ (148,394 × $CC(1)$)
$CC(1) \geq$ $2.49	0	ETS-1	$SW(\tilde{A}_{01})$ = $3,083,220

devices (table 3). It is apparent that with perfect information, the regulator would allow the full range of abatement activities and would distribute approximately 66,000 permits to generate $3.5 million in social welfare. However, under asymmetric information and an endogenous budget constraint, the optimal selection of *m* and *d* will depend on the costs of investing in monitoring devices. Following from (4), the regulator will invest in monitoring devices so long as the increased benefits from the additional abatement exceed the increased abatement and investment costs.

The effect of investment costs on the optimal selection of *m* and *d* is reported in table 4 for ranges of monitoring costs. Treating each acre of agricultural land as a nonpoint source, it can be seen from table 4 that if the cost to monitor fertilizer application methods exceeds $2.49 per acre (i.e., $370,174 ÷ 148,394 acres), then the regulator will employ the restricted trading program (ETS-1) with no investments in monitoring. Similarly, if the cost to monitor both application rates and methods is less than $2.83 per acre [i.e., ($3,500,029 $-$ $3,079,450) ÷ 148,394 acres] and is marginally less expensive than the cost to only monitor application methods, then the regulator will invest in both monitoring devices and employ the most flexible trading program (ETS-2). Under no circumstances will the regulator choose the most restrictive trading program (ETS-0).

Potential Monitoring Costs

To compare possible monitoring costs for agricultural nonpoint pollution, 14 current national monitoring programs (U.S. EPA, 2001b) were evaluated. Monitoring efforts vary greatly among these programs. The majority of the watersheds employ water quality monitoring along the affected river to control for up- and downstream effects. The watersheds are also separated into treatment and control regions to measure the impact of BMP implementation, including different fertilizer application rate and method regimes.

The intensity of these monitoring programs can be broadly separated into two categories: low

Table 5. Monitoring Costs and Intensity for Selected Watersheds

Watershed Location	Monitoring Cost ($)	Acres	Intensity ($/acre/year)	
Bad River, SD	16,728	2,053,760	0.01	
Waukegan River, Il	1,441	7,640	0.19	
Elm Creek, NE	18,125	35,800	0.51	
Sycamore Creek, MI	84,500	67,740	1.25	
Swatara Creek, PA	35,000	27,520	1.27	
Morro Bay Watershed, CA	62,000	48,450	1.28	
Totten and Eld Inlet, WA	94,167	67,200	1.40	
Potential Sand Creek 1	***222,600***	***148,400***	***1.50***	2
Long Creek, NC	71,648	28,480	2.52	
Otter Creek, WI	25,000	7,040	3.55	
Lightwood Knot Creek, AL	181,429	47,300	3.84	
Potential Sand Creek 2	***593,600***	***148,400***	***4.00***	2
Walnut Creek, IA	110,100	24,570	4.48	
Sny Magill Watershed, IA	111,116	22,780	4.88	
Lake Pittsfield, IL	88,540	7,000	12.65	
Lake Champlain Basin, VT	109,718	7,576	14.48	

Source: U.S. Environmental Protection Agency (2001b).

Table 6. Policy Comparisons: ETS Trading Programs vs. Uniform Abatement Policies

	Policy Comparison		Policy Comparison	
Description	ETS-2-2	Uniform-2	ETS-1-1	Uniform-1
Aggregate Measures:				
Abatement (pounds)	48,800	48,800	47,804	47,804
Monitoring Costs ($)	593,600	593,600	222,600	222,600
Abatement Costs ($)	1,050,215	2,093,754	1,053,488	2,001,089
Benefits ($)	4,550,244	4,550,244	4,506,882	4,506,882
Welfare ($)	2,906,429	1,862,870	3,230,794	2,283,193
(Full Information) ($)	(3,500,029)	(2,456,470)	(3,453,394)	(2,505,793)
Average Cropland Measures (per acre):				
Abatement (pounds)	0.268	0.215	0.259	0.210
Monitoring Costs ($)	4.00	4.00	1.50	1.50
Abatement Costs ($)	5.12	4.03	4.89	3.86
Permit Price ($)	43.04	—	44.08	—
Permit Revenue ($)	2.32	—	2.15	—
Net Cost per Acre ($)	6.80	8.03	4.24	5.36
(Full Information) ($)	(2.80)	(4.03)	(2.74)	(3.86)

Notes: ETS-2-2 is the first-best trading program and ETS-1-1 is the second-best trading program, under asymmetric information. Uniform-2 and Uniform-1 are the respective uniform abatement policy counterparts (i.e., conventional policies requiring uniform phosphorus abatement across all sources given the same levels of aggregate abatement).

intensity and high intensity (table 5). Choosing representative values of $1.50 per acre per year and $4.00 per acre per year, respectively, for these two categories, suppose that these approximate $CC(1)$ and $CC(2)$. While these programs do not expressly monitor fertilizer rates and machinery on all farms, the costs for the Sand Creek would correspond to $222,600 per year and $593,600 per year, which would be upper bounds for conventional monitoring costs compared to other watersheds of this size.

The differences between the first- and second-best policies are summarized in table 6. The solution to the endogenous budget, social welfare maximization problem is to employ ETS-1 and to invest in monitoring costs of \$1.50 per acre to reveal fertilizer application methods: $SW(A_{11}^{0})$ = \$3,230,794. Here, the second-best policy (ETS-1) outperforms the first-best policy (ETS-2) by approximately 11%. Under full information, the first-best mechanism is marginally more efficient than the second-best mechanism, by 1.3%. As a point of reference, the two trading policies are compared to conventional policies requiring uniform phosphorus abatement (Uniform) across all sources given the same levels of aggregate abatement. In both cases, the investment in monitoring equipment is assumed to be the same as with tradable permits.

From table 6, it can be seen that trading programs significantly outperform the uniform reduction policies. The first-best trading program (ETS-2-2) outperforms its uniform reduction counterpart (Uniform-2) by 36%. The second-best trading program (ETS-1-1) outperforms its uniform reduction counterpart (Uniform-1) by 29%. Note these preferences would change given an exogenous budget greater than \$593,600. In such a case, the regulator would choose the first-best trading program resulting in $SW(A_{22}^{0})$ = \$3,500,029.

The treatment of agricultural producers under the two tradable permit mechanisms and the uniform abatement policies is important to disentangle from the results. Under the most flexible trading program (ETS-2), agricultural producers abate more phosphorus and sell more permits than under the more restrictive program (ETS-1). However, the optimal level of abatement required to maximize social welfare is lower under ETS-1 and the equilibrium permit price is higher (fewer permits and fewer NPS abatement possibilities). In addition, the per acre tax imposed on the NPSs to fund monitoring efforts is less under the more restrictive trading program than under the flexible trading program.

Given these three effects, the cost to comply with a phosphorus abatement policy is less for agricultural producers under the second-best trading program for both the full- and asymmetric-information case (table 6). Under both trading programs, agricultural crop producers incur approximately 80% of the total abatement costs, whereas under the uniform reduction policies, this percentage falls to 29%. However, revenue earned from trading reduces overall costs to crop producers, making these policies more attractive when compared to uniform reduction policies (i.e., ETS-2-2 is preferred to Uniform-2; ETS-1-1 is preferred to Uniform-1).

Conclusions

It is clear from the burgeoning literature on NPS pollution and market-based regulatory policies that the effects of asymmetric information on NPS regulation are both interesting and important to consider. This is especially true in light of the increased desire to include NPS abatement in states' Total Maximum Daily Load (TMDL) water quality efforts for nutrients and sediment. Trading programs offer a means to encourage NPS offsets of PS abatement obligations under these standards at lower cost to society (U.S. EPA, 2002).

While many investigations have critiqued such approaches because of asymmetric information, few have actually evaluated what the loss in efficiency might be due to noncompliance. A simple framework is developed in this study to consider PS and NPS phosphorus discharges and performance-based regulation. This framework illustrates how regulatory efficiency can be improved by using market mechanisms to target abatement, and evaluates the degree to which social welfare may be compromised when NPSs are in noncompliance.

Subject to an endogenous budget constraint and known costs and benefits of abatement, the deadweight losses due to moral hazard and investments in monitoring equipment are evaluated for Sand Creek, a small, phosphorus-impaired watershed in southern Minnesota. Using representative costs from the EPA's national water monitoring programs, it is possible to delineate ranges of costs potentially needed to monitor phosphorus abatement policies in this watershed.

Respective per acre costs of \$4.00 and \$1.50 were chosen to represent high- and low-intensity monitoring efforts. Given these costs and the desire of the regulator to maximize social welfare, it is shown that a restricted trading program (ETS-1) with monitoring costs of \$1.50 per acre to determine fertilizer application methods resulted in the highest social welfare (\$3,230,794) across the chosen policies. This was approximately 11% higher than the first-best policy, which required a greater investment in monitoring equipment. Both of these trading programs outperformed by more than 29% an equivalent policy requiring uniform abatement across all sources. Finally, agricultural crop producers would prefer the restricted trading program to the less restrictive trading program because of decreased abatement and increased permit prices.

It should be noted that these results are tempered by many factors omitted from consideration. For example, this analysis has based permit allocations and trades on expected abatement levels. In such a case, the trading ratio is assumed to be 1:1 for point and nonpoint sources, essentially treating nonpoint sources as a special case of point sources (Xepapadeas, 1991). When this trading ratio exceeds parity to correct for uncertain nonpoint source discharges, the expected gains to trading will diminish (Malik, Letson, and Crutchfield, 1993; Hoag and Hughes-Popp, 1997). The effect of changing trading ratios on the incentives to misrepresent abatement efforts is unclear. In addition, the assumptions surrounding monitoring and enforcement could be relaxed in future research to include heterogeneous auditing probabilities, detection probabilities, and enforcement costs.

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