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The Design and Comparative Economic Performance of Alternative Second-Best Point/Nonpoint Trading Markets

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Abstract

There is considerable interest in the use of pollution trading between point and nonpoint sources to improve the cost-effectiveness of water pollution control, but little literature to guide the design of trading systems involving nonpoint sources. We explore the design of two types of trading systems that would allow trading among and between point and nonpoint sources.

Introduction

Pollution trading is gaining increasing acceptance as a means for achieving emissions reductions. The main appeal of trading is its potential to achieve environmental goals at lower social cost than the command and control instruments that have been the dominant approach to pollution control in the U.S. and other developed countries [see e.g., Baumol and Oates, 1988; Hahn, 1989; Hanley et al., 1997; Tietenberg, 1995a, b]. Air- and water-based permit systems have been implemented in the U.S., Germany, Canada, and Chile to control point sources emitting organic effluents, volatile organic compounds, carbon monoxide, sulfur dioxide, particulates, and nitrogen oxides [Tietenberg, 1995a, b]. Proposed future applications include an international market for reducing emissions of greenhouse gases (e.g., carbon trading under the Kyoto Protocol). There is also a growing interest in broadening pollution trading systems to include nonpoint sources of water pollution.

Nonpoint source water pollution controls have tended to be weak by comparison to point source pollution controls, limiting water quality improvements in regions where nonpoint sources are an important cause of environmental degradation [Duda, 1993; Shortle and Abler 1997]. Moreover, reliance on point sources in regions where nonpoint sources are important increases the costs of environmental protection by precluding efficient allocation of control between point and nonpoint sources [Freeman, 1990]. In the U.S., the limitations of current approaches, along with the recent emphasis on Total Maximum Daily Load (TMDL) requirements, have led to substantial interest in trading between point and nonpoint sources as a means to strengthen nonpoint pollution controls and to enhance the coordination of point and nonpoint source policies [Elmore et al., 1985; USDA and USEPA, 1998; GLTN, 2000; Faeth, 2000]. Pilot point-nonpoint trading programs were first implemented for the Tar-Pamlico estuary in North Carolina, the Dillon Creek Reservoir in Colorado, and Cherry Creek, Colorado. A recent assessment indicates that the success of these programs has been limited by flaws in their design

[Hoag and Hughes-Popp, 1997]. More recently, a number of other planned or pilot programs are being developed or researched (Table 1).

While there may be significant potential gains from reallocating pollution control between point and nonpoint sources, there are also significant challenges in the design of point/nonpoint trading systems that can realize these gains. Point/nonpoint trading entails a fundamental departure from text book tradeable discharge markets [Crutchfield et al., 1994; Letson, 1992; Malik et al., 1993; Shortle, 1987]. Conventionally, pollution permits define allowable emissions for the permit holder. With tradeable permits, firms can adjust their allowances by buying from or selling to other permit holders subject to rules governing trades. However, because nonpoint emissions cannot be routinely and accurately metered at reasonable cost, and have a significant random component, they cannot be directly traded [Letson, 1992; Malik et al., 1993; Shortle, 1987]. In consequence, a fundamental issue in the design of nonpoint trading programs is what nonpoint sources will trade. Options include inputs that are correlated with pollution flows (e.g., trading point source emissions permits for nonpoint permits restricting the use of polluting inputs such as fertilizers), emissions or loadings estimates constructed from observations of inputs or techniques that influence the distribution of pollution flows (e.g., trading point source emissions permits for nonpoint permits restricting an estimate of field losses of fertilizer residuals to surface or ground waters), and estimated contributions to ambient environmental conditions [Shortle and Abler, 1997].[2]

In this paper, we examine the design and performance of trading systems involving point source emissions and expected nonpoint emissions, and point source emissions and nonpoint source inputs. Ambient trading systems have merit in theory, but may be too complex for practical implementation [Tietenberg, 1995a]. Emissions-for-expected loadings and emissions-for-inputs trading systems are plausible and of significant practical interest. Existing and planned point/nonpoint trading programs are

of the emissions-for-expected loadings type [Crutchfield et al., 1994; Hoag and Hughes-Popp, 1997; Letson, 1992; Malik et al., 1993; Shortle and Abler, 1997], whereby point sources purchase expected loadings reductions from nonpoint sources, under established trading ratios.[3] While we are aware of no actual emissions-for-inputs trading programs, this approach has been proposed for cases where inputs that are highly correlated with nonpoint emissions can be metered at reasonable cost [Hanley et al., 1997; Shortle and Abler, 1997].

Theoretical research has demonstrated that emissions-for-inputs systems can be designed to provide greater economic efficiency, transactions costs aside, than emissions-for-expected loadings systems because they are better able to manage the variability of nonpoint loads [Shortle and Abler, 1997]. However, emissions-for-input systems that can fully exploit this advantage are so complex as to be impractical [Shortle et al., 1998]. For this and other reasons we discuss below, the relevant comparisons are between second-best forms of emissions-for-expected loadings and emissions-for-input trading systems.[4]

In addition to the question of what to trade, another fundamental issue in the design of any trading system is the rate at which nonpoint allowances are traded for point source allowances [Letson, 1992; Malik et al., 1993; Shortle, 1987]. Because nonpoint inputs and expected loadings are imperfect substitutes for point source emissions, trades should not occur at a ratio of one for one. Existing literature provides little guidance, but suggests factors such as risk and relative contributions to ambient pollution are important in the design of first-best markets [Malik et al., 1993; Shortle, 1987]. There is no theoretical or empirical literature to suggest relative values for second-best trading ratios for either system.

This paper begins with a theoretical analysis of second-best emissions-for-expected emissions and emissions-for-inputs trading systems since there does not currently exist a conceptual framework upon

which an empirical examination can be developed. We define the alternative systems and obtain expressions for second-best trading ratios. This enables us to identify factors that will influence the relative performance of the alternative trading systems, and the sign and size of the corresponding trading ratios. In a companion paper [Horan et al., 2001], we build on the theoretical analysis to address questions about the conditions under which one system will outperform another and the likely values of optimal trading ratios. This is accomplished by simulating various trading markets in the Susquehanna River Basin.

A Model of Point Source and Nonpoint Source Pollution

Building on the model of Shortle et al. [1998], assume a particular resource (e.g., a lake) is damaged by a single residual (e.g., nitrogen). The ambient concentration of the residual, a, depends on loadings from nonpoint sources, r_i (i = 1, 2,..., n), point source discharges, e_k ($k = 1, \ldots, s$), natural generation of the pollutant, ζ, stochastic environmental variables that influence transport and fate, δ, and watershed characteristics and parameters, ψ, i.e., $a = a(r_1, r_2, \ldots, r_n, e_1, e_2, \ldots, e_s, \zeta, \delta, \psi)$ $(\partial a/\partial r_i, \partial a/\partial e_i \geq 0 \ \forall i)$. For heuristic purposes, denote point source (PS) polluters as firms and nonpoint source (NPS) polluters as farms.[5] PS emissions are observable and nonstochastic.[6] NPS loadings cannot be observed directly (at least not at an acceptable cost) and, via stochastic variations in environmental drivers (e.g., weather), are stochastic. Accordingly, NPS farms can only influence the distribution of their loadings. Loadings depends on an (mx1) vector of variable inputs, x_i (with jth element x_{ij}), site-specific, stochastic environmental variables, v_i, and site characteristics (e.g., soil type and topography), α_i. The relationship for site i is $r_i = r_i(x_i, v_i, \alpha_i)$.

Cost-effective nonpoint pollution management

Cost-effectiveness is a standard benchmark for analyzing pollution control resource allocations. Useful notions of cost-effectiveness for nonpoint pollution control must consider variations in the ambient impacts of different sources and the natural variability of nonpoint loadings. There are several possibilities. The simplest is a combination of point and nonpoint pollution control efforts that minimizes costs subject to an upper bound on the expected ambient concentration. For instance, if the ambient target is a_0, then the proposed allocation minimizes costs subject to $E\{a(\cdot)\} \leq a_0$. However, this allocation may not have economically desirable properties. An important limitation of this constraint is that it does not explicitly constrain the variation in ambient pollution. An allocation that satisfies the constraint could in principal result in frequent harmful violations of the target. Another approach to defining least-cost allocations uses probabilistic constraints of the form $\text{Prob}(a \geq a_0) \leq \Phi$ $(0 < \Phi < 1)$. This "safety-first" approach has received attention in economic research on pollution control when ambient concentrations are stochastic and is consistent with regulatory approaches to drinking water quality and other types of environmental protection [Beavis and Walker, 1983; Lichtenberg and Zilberman, 1988; Lichtenberg et al., 1989]. The most interesting cost-effectiveness concept when a is stochastic is an upper bound on expected damage costs. Only in this case will allocations that achieve the target at least cost be unambiguously more efficient than allocations that achieve the target at higher cost [Shortle, 1990; Horan, 2001].

We assume a target of the form

$$E\{D(a)\} \leq T \tag{1}$$

where $D(a)$ is continuous and increasing. Constraint (1) is an expected damage cost constraint if $D(a)$ is the damage cost function. For heuristic purposes, $D(a)$ is taken to be the damage cost function; however, the relation defined by $D(a)$ is fairly general and could just as easily encompass a variety of other types of environmental quality constraints. For example, the constraint is simply an upper bound

on the expected ambient concentration if $D' = 1$. If $D(a)$ is quadratic, then the constraint implies an upper bound on a linear combination of the mean and variance of the ambient concentration [Samuelson, 1970], which could represent a deterministic equivalent of probabilistic constraints for some pdf's [Vajda, 1972]. $D(a)$ could also represent $\Phi(a)$, in which case the expectations operator vanishes.

The costs of reducing emissions from point sources of water pollution have been treated extensively in the literature [see Baumol and Oates, 1988; Hanley et al., 1997]. Conventionally, costs are treated as an increasing function of the level of emissions reduction, or abatement. Following this convention, we define the *k*th PS firm's expected pollution control costs to be a function of abatement, denoted $e_{k0} - e_k$, where e_{k0} is some base level of emissions. Given that e_{k0} is a constant, we simplify notation by defining abatement costs as a function of emissions, $c_{ek}(e_k)$ ($c_{ek}^{/} < 0$, $c_{ek}^{//} \geq 0$).

The diffuse and stochastic features of nonpoint loadings require a different approach to the representation of control costs. Nonpoint pollution reductions are achieved by the use of practices that affect the quantity, quality, and timing of pollution loads. These features make routine and reasonably accurate monitoring of the quantity and quality of loads prohibitively expensive in most instances. The high cost of metering along with the stochastic nature of nonpoint loads suggest that compliance with nonpoint controls must be measured in terms of either measurable pollution control practices, or in terms of *estimates* of the impacts of practices on pollution loads. Accordingly, a deterministic abatement cost function of the type conventionally assumed for point sources is not appropriate. Instead, the cost function must be defined in terms of changes in resources controlled by the firm or in terms of changes in selected estimators of performance [Shortle and Dunn, 1986; Shortle, 1990].

For our agricultural example, let $\pi_{ri}(x_i)$ denote the economic returns to the *i*th farm for a vector on farm management choices, *x*. These choices would include both standard production decisions (e.g., the amount of land allocated to particular crops, the use of fertilizer and pesticides, tillage practices) and

also practices undertaken specifically to control pollution (e.g., the use of buffer strips). For simplicity, we will refer to this vector as an input vector. The cost of pollution control activities is by definition the reduction in economic returns that the farmer would incur relative to the case where the farmer is maximizing economic returns without pollution controls [Freeman, 1993], i.e., $c_{ri}(x_i) = \pi^*_{ri} - \pi_{ri}(x_i)$, where π^*_{ri} represents maximized economic returns in the unregulated environment. Thus, $\partial c_{ri}/\partial x_{ij} = -\partial \pi_{ri}/\partial x_{ij}$, which is non-positive for most inputs (except possibly those only involved with abatement). Given these specifications, the least-cost allocation solves $\underset{e_k, x_{ij}}{Min} \quad TC = \sum_{k=1}^{s} c_{ek}(e_k) + \sum_{i=1}^{n} c_{ri}(x_i)$, subject to (1).[7]

Permit Trades Between PS Emissions and NPS Expected Loadings

We now consider an emissions-for-expected loadings (E-EL) trading system. Our primary interest at this point is to gaining insight about the rate at which permits should trade across categories. As in much of the prior literature on emissions trading, we analyze the system under the assumption that the permit market is perfectly competitive [e.g., Montgomery, 1972; Hanley et al., 1997]. We begin with some details of the market. Next we examine how firms will behave in a perfectly competitive trading equilibrium, and based on this behavior, examine the optimal choice of permits to achieve the probabilistic environmental quality goal.

The E-EL system requires two categories of permits: point source permits, $\hat{e}$, and nonpoint source permits, $\hat{r}$. The former are denominated in terms of emissions while the latter are denominated in terms of expected loadings. Firms must have a combination of both types at least equal to their emissions, in the case of point sources, or expected loadings in the case of nonpoint sources.[8] We assume 1:1 trading of permits within source categories, with trading ratios applicable for trades between categories. The cross category trading ratio is denoted t, i.e., $t = |d\hat{r}/d\hat{e}|$.

The restriction of 1:1 trading within categories is analogous to existing trading systems and allows us to focus more directly on trading between rather than within source categories. However, it also implies certain inefficiencies. First, it is well established that 1:1 emissions-for-loadings trades are inefficient when firms' emissions (and/or loadings) have differential marginal environmental impacts [McGartland and Oates, 1985; Montgomery, 1972; Tietenberg, 1995a]. Second, even if the trading system is modified to account for differential impacts (e.g., using spatial trading ratios or zonal permits), permits based on expected loadings would still be inefficient due to the stochastic nature of pollution [Shortle and Dunn, 1986]. Prior work on nonpoint pollution instruments indicates that even if all firms and farms have identical marginal effects, an E-LO trading system can be efficient only if: (i) only one production choice influences pollution, or (ii) the covariance between marginal loadings and the marginal contribution of each farm's loadings to damages is zero $\forall j$ [Horan et al., 1998; Shortle and Dunn, 1986]. This is in contrast to Malik et al. [1993] and Shortle [1990], whose models basically imply that condition (i) holds. In reality, situations in which conditions (i) or (ii) are satisfied are improbable. Thus, the efficiency of E-EL trading is inherently limited by the inability of such trading to fine tune the risk impacts of nonpoint polluters' pollution control decisions.

Denote the market price of expected loadings permits as p_r and the price of emissions permits as p_e. Nonpoint sources will choose inputs, nonpoint source permit holdings, $\hat{r}_i$, and point source permit holdings, $\hat{e}_i$, to minimize costs, $V_i = c_{ri}(x_i) + p_e(\hat{e}_i - \hat{e}_{i0}) + p_r(\hat{r}_i - \hat{r}_{i0})$, subject to the constraint $E\{r_i\} \leq t\hat{e}_i + \hat{r}_i$, where $\hat{r}_{i0}$ and $\hat{e}_{i0}$ are initial nonpoint and point source permits held by farm *i*, respectively. Assuming the expected loadings constraint is satisfied as an equality and, without loss of generality that $\hat{e}_{i0} = 0$, $\hat{r}_i$ can be eliminated as a choice variable. The resulting first order conditions are

$$\frac{\partial V_i}{\partial x_{ij}} = \frac{\partial c_{ri}}{\partial x_{ij}} + p_r E\left\{\frac{\partial r_i}{\partial x_{ij}}\right\} = 0 \quad \forall i, j \tag{2}$$

$$\frac{\partial V_i}{\partial \hat{e}_i} = p_e - p_r t \begin{matrix} > \\ = \\ < \end{matrix} 0 \qquad (3)$$

In a market equilibrium with positive prices for both types of permits, farms will be indifferent between the permits at the margin. Accordingly, (3) will be satisfied as an equality, implying $t = p_e/p_r$ and hence $V_i = c_{ri}(x_i) + p_r[E\{r_i\} - \hat{r}_{i0}]$.

Similarly, point sources will choose emissions levels and permit holdings to minimize costs, $J_k = c_{ek}(e_k) + p_e(\hat{e}_k - \hat{e}_{k0}) + p_r(\hat{r}_k - \hat{r}_{k0})$, subject to the constraint $e_k \le \hat{e}_k + (1/t)\hat{r}_k$. Assuming that the emissions constraint is satisfied as an equality and, without loss of generality, that $\hat{r}_{k0} = 0$, $\hat{e}_k$ can be eliminated as a choice variable. The resulting first order conditions are

$$\frac{\partial J_k}{\partial e_k} = \frac{\partial c_{ek}}{\partial e_k} + p_e = 0 \qquad (4)$$

$$\frac{\partial J_k}{\partial \hat{r}_k} = -(1/t)p_e + p_r \begin{matrix} > \\ = \\ < \end{matrix} 0 \qquad (5)$$

Given indifference between point and nonpoint permits at the margin in a competitive market equilibrium, (5) is satisfied as an equality, implying $t = p_e/p_r$ and hence $J_k = c_{ek}(e_k) + p_e(e_k - \hat{e}_{k0})$.

There are two ways to determine the number of permits and the trading ratio that minimize *TC*, subject to (1). A primal approach would be to choose the optimal trading ratio, *t*, the optimal number of total permits, $\hat{R}$ (any combination of $\hat{r} = \sum_{i=1}^{n} \hat{r}_i$ and $\hat{e} = \sum_{k=1}^{s} \hat{e}_k$ can be chosen such that the condition $\hat{r} + t\hat{e} = \hat{R}$ is satisfied), and distributing the permits according to some rule.[9] In contrast, a dual approach is to take as given the nonpoint source input and point source emissions demand functions that result from first order conditions (2) and (4), $x_i(p_r)$ and $e_k(p_e)$, and choose permit prices optimally. Specifically, the objective function for the dual approach is

$$\underset{p_e, p_r}{Min} \quad TC = \sum_{k=1}^{s} c_{ek}(e_k(p_e)) + \sum_{i=1}^{n} c_{ri}(x_i(p_r))$$
$$\text{s.t.} \quad E\{D(a)\} \le T$$

Using the dual approach, the first order necessary conditions for an interior solution can be used along

with the relationships in (2) and (4) to provide the following expressions for optimal permit prices

$$p_r^* = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} \lambda^* \left[E\{D'(a^*)\} E\left\{\frac{\partial a^*}{\partial r_i}\right\} E\left\{\frac{\partial r_i^*}{\partial x_{ij}}\right\} + cov\left\{D'(a^*), \frac{\partial a^*}{\partial r_i}\right\} E\left\{\frac{\partial r_i^*}{\partial x_{ij}}\right\} + cov\left\{D'(a^*)\frac{\partial a^*}{\partial r_i}, \frac{\partial r_i^*}{\partial x_{ij}}\right\}\right] \kappa_{ij}^*}{\sum_{i=1}^{n}\sum_{j=1}^{m} E\left\{\frac{\partial r_i^*}{\partial x_{ij}}\right\} \kappa_{ij}^*} \quad (6)$$

$$p_e^* = \sum_{k=1}^{s} \lambda^* \left[E\{D'(a^*)\} E\left\{\frac{\partial a^*}{\partial e_k}\right\} + cov\left\{D'(a^*), \frac{\partial a^*}{\partial e_k}\right\}\right] \eta_k^* \quad (7)$$

where λ^* is the shadow price of constraint (1), $\kappa_{ij}^* = (\partial x_{ij}^*/\partial p_r)/(\sum_{i=1}^{n}\sum_{j=1}^{m} \partial x_{ij}^*/\partial p_r)$, $\eta_k^* = (\partial e_k^*/\partial p_e)/(\sum_{k=1}^{s} \partial e_k^*/\partial p_e))$, and r_i^* and a^* are functions of e_k^* and x_{ij}^*, which along with λ^* are the solutions to (1), (2) , (4), the first order conditions for p_e and p_r, and the zero profit conditions defining entry and exit, $V_n = 0$ and $J_s = 0$.[10]

Interpreting κ_{ij} as a weight (since $\sum_{i=1}^{n}\sum_{j=1}^{m} \kappa_{ij} = 1$), the numerator of the expression for p_r^* is the expected marginal social cost of input use, averaged across all farms and inputs. The denominator is the expected marginal contribution of input use in loadings production, averaged across all farms and inputs. The averaging of impacts across all farms in equation (6) is a consequence of the restriction of a 1:1 trading ratio within the nonpoint source category, and the averaging of impacts across all inputs is due to the use of a loadings-based instrument rather than an input-based instrument for nonpoint sources. The result is that the second-best price, p_r^*, does not give farms incentives to exploit differences in their relative marginal environmental impacts as a differentiated price system (i.e., one that would emerge from having differentiated trading ratios) would. The degree to which this creates inefficiencies depends on the degree of heterogeneity marginal impacts and on correlations between key environmental and cost relationships. For example, we suspect the efficiency loss may be diminished when there is a positive correlation between marginal loadings and marginal ambient impacts and/or

when there is a negative correlation between marginal abatement costs and marginal ambient impacts.

The second-best price, p_r^*, also does not give farms incentives to exploit differences in risk-effects among inputs. The risk-effects are represented by the covariance terms on the RHS of (6). If damages are convex in *a*, then the covariance term $cov\{D'(a^*), \partial a^*/\partial r_i\}$ is of the same sign as $\partial Var(a^*)/\partial r_i$.[11] Thus, if increased loadings increase the variance of ambient pollution and hence damages (on average across farms), then average risk is increased and p_r^* is larger, other things equal. Similarly, if damages are convex in loadings, then the covariance term $cov\{D'(a^*)\partial a^*/\partial r_i, \partial r_i^*/\partial x_{ij}\}$ is of the same sign as $\partial Var(r^*)/\partial x_j$. Thus, if increased input use increases the variance of loadings and hence damages (on average across inputs), then average risk is increased and p_r^* is larger, other things equal. In contrast, average risk is reduced and p_r^* is smaller when damages are concave in ambient pollution or loadings.

Interpreting η_k as a weight (since $\sum_{k=1}^{s} \eta_k = 1$), the emissions permit price p_e^* equals the expected marginal social cost of emissions, averaged across firms. The averaging of impacts across firms is again a consequence of the restriction of a 1:1 trading ratio within the point source category and implies cost-increasing inefficiencies in the allocation of pollution control efforts (to varying degrees depending on correlations between key relationships). The inefficiencies occur because p_e^* does not give firms incentives to exploit differences in their relative marginal environmental impacts, as a differentiated price system would, or incentives to exploit differences in risk-effects among firms. Risk is represented by the covariance terms on the RHS of (7). The *k*th covariance term is of the same sign as $\partial Var\{a^*\}/\partial e_k$ when *D* is convex in *a*. If increases in emissions increase the variance of *a* and *D* (on average across firms), then average risk and hence p_e^* are increased, other things equal. The opposite is true when *D* is concave in *a*.

As discussed above, the second best trading ratio is simply $t = p_e^*/p_r^*$,

$$t = \frac{\theta \sum_{k=1}^{s} \lambda^* \left[E\{D'(a^*)\} E\left\{\frac{\partial a^*}{\partial e_k}\right\} + cov\left\{D'(a^*), \frac{\partial a^*}{\partial e_k}\right\}\right] \eta_k^*}{\sum_{i=1}^{n}\sum_{j=1}^{m} \lambda^* \left[E\{D'(a^*)\} E\left\{\frac{\partial a^*}{\partial r_i}\right\} E\left\{\frac{\partial r_i^*}{\partial x_{ij}}\right\} + cov\left\{D'(a^*), \frac{\partial a^*}{\partial r_i}\right\} E\left\{\frac{\partial r_i^*}{\partial x_{ij}}\right\} + cov\left\{D'(a^*)\frac{\partial a^*}{\partial r_i}, \frac{\partial r_i^*}{\partial x_{ij}}\right\}\right] \kappa_{ij}^*} \quad (8)$$

where $\theta = \sum_{i=1}^{n}\sum_{j=1}^{m} E\{\partial r_i^* / \partial x_{ij}\}\kappa_{ij}^*$. A ratio t =1 implies indifference at the margin between the source of pollution reduction. Ratios greater than one imply a high cost of NPS control relative to PS control and thus a preference for point source reductions at the margin. The reverse is true for ratios of *less than one*.

If risk-effects are negligible (i.e., if each of the covariance terms vanishes), then the ratio is a weighted average of the expected marginal ambient impacts of point sources to the expected marginal ambient impacts of nonpoint sources, i.e.,

$$t = \frac{\sum_{k=1}^{s} E\left\{\frac{\partial a^*}{\partial e_k}\right\} \eta_k^*}{\sum_{i=1}^{n}\sum_{j=1}^{m} E\left\{\frac{\partial a^*}{\partial r_i}\right\} \theta_{ij}}$$

where $\theta_{ij} = E\{\partial r_{ij}/\partial x_{ij}\}\kappa_{ij}/\theta$ $(\sum_{i=1}^{n}\sum_{j=1}^{m} \theta_{ij} = 1)$.[12] This ratio will be unity in the special case of uniformly transported and mixed pollutants. Alternatively, with non-uniformly mixed pollutants, t>1 in watersheds in which, on average, point sources have a larger expected marginal contribution to ambient pollution than nonpoint sources, and t<1 in the opposite situation.

The variance and covariance terms in (8) adjust t to account for the variability (risk) associated with pollution from each source, and represent the average contributions of risk from each production choice. With convex damages, if increased input use increases the variance of ambient pollution and/or loadings (on average, across farms and inputs), then average risk is increased and t is adjusted downward so that fewer NPS permits trade for one PS permit (t is adjusted upward for concave damages). Similarly, if increased emissions increase the variance of ambient pollution (on average, across firms), then

average risk is increased and *t* is adjusted upward so that more NPS permits trade for one PS permit (*t* is adjusted downward for concave damages). In each case, greater control of a particular source category is encouraged when that source category is an important source of risk and when risk is socially costly (as it is for convex damages). In general, however, the signs of the covariance terms are ambiguous.

These findings for the second-best E-EL trading ratio are qualitatively similar to those of Shortle [1987] and Malik et al. [1993] for first-best ratios. However, an important difference is the effect of the restriction of 1:1 trading between source categories (as reflected by the averaging of impacts across farms) and the inability to account for input-specific risk-effects (as reflected by the averaging of impacts across inputs). As described above in relation to the optimal prices, the second-best trading ratio is likely to be significantly influenced by correlations between key cost and environmental relationships.

A Permit Market Based on PS Emissions and NPS Inputs

We now consider an emissions-for-inputs (E-I) trading system. As above, we begin with some details of the market, examine how firms will behave in a perfectly competitive trading equilibrium, and based on this behavior, examine the optimal choice of permits to achieve the probabilistic environmental quality goal.

As with E-EL trading, the E-I system will require multiple categories of permits. PS permits are denominated in terms of emissions as in the E-EL system. NPS permits are differentiated further and denominated in terms of specific inputs. Let z_i denote the $(m' \times 1)$ vector of inputs for which a permit is needed, and let y_i denote the $([m - m'] \times 1)$ vector of inputs that can be used without a permit ($x_i' = [y_i \;\; z_i]$). Input permits are denoted $\hat{z}_j$ $(j = 1, \ldots, m')$. We assume (i) 1:1 trading of permits within source categories, with trading ratios applicable for trades between source categories, $t_u = |d\hat{z}_u / d\hat{e}|$, and input categories, $t_{ul} = |d\hat{z}_l / d\hat{z}_u|$, and (ii) only a subset of inputs are traded (i.e.,

$m' \leq m$). Like our assumption of 1:1 trading within categories for the E-EL system, condition (i) is more restrictive than necessary and implies certain inefficiencies. However, as above this allows us to focus on trading between source categories. Condition (ii) is a practical consideration because it will likely be difficult and costly to monitor and set up trading systems for all inputs that affect loadings (Shortle et al., 1998). For example, the quantity of fertilizer a farmer purchases can be relatively easy to track, and tradeable rights for fertilizer application are quite plausible. But the same is not true for a range of other factors that affect nutrient losses to water resources.

Define the permit price of the *j*th nonpoint input by p_{rj}. Given this specification and using an approach similar to the one used in defining restricted profits for an expected loadings permit system, each farm will choose input levels to minimize expected control costs, $V_i = c_{ri}(z_i, y_{ij}) + \sum_{j=1}^{m'} p_{rj}[z_{ij} - \hat{z}_{ij0}]$. Assuming an interior solution, the first order necessary conditions for a maximum are

$$\frac{\partial c_{ri}}{\partial z_{ij}} + p_{rj} = 0 \quad \forall i, j \tag{9}$$

$$\frac{\partial c_{ri}}{\partial y_{ij}} = 0 \quad \forall i, j \tag{10}$$

Solution to (9)-(10) yields input choices as functions of the permit prices for all inputs (i.e., $z_{ij} = z_{ij}(p_{rI})$ and $y_{ij} = y_{ij}(p_{rI})$, where p_{rI} is an (m' x 1) vector with *j*th element p_{rj}). In addition, without any additional instruments, farms will enter/exit the industry until the marginal farm earns zero profits (i.e., $V_n = 0$). The optimal number of permits and the trading ratios are determined, using a dual approach, by taking all input demand functions as well as emissions demand functions as given and choosing input and emissions permit prices to solve

$$\underset{p_e, p_{rj}}{Min} \quad TC = \sum_{k=1}^{s} c_{ek}(e_k(p_e)) + \sum_{i=1}^{n} c_{ri}(x_i(p_{rI}))$$
$$\text{s.t.} \quad E\{D(a)\} \leq T$$

The first order conditions for this problem can be used along with the relationships in (9) and (10) to

provide the following expression for the optimal permit price for the *j*th input

$$p_{ru}^{**} = \sum_{i=1}^{n} \lambda^{**} b(z_{iu}^{**}) \rho_{iu}^{**} + \sum_{i=1}^{n} \sum_{j \neq u}^{m'} \left[\lambda^{**} b(z_{ij}^{**}) + \frac{\partial c_{ri}^{**}}{\partial z_{ij}} \right] \omega_{iju}^{**} \rho_{iu}^{**} + \sum_{i=1}^{n} \sum_{j=1}^{m'-m} \lambda^{**} b(y_{ij}^{**}) \gamma_{iju}^{**} \rho_{iu}^{**} \quad \forall u \quad (11)$$

where

$$b(x_{iu}^{**}) = E\left\{D'(a^{**})\right\} E\left\{\frac{\partial a^{**}}{\partial r_i}\right\} E\left\{\frac{\partial r_i^{**}}{\partial x_{iu}}\right\} + cov\left\{D'(a^{**}), \frac{\partial a^{**}}{\partial r_i}\right\} E\left\{\frac{\partial r_i^{**}}{\partial x_{iu}}\right\} + cov\left\{D'(a^{**}) \frac{\partial a^{**}}{\partial r_i}, \frac{\partial r_i^{**}}{\partial x_{iu}}\right\},$$

$$\rho_{iu}^{**} = (\partial z_{iu}^{**} / \partial p_{ru}) / \sum_{i=1}^{n} (\partial z_{iu}^{**} / \partial p_{ru}), \ \omega_{iju}^{**} = \frac{\partial z_{ij}^{**} / \partial p_{ru}}{\partial z_{iu}^{**} / \partial p_{ru}}, \text{and } \gamma_{iju}^{**} = \frac{\partial y_{ij}^{**} / \partial p_{ru}}{\partial z_{iu}^{**} / \partial p_{ru}}, \text{and } z_{ij}^{**}, \ y_{ij}^{**}, \text{and } \lambda^{**}$$

are the solutions to (9), (10), the first order conditions for $\square_e$ and p_{ru}, and the zero profit conditions. The optimal emissions permit price, p_e^{**}, is of the same form as in (7), evaluated at the new optimum. These prices the same as those that would result from a primal approach in which the regulatory agency chooses the optimal trading ratios for point and nonpoint sources, the optimal number of total permits, and distributing the permits according to some rule. As with E-EL trading, the initial permit allocation for either source (e.g., point sources) and/or for any inputs may be greater than the optimal number of permits for that source and/or inputs provided the initial permit allocation for the other source (e.g., nonpoint polluters) and/or inputs is offset by an appropriate amount according to the trading ratios.

If $p_{ru}^{**} < 0$, then the market must be designed so that permits allow farmers to reduce their input use from a minimum level. For example, farmers may be required to have a one acre buffer strip to reduce loadings. Under a permit system, farmers would pay $-p_{ru}^{**}$ for a permit that allows them to reduce the required buffer area by one-half acre. Permit price p_{ru}^{**} may be negative for inputs that reduce loadings (i.e., for which $\partial r_i / \partial z_{ij} < 0$). However, the sign of p_{ru}^{**} depends on input substitution and output effects. For example, the permit price of a pollution-decreasing input will be positive if an increase in the use of the input is associated with increased demand for the use of pollution-increasing

inputs, resulting in adverse environmental consequences.

The first term on the RHS of (11) can be interpreted as the average change in expected social costs that result due to an increase in the use of the *u*th restricted input at the margin. The term ω_{iju}^{**} is the rate of substitution of farm *i*'s use of the *j*th restricted input for the *u*th restricted input. Thus, the second term on the RHS of (11) accounts for the average marginal impacts of (restricted) input substitution on expected social and private costs. The term γ_{iju}^{**} is the rate of substitution of farm *i*'s use of the *j*th unrestricted input for the *u*th restricted input. Thus, the third term on the RHS of (11) accounts for the average marginal impacts of (unrestricted) input substitution on expected social costs. This term reflects the restriction of a truncated input permit base and implies inefficiencies because p_{ru}^{**} does not give farms incentives to consider the environmental impacts of all of their inputs. The averaging of all of these impacts across farms reflects the restriction of a 1:1 trading ratio within the nonpoint source category. The averaging implies cost-increasing inefficiencies in the allocation of pollution control efforts because, unlike a differentiated price system, p_{ru}^{**} does not give farms incentives to exploit differences in their relative marginal environmental impacts. Included among these inefficiencies is the inability to target individual sources according to their risk-effects. As with the E-EL system, the degree of inefficiency depends on correlations between key environmental and cost relationships. For example, we suspect the efficiency loss may be diminished when there is a negative correlation between marginal costs of input use and marginal ambient impacts.

The impact of risk on p_{ru}^{**} can be seen by the covariance terms. These terms are signed as described above for E-EL trading, and their impacts are intuitive. When damages are convex (concave), risk and hence p_{ru}^{**} are increased (decreased) when an increase in the use of the input increases the variance of *a* and hence damages on average. Similarly, when damages are convex (concave), risk and hence p_{ru}^{**} are increased (decreased) when substitution away from more expensive and/or restricted inputs

towards less expensive and/or unrestricted inputs has the net effect of increasing the variance of *a* on average. The averaging of farm risk-effects and the truncated input permit base create inefficiencies because p_{ru}^{**} is unable to transmit information about individual sources of risk.

The optimal trading ratio involving point source emissions and the *u*th nonpoint input is $t_u = p_e / p_{ru}$,

$$t_u = \frac{\sum_{k=1}^{s} \lambda^{**}\left[E\{D'(a^{**})\}E\left\{\frac{\partial a^{**}}{\partial e_k}\right\} + cov\left\{D'(a^{**}),\ \frac{\partial a^{**}}{\partial e_k}\right\}\right]\eta_k^{**}}{\sum_{i=1}^{n} \lambda^{**} b(z_{iu}^{**})\rho_{iu}^{**} + \sum_{i=1}^{n}\sum_{j\neq u}^{m'}\left[\lambda^{**} b(z_{ij}^{**}) + \frac{\partial c_{ri}^{**}}{\partial z_{ij}}\right]\omega_{iju}^{**}\rho_{iu}^{**} + \sum_{i=1}^{n}\sum_{j=1}^{m'-m} \lambda^{**} b(y_{ij}^{**})\gamma_{iju}^{**}\rho_{iu}^{**}} \quad \forall\, u \qquad (12)$$

Similar to the ratio for E-EL trading, when risk-effects and substitution effects are negligible, t_u is simply the ratio of the average expected marginal ambient contribution of emissions to the average expected marginal ambient contribution of input *u*,

$$t_u = \frac{\sum_{k=1} E\left\{\frac{\partial a^{**}}{\partial e_k}\right\}\eta_k^{**}}{\sum_{i=1}^{n} E\left\{\frac{\partial a^{**}}{\partial r_i}\right\}E\left\{\frac{\partial r_i^{**}}{\partial z_{iu}}\right\}\rho_{iu}^{**}} \quad \forall\, u$$

The absolute value of this term is less than one if (on average) the absolute marginal ambient impact of emissions is greater than that of the *u*th input, greater than one if (on average) the absolute marginal ambient impact of emissions is less than that of the *u*th input, and equal to one if (on average) the absolute marginal ambient impacts of emissions and the *u*th input are equal.

Additional adjustments are required when risk-effects and substitution effects are important. First, consider the impacts of risk-effects, assuming damages are convex in ambient pollution and loadings. Essentially, if increased input use increases the variance of ambient pollution and/or loadings (on average, across farms), then average risk is increased and t_u is adjusted downward so that fewer NPS permits trade

for one PS permit. A downward adjustment may also be required if substitution away from more expensive and/or restricted inputs towards less expensive and/or unrestricted inputs has the net effect of increasing the variance of *a* or loadings on average. The averaging of farm risk-effects and the truncated input permit base create inefficiencies because t_u is unable to transmit information about individual sources of risk. Similarly, if increased emissions increase the variance of ambient pollution (on average, across firms), then average risk is increased and t_u is adjusted upward so that more NPS permits trade for one PS permit. In each case, greater control of a particular source category is encouraged when that source category is an important source of risk, which is socially costly. In general, however, the signs of the adjustments are ambiguous. Adjustments occur in the opposite direction when damages are concave in ambient pollution or loadings.

Second, consider the impacts of substitution effects. If increased pollution control related to the *u*th input increases undesirable substitution effects (in terms of impacts on the environmental constraint or control costs) on average, then the effect is to increase t_u and make it more expensive for point sources to purchase NPS permits, leaving more permits for nonpoint sources and reducing their necessary control efforts. The signs of these adjustments are also generally ambiguous.

Finally, the interpretation for the ratio defining trades between the *u*th and *l*th input, $t_{ul} = p_{ru}/p_{rl}$, is similar to that of t_u. The ratio will make it relatively less expensive to trade for permits for those inputs that have greater expected marginal impacts on ambient pollution on average, and that create greater risk on average. For example, suppose use of input *j* has a high environmental opportunity cost relative to input *l*. The optimal trading ratio in this case will make it less expensive to trade permits denominated in terms of *j* for permits denominated in terms of *l*. With fewer *j*-type permits on the market, less of input *j* will be used in equilibrium.

It is apparent that even less can be said *a priori* about the E-I trading ratio relative to the E-EL

trading ratio. If risk-effects are negligible and permits are defined for all inputs that affect loadings, then the ratio will be a weighted average of the expected marginal ambient impacts of point sources to the expected marginal ambient impacts of the nonpoint source input. This ratio may be more or less than one and will be negative for pollution-reducing inputs, even in the special case of uniformly mixed pollutants. Additional adjustments are needed when risk-effects are important and/or the set of permitted inputs is restricted, but the direction of these adjustments is ambiguous. When the set of inputs subject to permit restrictions is a subset of the all inputs that affect loadings, the ratio is not necessarily negative for pollution-reducing inputs or positive for pollution increasing inputs.

Comparison of Trading Systems

Given the discussion above, the relative efficiency of each trading system is ambiguous without further empirical specification. One important difference between the two systems is that E-I trading allows differential targeting of inputs whereas E-EL trading does not. Differential treatment of inputs may provide advantages to E-I trading relative to E-EL trading in terms of a better ability to fine tune input risk-effects. However, with a uniform trading ratio across nonpoint sources and a truncated permit base, these advantages are diminished. If the risk-effects associated with the use of NPS inputs are very small, then there should be little difference in the performance of the E-EL and E-I systems, given that there are markets for all inputs that affect loadings. Given that the risk-effects are small, we would expect the relative performance of E-EL trading to improve relative to E-I trading as inputs that affect loadings are excluded. Conversely, if risk effects are important, E-I trading may be advantageous relative to E-EL trading provided that the set of inputs in the regulated set is not overly restricted.

Another important difference between the two systems is that the E-EL trading system has the advantages of transmitting more site-specific information to producers about their environmental pressures

(i.e., mean loadings) relative to the E-I system and of indirectly targeting all inputs contributing to loadings. However, these advantages could be diminished with a uniform trading ratio across nonpoint sources, depending on the correlation between key environmental and cost relationships.

Discussion

There has been a growing interest in permit markets as a comprehensive method of controlling both point and nonpoint sources of pollution. However, relatively little economic research has examined the design of trading systems involving nonpoint sources. This paper has considered two types of point/nonpoint trading systems, differentiated by the permit bases used for nonpoint sources. Specifically, we analyzed systems in which nonpoint permits were denominated in terms of expected loadings or production inputs. The second-best construction of these systems limits our ability to compare the relative efficiency of these systems and the relative magnitudes of the corresponding trading ratios on the basis of theoretical properties alone. However, we can identify a number of factors that could influence relative performance of the various systems and also the signs and relative magnitudes of the corresponding trading ratios. In a companion paper [Horan et al., 2001], we show how this information can be used to better understand environmental and economic performance differences and program design issues in an actual watershed.

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Table 1. A Description of Some Existing, Pilot, and Planned Point/Nonpoint Trading Programs

Program	Sources Involved	Pollutants Traded	Primary Nonpoint Sources	PS/NPS Trading Ratio
Cherry Creek, CO	PS/PS and PS/NPS	phosphorous	land use projects managed by Cherry Creek Basin Water Quality Authority	Range from 1.3:1 to 3:1
Chesapeake Bay Program (multi-state)	PS/NPS	nutrients	agriculture and urban	Greater than 1:1 is suggested to deal with uncertainty
Dillon Creek, CO	PS/NPS and NPS/NPS	phosphorous	urban, septic, ski areas	2:1
Fox-Wolf Basin 2000 Project, WI	PS/NPS	nutrients	agriculture	not available
Long Island Sound (multi-state)	PS/PS and (eventually) PS/NPS	nitrogen	not yet identified (small % of total loads)	not available
Lower Boise River, ID	PS/PS and PS/NPS	phosphorous	agriculture	site-specific with uncertainty discount built in
Michigan (statewide)	PS/NPS	nutrients and other	agriculture	2:1 with site-specific factors
Red Cedar River, WI	PS/NPS	phosphorous	agriculture	not yet available
Rock River, WI	PS/NPS	phosphorous	agriculture	site-specific with a base ratio of 1.75:1
Tar-Pamlico, NC	PS/NPS	nutrients	agriculture	3:1 for cropland 2:1 for livestock
Preliminary analyses underway in Ohio, Texas, Maryland, Indiana, Illinois, and Virginia				

Note: This list is not exhaustive. Also, some changes are likely given the preliminary nature of some programs.
Source: Horan, forthcoming.

Endnotes

1. This research was funded in part by Cooperative Agreement number 43-3AEL-8-80058 with the U.S. Department of Agriculture, Economic Research Service, Resource Economics Division. All remaining errors are our own. The views expressed here are the authors' and do not necessarily reflect those of ERS or the USDA.

2. There are a variety of models available for simulating estimated field losses given site-specific input choices and geographic and weather characteristics.

3. Under existing programs, reductions in expected loadings are calculated based on the installation of nonpoint best management practices (BMP's).

4. A first-best trading system minimizes the expected net social costs of pollution control relative to all other systems. A second-best trading system minimizes the expected net social costs of pollution control, subject to certain restrictions on methods of implementation. Such restrictions may reduce the complexity of the system, easing implementation and reducing transactions costs. When transactions costs are considered, a second-best system may be preferred.

5. The term farm is used for heuristic purposes because current U.S. point/nonpoint trading markets are designed with agriculture as the primary target of trading [Hoag and Hughes-Popp, 1997] due to agriculture's role as the leading contributor of polluted runoff. To the extent that agriculture impacts global warming, it could be involved in future trading programs such as one based on carbon.

6. Point emissions are in fact often measured with error and subject to stochastic influences. Nevertheless, this treatment is standard and helps to contrast the typical theoretical treatment of point sources with nonpoint sources.

7. Cost-effectiveness is improved if additional conditions are defined for the number of polluters for each source. In effect, n and s would be choice variables to capture the expected incremental effects of NPS farm n and PS firm s on damages.

8. In existing and planned point/nonpoint trading programs that include agricultural sources, agricultural sources are not required to have permits. Instead, these sources have an implicit, initial right to pollute, which is consistent with having permits equal to unregulated expected loadings levels. Trading occurs as nonpoint sources contract with point sources to reduce expected loadings in exchange for a fee. Such contracts represent the only enforceable regulations on agricultural sources. However, point sources are ultimately held responsible for meeting water quality goals if they are not met through nonpoint source reductions.

9. Options range from public auctions to free-of-charge assignments. See Hanley et al., [1997] for discussion of options and issues.

10. The regulatory agency will not be able to induce optimal entry and exit when only permits are used, and the zero profit conditions are different than the conditions the regulatory agency would optimally choose.

11. Let $f=f(q)$ ($f' , f'' > 0$), where $q=q(h, v)$, h is deterministic and v is a stochastic variable. Then $cov\{f'(q), \partial q/\partial h\}$ is of the same sign as $cov\{q, \partial q/\partial h\} = .5(\partial var\{q\}/\partial h)$, where this equality follows from: $\partial var\{q\}/\partial h = \partial(E\{q^2\} - E\{q\}^2)/\partial h =$ $2(E\{q\partial q/\partial h\} - E\{q\}E\{\partial q/\partial h\}) = 2cov\{q, \partial q/\partial h\}$. If $f'' < 0$, then $cov\{f'(q), \partial q/\partial h\}$ will have the opposite sign relative to $\partial var\{q\}/\partial h$. This result is used throughout the paper, although with different definitions for f, q, and h.

12. Although they are not modeled explicitly, transactions costs (enforcement costs in particular) can influence the optimal values of policy variables such as the trading ratio, thereby affecting the optimal allocation of control between point and nonpoint sources [Malik et al. 1993].