Spatial Heterogeneity
and the Choice of Instruments to Control Nonpoint Pollution

JunJie Wu and Bruce A. Babcock

Working Paper 96-WP 164
August 1996

Center for Agricultural and Rural Development
Iowa State University
Ames, IA 50011-1070

JunJie Wu is a visiting scientist, CARD; and Bruce A. Babcock is an associate professor of economics and head of the Resource and Environmental Policy Division, CARD, Iowa State University.

This research was partially supported by EPA Cooperative Agreement CR822045-01-1. Journal paper No. J-17035 of the Iowa Agriculture and Home Economics Experiment Station, Ames, IA. Project No. 3363.

ABSTRACT

Because it is difficult to monitor emissions by sources in nonpoint pollution and to implement differential taxes and standards, uniform taxes and standards on chemical use are often proposed to control nonpoint pollution. This paper analyzes the relative efficiency of these uniform instruments in the presence of spatial heterogeneity. We demonstrate that the relative slopes of the marginal cost and benefits of chemical use are only one of the factors that affect the relative efficiency. Other factors include correlation between marginal costs and benefits, and the variability of both marginal benefits and the slopes of marginal benefits. In addition, we show how consideration of prohibitive taxes on low-productivity land and nonbinding standards on low-input land affect the relative efficiency.

SPATIAL HETEROGENEITY
AND THE CHOICE OF INSTRUMENTS TO CONTROL NONPOINT POLLUTION

I. Introduction

Environmental authorities face at least three difficulties in designing policies to control nonpoint pollution. First, they cannot employ emission-based instruments because, by definition, emissions cannot be monitored by sources in nonpoint pollution (Shortle and Dunn [14]). Second, they are often uncertain about the costs and benefits of pollution abatement. This uncertainty may come from either imperfect information about the true costs and benefits of pollution abatement or from stochastic factors such as weather. This difficulty is not unique in the control of nonpoint pollution. There is a large body of literature on the choice of pollution control instruments under uncertainty (see, e.g., Weitzman [18], Adar and Griffin [1], Fishelson [6], Roberts and Spence [12],Yohe [17]). These studies, however, give limited insight into control of nonpoint pollution because they generally assume that emissions can be monitored by source. Third, the source of nonpoint pollution is typically from areas with diverse physical characteristics and production systems. Because of this spatial heterogeneity, environmental authorities often find that the information they need for policy design is known only by those who are to be regulated. This type of information asymmetry has been previously recognized and has motivated an interest in the design of incentive schemes for eliciting truthful revelation of information to environmental authorities (see, e.g., Groves [5]; Weitzman [19]; Kwerel [10]; and Dasgupta, Hammond, and Maskin [3]). Incentive schemes that can achieve such revelation, in principle, have been identified for nonstochastic emissions (Dasgupta, Hammond, and Maskin [3]). But application of these emission-based schemes to nonpoint pollution control is infeasible because of difficulties of measuring discharges from individual sources.

Accordingly, the literature on nonpoint pollution control has focused on indirect instruments, especially control over firms' input decisions or management practices. Several theoretical analyses have attempted to design these instruments to achieve optimal solutions. Segerson [13] developed a general incentive scheme for controlling nonpoint pollution, whereby polluters would be subject to a tax based, not on their emissions, but on the observed level of environmental quality. Segerson [13] showed that such a scheme can induce efficient abatement and entry/exit behavior and avoid free-rider problems. Two disadvantages of this scheme limit its practical application, however. First, it requires firm-level information on abatement costs, damages from ambient pollution, and the effects of individual abatement on the ambient level. Second, such a scheme implies differential or discriminatory taxation. Griffin and Bromley [4] analyzed the cost effectiveness of incentives and standards applied to agricultural runoff or management practices assuming no uncertainty. They concluded that all four policies are equally effective when properly specified. But optimum control on management practices must be accomplished using differential incentives or standards. Shortle and Dunn [14] reevaluated versions of these four strategies by incorporating uncertainty and information asymmetry. They found that management-practice incentives are generally more efficient than the other three strategies in the limiting case of a single farm. Although they did not extend this result to heterogeneous sources, they argued that it is likely to hold in this case as well. In contrast to Griffin and Bromley's [4] conclusion, Shortle and Dunn [14] found that none of these four strategies can be specified to attain the social optimum when there are multiple sources of pollution.

Because it is difficult, both politically and administratively, to implement differential taxes and standards, a number of empirical studies have evaluated uniform input-use taxes and standards for controlling nonpoint-source water pollution. Most of these studies (e.g., Johnson, Adams, and Perry [9]; Taylor, Adams, and Miller [16]; and Mapp et al. [11]) evaluate the effects of specific policy changes (e.g., a 100% nitrogen-use tax or a one-third nitrogen use reduction) on farm income and water quality. Two recent empirical studies (Wu et al. [20]; Helfand and House [7]) evaluated the relative efficiency of uniform input-use taxes and standards for controlling nitrate water pollution. These case studies, however, do not provide general conditions under which the relative efficiency of input-use taxes and standards can be judged.

The primary objective of this study is to provide these conditions by focusing on the effect of spatial heterogeneity on the efficiency of a uniform chemical tax relative to a uniform chemical use standard in agriculture. Spatial heterogeneity can be viewed as one source of uncertainty on the part of regulators who rarely have complete information about individual farms' physical characteristics. Environmental economists typically judge the comparative advantage of price over quantity instruments under uncertainty by the relative slopes of the marginal cost and benefit functions. Stavins [15] demonstrated convincingly that the presence of correlated marginal costs and benefits can reverse the typical prescription of a price instrument.

In this paper we also demonstrate that the relative slopes of the marginal cost and benefits of chemical use are only one of the factors that affect the advantage of a uniform tax over a uniform standard. Other factors include correlation between marginal costs and marginal benefits and the variability of both marginal benefits and the slopes of marginal benefits. In addition, we show how consideration of prohibitive taxes on low productivity land and nonbinding standards on land where marginal benefits decline rapidly affect the comparative advantage of a uniform tax.

II. Uncertainty and Spatial Heterogeneity

Consider a region where nonpoint pollution from agriculture can be reduced by using less of a chemical. Agricultural land in the region is distinguished by a set of physical attributes, denoted μ, that affect both agricultural productivity and the production of pollution. Let $B(q,\mu,\theta)$ be the net returns on type-μ land when the chemical application rate is q, where θ is a random variable representing stochastic weather conditions such as rainfall. That is, $B(q,\mu,\theta) = Pf(q,\mu,\theta) - wq$ where *P* is output price, *f*( ) is the per acre production function and *w* is the per-unit cost of *q*. Let $C(q,\mu,\eta)$ be the per acre pollution cost (damage) on type-μ land, where η is a random variable. $C(q,\mu,\eta)$ is stochastic either because pollution costs may be imperfectly known or because random variables such as weather affect pollution damage. It is assumed that $B_1(q,\mu,\theta) \geq 0$, $B_{11}(q,\mu,\theta) \leq 0$, $C_1(q,\mu,\eta) \geq 0$, and $C_{11}(q,\mu,\eta) \geq 0$, where subscripts denote partial derivatives.[1]

To delimit the circumstances under which uncertainty matters, it is necessary to distinguish the types and sources of uncertainty. First, producers are assumed to make their chemical use decisions before the realization of stochastic weather, and both producers and the government have identical information about weather. Second, producers are assumed to know the physical characteristics of their own land, but the agency does not have this information. The agency, however, is assumed to know the probability distribution of the physical characteristics and can use this information in policy formation. In this way spatial uncertainty differs fundamentally from weather uncertainty because, although the agency can obtain information about each individual farm's physical attributes through data collection efforts, they are always uncertain of weather and the true costs of pollution. Finally, it is assumed that producers and the agency may have the same or different information about the distribution of the random variables affecting the pollution costs of chemical use.

The socially optimal *ex ante* application rate of the chemical on type-μ land, $q^*(\mu)$, is given by

$$\max_{q} \; E\left[B(q,\mu,\theta) - C(q,\mu,\eta)\right], \tag{1}$$

where E is the expectation operator taken with respect to θ and η. The first-order condition to this maximization problem is

$$E\left[B_1(q^*,\mu,\theta)\right] = E\left[C_1(q^*,\mu,\eta)\right]. \tag{2}$$

If the agency knows each individual farm's physical characteristics, then it makes no difference whether it imposes the differential chemical-use standards $q^*(\mu)$ or levies the differential chemical-use taxes $\tau^*(\mu) \equiv E[C_1(q^*(\mu),\mu,\eta)]$ and has producers maximize their expected profits,

$$\max_{q} \; E\left[B(q,\mu,\theta)\right] - \tau^*(\mu)q. \tag{3}$$

This equivalence between taxes and standards depends on two assumptions: (1) producers make chemical use decisions before weather is observed and they have the same information about weather as does the agency, and (2) the agency knows each individual farm's physical attributes and can impose differential taxes or standards. Previous studies (Weitzman [19]; Adar and Griffin [1]; Fishelson [6]) focused on the choice of policy instruments under uncertainty when the first assumption is violated. These studies found that there is a fundamental asymmetry between taxes and standards when uncertainty in pollution control costs exists only at the agency. In our model, that is equivalent to assuming that the farmer learns about θ before choosing *q*.

In a seminal article, Weitzman [18] modeled such an asymmetry for the case in which producers are initially uncertain of the true cost of production but can eventually find it out by "testing out the relevant technological alternatives" or by "trial and error" (p. 480). So Weitzman effectively assumed that uncertainty in pollution control costs will eventually exist only at the agency level. Because Weitzman allowed differential standards and taxes in his multi-production unit case, his results correspond to the situation in which only the first assumption is violated. The same is true for the results derived by Adar and Griffin [1] and Fishelson [6]. To our knowledge, no study has examined the general implication of the second assumption on the choice between taxes and standards.

This lack of analysis is somewhat surprising because spatial uncertainty is a primary reason why nonpoint pollution is difficult to control. Even if the agency knows the cost and benefit functions of chemical use and can determine the optimal application rates or taxes for each type of land, it is politically infeasible and technically difficult to apply differential taxes or standards. Information asymmetry and moral hazard may be involved because physical characteristics are frequently known only by the producers. Even if the agency can identify individual farms' physical characteristics, the amounts of the chemical used by individuals must be monitored. Otherwise, those facing lower prices could buy large amounts and resell to those who would otherwise face higher taxes. Because of these difficulties, uniform policies are often used or proposed to control agricultural nonpoint source pollution (Helfand and House [7]). In the next section, we examine the effect of spatial heterogeneity of physical characteristics on the choice between uniform taxes and uniform standards.

III. The Effect of Spatial Heterogeneity

When a uniform tax τ is levied on the chemical, each producer will choose the application rate that maximizes expected net returns after the tax

$$\max_{q} \; B(q,\mu) - \tau q, \quad \text{s.t. } q \geq 0, \tag{4}$$

where $B(q,\mu) = E\left[B(q,\mu,\theta)\right]$. Likewise, in the remainder of this paper, $E\left[C(q,\mu,\eta)\right]$ is simply written as $C(q,\eta)$. The application rate under the tax, $q(\tau,\mu)$, equals zero or satisfies

$$\tau = B_1(q(\tau,\mu),\mu). \tag{5}$$

And $q(\tau,\mu) = 0$ if and only if $\tau \geq B_1(0,\mu)$. To simplify notations, in this section, μ is assumed to be a scalar and is normalized to be in [0, 1], and more chemical is applied to land with a larger μ. Let $\mu(\tau)$ be the solution to $\tau = B_1(0,\mu)$. Then no chemical will be applied to land with $\mu \leq \mu(\tau)$.

The objective of the agency is to find the tax rate that maximizes social surplus from production on all land:

(6)
$$\max_{\tau} \; E_\mu\big[B(q(\tau,\mu),\mu) - C(q(\tau,\mu),\mu)\big] =$$
$$\int_0^{\mu(\tau)} \big[B(0,\mu) - C(0,\mu)\big] f(\mu)d\mu + \int_{\mu(\tau)}^{1} \big[B(q(\tau,\mu),\mu) - C(q(\tau,\mu),\mu)\big] f(\mu)d\mu,$$

where E_μ is the mean operator taken with respect to the physical characteristics, $f(\mu)$ is the probability density function of μ (measuring the spatial distribution of μ in the region). The first-order condition is obtained by differentiating (6) with respect to τ:

(7)
$$\big[B(0,\mu(\tau)) - C(0,\mu(\tau))\big] f(\mu(\tau))\mu'(\tau) +$$
$$-\big[B(q(\tau,\mu(\tau)),\mu(\tau)) - C(q(\tau,\mu(\tau)),\mu(\tau))\big] f(\mu(\tau))\mu'(\tau) +$$
$$\int_{\mu(\tau)}^{1} \big[B_1(q(\tau,\mu),\mu) - C_1(q(\tau,\mu),\mu)\big] q_1(\tau,\mu) f(\mu)d\mu = 0.$$

Since $q(\tau,\mu(\tau)) = 0$, the first and second terms in (7) offset each other. Thus, the optimal tax, $\tau*$, must satisfy

(8)
$$\int_{\mu(\tau*)}^{1} B_1(q(\tau*,\mu),\mu) q_1(\tau*,\mu) f(\mu)d\mu = \int_{\mu(\tau*)}^{1} C_1(q(\tau*,\mu),\mu) q_1(\tau*,\mu) f(\mu)d\mu$$

Divide both side of (8) by $S = \int_{\mu(\tau*)}^{1} f(\mu)d\mu$

(9)

$$E_\mu\big[B_1(q(\tau*,\mu),\mu) q_1(\tau*,\mu) | \tau* < B_1(0,\mu)\big] = E_\mu\big[C_1(q(\tau*,\mu),\mu) q_1(\tau*,\mu) | \tau* < B_1(0,\mu)\big].$$

The first-order condition implies that the average marginal cost under the optimal uniform tax equals the average marginal benefit on land where the chemical is still applied. From Equation (5), Equation (9) can be rewritten as

(10)
$$\tau* = \frac{E_\mu\big[C_1(q(\tau*,\mu),\mu) q_1(\tau*,\mu) | \tau* < B_1(0,\mu)\big]}{E_\mu\big[q_1(\tau*,\mu) | \tau* < B_1(0,\mu)\big]}.$$

Let $q^t(\mu)$ be the application rate on type-μ land under the optimal tax. Then $q^t(\mu) \equiv q(\tau*,\mu)$.

Under a uniform chemical-use standard, a single limit, denoted L, is imposed on all land, and the chemical-use decisions on type-μ land become

(11)
$$\max_{q} \; B(q,\mu) \;\; \text{s.t.} \; q \le L.$$

If the initial application rate is less than the limit, then the chemical-use decision is not affected. If the initial application rate is greater than the limit, then the application rate must be reduced to the limit. Let $q^0(\mu)$ be the initial application rate, where $q^0(\mu)$ satisfies $B_1(q^0(\mu),\mu)=0$. Let $g(L,\mu)$ be the solution to the maximization problem in (11). Then $g(L,\mu)=L$ if $q^0(\mu)\geq L$ and $g(L,\mu)=q^0(\mu)$ if $q^0(\mu)<L$. Let $\mu(L)$ be the solution to $q^0(\mu)=L$. All land with $\mu>\mu(L)$ will be affected by the chemical use standard. The average social surplus from production under the standard will be

(12) $$E_\mu\left[B(g(L,\mu),\mu)-C(g(L,\mu),\mu)\right]=$$

$$\int_0^{\mu(L)}\left[B(q_0(\mu),\mu)-C(q_0(\mu),\mu)\right]f(\mu)d\mu+\int_{\mu(L)}^{1}\left[B(L,\mu)-C(L,\mu)\right]f(\mu)d\mu.$$

The objective of the agency is to find a limit that maximizes (12). The first-order condition for this maximization problem is obtained by differentiating (12) with respect to *L*:

(13) $$\left[B(q_0(\mu(L)),\mu(L))-C(q_0(\mu(L)),\mu(L))\right]f(\mu(L))\mu'(L)+$$

$$-\left[B(L,\mu(L))-C(L,\mu(L))\right]f(\mu(L))\mu'(L)+\int_{\mu(L)}^{1}\left[B_1(L,\mu)-C_1(L,\mu)\right]f(\mu)d\mu=0$$

Because $q_0(\mu(L))=L$, the first and second terms in (13) offset each other. Thus, the optimal limit L^* must satisfy

(14) $$E_\mu\left[B_1(L^*,\mu)\middle|q^0(\mu)\geq L^*\right]=E_\mu\left[C_1(L^*,\mu)\middle|q^0(\mu)\geq L^*\right].$$

Equation (14) indicates that, because the limit does not affect chemical use on land where the limit is nonbinding, it should be set where the mean marginal benefit equals the mean marginal cost for those types of land where the limit is binding. Let $q^r(\mu)$ be the application rate of the chemical on type-μ land under the optimal standard. Then $q^r(\mu)\equiv g(L^*,\mu)$.

Because neither the uniform tax nor the uniform standard is a first-best policy, the relevant question is which one is more efficient. Following Weitzman, the comparative advantage of the uniform tax and the uniform standard is defined as

(15) $$\Re\equiv E_\mu\left\{\left[\left(B(q^t(\mu),\mu)-C(q^t(\mu),\mu)\right)\right]-\left[\left(B(q^r(\mu),\mu)-C(q^r(\mu),\mu)\right)\right]\right\}.$$

$\Re$ is the expected difference in social surplus under the two instruments. The social loss from using a uniform tax rather than a first-best policy is defined as

(16) $$\ell_t \equiv E_\mu\left\{\left[\left(B(q^*(\mu),\mu) - C(q^*(\mu),\mu)\right)\right] - \left[\left(B(q^t(\mu),\mu) - C(q^t(\mu),\mu)\right)\right]\right\}.$$

The social loss from using a uniform standard is similarly defined as

(17) $$\ell_r \equiv E_\mu\left\{\left[\left(B(q^*(\mu),\mu) - C(q^*(\mu),\mu)\right)\right] - \left[\left(B(q^r(\mu),\mu) - C(q^r(\mu),\mu)\right)\right]\right\}.$$

IV. Comparative Advantage

In this section, we identify the factors that determine the relative efficiency of uniform taxes and uniform standards. As in Weitzman [18], the expected cost and benefit functions are assumed to be quadratic:

(18) $$B(q,\mu) = b_0(\mu) + b_1\beta_1(\mu)(q - q^r(\mu)) + \frac{1}{2}b_2\beta_2(\mu)(q - q^r(\mu))^2,$$

(19) $$C(q,\mu) = c_0(\mu) + c_1\alpha_1(\mu)(q - q^r(\mu)) + \frac{1}{2}c_2\alpha_2(\mu)(q - q^r(\mu))^2,$$

where $c_0(\mu) = C(q^r(\mu),\mu)$ and $b_0(\mu) = B(q^r(\mu),\mu)$ are the total cost and benefit of chemical use on type-μ land under the optimal chemical-use standard; b_1, b_2, c_1 and c_2 are fixed coefficients; and $\alpha_1(\mu), \alpha_2(\mu), \beta_1(\mu),$ and $\beta_2(\mu)$ are functions of the physical attributes. Without loss of generality, the means of $\alpha_1(\mu), \alpha_2(\mu), \beta_1(\mu),$ and $1/\beta_2(\mu)$ conditional on $\tau^* < B_1(0,\mu)$ are assumed to be one. We work with $1/\beta_2(\mu)$ rather than $\beta_2(\mu)$ because we want to see how physical characteristics affect the response of the application rate to a tax, $1/B_{11}(q,\mu)$. Note that from Equation (5)

(20) $$E_\mu\left[\frac{\partial q(\tau,\mu)}{\partial \tau}\right] = E_\mu\left[\frac{1}{B_{11}(q,\mu)}\right] = E_\mu\left[\frac{1}{b_2\beta_2(\mu)}\right] = \frac{1}{b_2}.$$

It is evident that $c_1\alpha_1(\mu) = C_1(q^r(\mu),\mu)$ and $b_1\beta_1(\mu) = B_1(q^r(\mu),\mu)$ are the marginal cost and benefit of chemical use under the optimal standard on type-μ land, and $c_1 = E_\mu[c_1\alpha_1(\mu) | \tau^* < B_1(0,\mu)]$ and $E_\mu[b_1\beta_1(\mu) | \tau^* < B_1(0,\mu)] = b_1$ are the mean marginal costs and benefits, evaluated at the application rates under the optimal standard, on lands where the chemical is still applied under the optimal tax. The variance and covariance of these marginal costs and benefits are

(21) $$\sigma_{mc}^2 \equiv c_1^2\left[E_\mu\left(\alpha_1^2(\mu) \middle| \tau^* < B_1(0,\mu)\right) - 1\right],$$

(22) $$\sigma_{mb}^2 \equiv b_1^2\left[E_\mu\left(\beta_1^2(\mu) \middle| \tau^* < B_1(0,\mu)\right) - 1\right],$$

(23) $$\nu_{bc} \equiv c_1 b_1 \left[E_\mu \left(\alpha_1(\mu)\beta_1(\mu) \middle| \tau^* < B_1(0,\mu) \right) - 1 \right].$$

Likewise, $c_2\alpha_2(\mu) = C_{11}(q,\mu)$ and $b_2\beta_2(\mu) = B_{11}(q,\mu)$ are the slopes of the marginal cost and benefit functions on type-μ land. $c_2 = E_\mu[c_2\alpha_2(\mu) | \tau^* < B_1(0,\mu)]$ is the mean of the slopes of the marginal costs on land where the chemical is still used under the optimal tax. $1/b_2\beta_2(\mu)$ is the change in application rate of the chemical in responding to a per unit change in tax rate on type-μ land, and $1/b_2 = E_\mu[1/b_2\beta_2(\mu) | \tau^* < B_1(0,\mu)]$ is the mean of these changes conditional on the chemical still being used under the tax. The variance of $1/b_2\beta_2(\mu)$ on these lands is

(24) $$\sigma_{sb}^2 \equiv \frac{1}{b_2^2}\left[E_\mu \left(\frac{1}{\beta_2^2(\mu)} \middle| \tau^* < B_1(0,\mu) \right) - 1 \right].$$

For simplicity $\alpha_2(\mu)$ and $\beta_2(\mu)$ are assumed not to be correlated with each other or with $\alpha_1(\mu)$ and $\beta_1(\mu)$.

Chemical use under a tax τ can be derived by substituting (18) into (5):

(25) $$q(\tau,\mu) = \begin{cases} q^r(\mu) + \dfrac{\tau - b_1\beta_1(\mu)}{b_2\beta_2(\mu)} & \text{if } \tau < B_1(0,\mu) \\ 0 \ \text{otherwise} \end{cases}.$$

Substitute $q^t(\mu) \equiv q(\tau^*,\mu)$ into (18) and (19) and substitute the resulting values into (15):

(26) $$\begin{aligned} \Re = S \cdot E_\mu \Bigg[& b_1\beta_1 \left(\frac{\tau^*}{b_2\beta_2} - \frac{b_1\beta_1}{b_2\beta_2} \right) + \frac{b_2\beta_2}{2} \left(\frac{\tau^*}{b_2\beta_2} - \frac{b_1\beta_1}{b_2\beta_2} \right)^2 \\ & - c_1\alpha_1 \left(\frac{\tau^*}{b_2\beta_2} - \frac{b_1\beta_1}{b_2\beta_2} \right) - \frac{c_2\alpha_2}{2} \left(\frac{\tau^*}{b_2\beta_2} - \frac{b_1\beta_1}{b_2\beta_2} \right)^2 \Bigg| \tau^* < B_1(0,\mu) \Bigg] \\ & + (1-S) \cdot E_\mu \left\{ [B(0,\mu) - C(0,\mu)] - [B(q^r(\mu),\mu) - C(q^r(\mu),\mu)] \middle| \tau^* \ge B_1(0,\mu) \right\}. \end{aligned}$$

By using Equations (21) to (24) and the independence assumption about $\alpha_1, \alpha_2, \beta_1$, and β_2, Equation (26) can be rewritten as

(27) $$\begin{aligned} \Re = & S\left\{ \frac{b_1\tau^*}{b_2} - \frac{b_1^2}{b_2}\left(1 + \frac{\sigma_{mb}^2}{b_1^2}\right) + \frac{1}{2b_2}\left[(\tau^* - b_1)^2 + \sigma_{mb}^2\right] \right\} \\ & - S\left\{ \frac{c_1\tau^*}{b_2} - \frac{c_1 b_1}{b_2}\left(1 + \frac{\nu_{bc}}{b_1 c_1}\right) + \frac{c_2\left(1 + b_2^2\sigma_{sb}^2\right)}{2b_2^2}\left[(\tau^* - b_1)^2 + \sigma_{mb}^2\right] \right\} \end{aligned}$$

$$+(1-S)\cdot E_{\mu}\left\{q^{r}(\mu)\left[MC\left(0.5q^{r}(\mu),\mu\right)-MB\left(0.5q^{r}(\mu),\mu\right)\right]\Big|\tau^{*}\geq B_{1}(0,\mu))\right\},$$

where $MC(0.5q^{r}(\mu),\mu)$ and $MB(0.5q^{r}(\mu),\mu)$ are the marginal cost and marginal benefit evaluated at half of the application rate under the standard. Combining terms in (27) gives

(28)

$$\Re = S\left\{\frac{b_1-c_1}{b_2}\left(\tau^{*}-b_1\right)+\frac{1}{b_2}\left(\nu_{bc}-\sigma_{mb}^{2}\right)+\frac{1}{2b_2^{2}}\left[b_2-c_2\left(1+b_2^{2}\sigma_{sb}^{2}\right)\right]\left[\left(\tau^{*}-b_1\right)^{2}+\sigma_{mb}^{2}\right]\right\}$$

$$+(1-S)\cdot E_{\mu}\left\{q^{r}(\mu)\left[MC\left(0.5q^{r}(\mu),\mu\right)-MB\left(0.5q^{r}(\mu),\mu\right)\right]\Big|\tau^{*}\geq B_{1}(0,\mu))\right\}.$$

To simplify (28), substitute (25) into the marginal cost and benefit functions and then substitute the results into (10):

(29) $$\tau^{*}=c_1+\frac{c_2(\tau^{*}-b_1)(1+b_2^{2}\sigma_{sb}^{2})}{b_2}$$

or

(30) $$\tau^{*}=\frac{c_1b_2-c_2b_1(1+b_2^{2}\sigma_{sb}^{2})}{b_2-c_2(1+b_2^{2}\sigma_{sb}^{2})}.$$

Substitute (30) into (28) and rearrange the terms:

(31) $$\Re = S\left\{\frac{-(b_1-c_1)^{2}}{2\left[b_2-c_2\left(1+b_2^{2}\sigma_{sb}^{2}\right)\right]}-\frac{c_2\sigma_{sb}^{2}\sigma_{mb}^{2}}{2}-\frac{\sigma_{mb}^{2}(c_2+b_2)}{2b_2^{2}}+\frac{\nu_{bc}}{b_2}\right\}$$

$$+(1-S)\cdot E_{\mu}\left\{q^{r}(\mu)\left[MC\left(0.5q^{r}(\mu),\mu\right)-MB\left(0.5q^{r}(\mu),\mu\right)\right]\Big|\tau^{*}\geq B_{1}(0,\mu))\right\}.$$

Expression (31) reveals the factors that determine the relative advantage of a uniform tax over a uniform standard. First, note that the spatial heterogeneity of social costs does not affect the comparative advantage of uniform taxes and standards so long as the marginal cost and benefit of chemical use are not correlated (i.e., $\nu_{bc}=0$). In this case, the spatial heterogeneity of pollution costs of chemical use affects uniform taxes and standards equally adversely. This is an important result because much more information is available about chemical use benefits than about pollution costs.

This result is illustrated in Figure 1, in which the region is assumed to have only two types of land, and each accounts for 50% of total acreage. MC_1 and MC_2 are the marginal pollution costs of chemical use on the two types of land, and *MB* is their common marginal benefits. The dashed line represents the mean pollution cost of chemical use. Because the marginal benefits of chemical use are the same on the two types of land, chemical use on the two types of land are equally responsive to the tax (i.e., $q_1(\tau,\mu)$ is a constant). In this case, the mean social cost of chemical use equals the mean private benefit under the optimal uniform tax (see Equation 9). Likewise, when the marginal benefits of chemical use are the same on both types of land, a uniform standard would affect chemical use on both types of land because the initial application rates are the same. In this case, the mean social cost of chemical use equals the mean private benefit under the optimal uniform standard (see Equation 14). Thus, the optimal uniform standard and the optimal uniform tax result in the same chemical use and pollution loss on the two types of land. The explanation for this equivalency is that the amount of chemical use, irrespective of the policy instrument, depends solely on the marginal benefit function, which is the same for both types of land, thereby resulting in identical social loss.

The effect on $\Re$ of each of the factors in (31) can best be understood with illustrations. To keep the illustrations reasonably simple and interpretable, we assume first (in Figures 2 - 7) that chemical use is positive on all land at the uniform tax, and the uniform standard is binding on all land. These conditions imply that $S = 1$ and $b_1 = c_1$ in Equation (31).

Deadweight losses, relative to the first-best outcome, from a uniform tax and a uniform standard are shown in Figure 2 for the special case where the covariance, υ_{bc}, is zero and the variance of the slope of marginal benefits, σ_{sb}^2, is zero. In this case, $\Re = -\dfrac{\sigma_{mb}^2(c_2+b_2)}{2b_2^2}$, which is essentially Weitzman's results. Both the optimal tax and the optimal standard are set where expected marginal benefits equal expected marginal cost. The first-best outcome, given by q_1^* and q_2^* in Figure 2, occurs when marginal benefit equals marginal cost. The standard imposes too much control on land 2 and too little control on land 1. If the land areas are equal, the resulting deadweight loss is given by the dark-shaded areas in Figure 1. The tax imposes too little control on land 2 and too much control on land 1. The resulting deadweight loss from the tax is given by the light-shaded areas.

As discussed in Weitzman, an increase in the slope of marginal damage from pollution will decrease the relative advantage of the tax. The effect of a rotation in marginal cost from *MC* to *MC'* is shown in Figure 3 for the special case considered in Figure 2. Such a rotation decreases the variability of first-best application rates, a situation that will tend to favor a uniform standard. In contrast, a decrease in the slope of marginal cost will increase the variability of first-best outcomes and, hence, the relative advantage of the uniform tax.

Another factor that influences the variability of first-best outcomes is the covariance between marginal costs and marginal benefits. Figure 4 shows two marginal benefit curves and two marginal cost curves. When $MC_1 = MC$ and $MC_2 = MC'$, covariance is positive, and the first-best outcomes are given by the points *a* and *b*. A decline in covariance can be shown in Figure 4 by letting $MC_1 = MC'$ and $MC_2 = MC$. The first-best outcomes change to points *c* and *d*. Such a change decreases the deadweight loss from a tax by the light-shaded areas and increases the deadweight loss from a standard by the dark-shaded area in Figure 4. The intuition behind these changes is that a negative covariance implies a greater variability in first-best chemical use rates, which, again, will tend to favor a tax. A positive covariance implies greater uniformity in optimal rates, which will tend to favor a uniform standard. This is exactly what the fourth term in Equation (31) shows. The large effects of correlation shown in Figure 4 are consistent with Stavins's [15] demonstration that this correlation can be sufficiently important to reverse a conventional finding of price and quantity instrument superiority based upon the relative-slope rule.

Figure 5 shows the effect of an increase in the average responsiveness of input use to a tax on deadweight losses. More responsiveness increases both the deadweight losses from the uniform tax as well as the uniform standard. The upper panel shows that when average input use is already relatively responsive, further growth will increase the deadweight loss from a uniform tax by a greater amount than the deadweight loss from a standard. The lower panel shows that the increase in deadweight loss is greater from a uniform standard than a uniform tax when input use is relatively unresponsive to a higher price.

The effect of an increase in variance of responsiveness, holding mean responsiveness constant, is shown in Figure 6. With two marginal benefit curves, one of the curves must become more responsive (MB_1') and one becomes less responsive (MB_2'). As shown in Figure 5, deadweight loss from a uniform tax increases on the more responsive land and it decreases on the less responsive land. Because deadweight losses increase rapidly as marginal benefits become more responsive, there is a net increase in deadweight loss from the uniform tax with an increase in variability of responsiveness. Deadweight loss from the uniform standard also increases on the more responsive land (area F in Figure 6) and decreases on the less responsive land (area A). As shown in Figure 6, the net effect on deadweight loss is small relative to the net change from the uniform tax, so $\Re$ is likely to decrease with an increase in the variance of responsiveness. This effect is reflected by the second term in Equation (31).

Figure 7 illustrates the effects of an increase in the variance of marginal benefits. Higher variance increases the variance of first-best chemical use levels, which will increase the deadweight loss from a uniform standard. The top panel shows that when marginal benefits are relatively responsive to a tax increase, and deadweight losses from a uniform tax are relatively high, then an increase in variance results in a relatively large increase in deadweight losses from the tax, which will tend to decrease $\Re$. The bottom panel shows that an increase in variance will increase $\Re$ when input use is relatively unresponsive because the increase in deadweight loss from the uniform tax will be small.

More exact results are presented in Table 1 for the special case of $S = 1$ and $b_1 = c_1$. Increases in the slope of marginal cost, covariance of marginal costs and marginal benefits, and the variance of input response to a tax all decrease the relative advantage of a uniform tax, as illustrated in Figures 3, 4, and 6. The results in Table 1 show sufficient conditions for signing the ambiguous effects of increasing the average input responsiveness and the variance of marginal benefits, as illustrated in Figures 5 and 7. If covariance is nonnegative and average responsiveness of input use is too inelastic, then higher input responsiveness will increase the advantage of a uniform tax. If the covariance is nonpositive and average input use is quite inelastic, then an increase in responsiveness will decrease the advantage of a uniform tax. And, as shown in Table 1, the effect of an increase in the variance of marginal benefits depends solely on whether the absolute value of b_2 is greater than c_2. If it is, then the variance of marginal benefits increases $\Re$. Otherwise, an increase in variance decreases $\Re$.

Now consider the first term in the first set of braces in Equation (31). Note first that this term is nonnegative and is positive only when $b_1 \neq c_1$. Second, this term is zero when the land where the standard is binding is identical to the land where the chemical is still applied under the tax. In this case, Equation (14) can be rewritten as

(32) $$E_\mu\left[B_1(L^*,\mu)\middle|\tau^* < B_1(0,\mu)\right] = E_\mu\left[C_1(L^*,\mu)\middle|\tau^* < B_1(0,\mu)\right].$$

Substituting (18) and (19) into (32) gives $b_1 = c_1$, and the first term in (31) becomes zero.

There will be a divergence between b_1 and c_1 when (a) there is some land on which the chemical is still applied under the tax and the standard is nonbinding, or (b) there is some land where the tax is prohibitive (chemical use is zero) and the standard is binding. Case (a) is likely to occur on land where marginal benefits are high at low levels of use (so some use is profitable under the tax), but decline rapidly (so the standard is not binding). Case (b) is likely to occur when there are some lands where marginal benefits are low (so chemical use is unprofitable under the tax), but decline slowly (so the standard is binding). First, we show that in case (a), $b_1 < c_1$. By definition,

(33)
$$b_1 = E_\mu\left[B_1(q^r(\mu),\mu)\middle|\tau^* < B_1(0,\mu)\right]$$
$$= S_1 E_\mu\left[B_1(q^0(\mu),\mu)\middle|\tau^* < B_1(0,\mu), L^* > q^0(\mu)\right]$$
$$+S_2 E_\mu\left[B_1(L^*,\mu)\middle|\tau^* < B_1(0,\mu), L^* \le q^0(\mu)\right],$$

where S_1 is the share of land where the tax is nonprohibitive and the standard is nonbinding, and S_2 is the share of land where the tax is nonprohibitive and the standard is binding. In Equation (33), $B_1(q^0(\mu),\mu)=0$ by the definition of $q^0(\mu)$. Also, $E_\mu\left[B_1(L^*,\mu)\middle|\tau^* < B_1(0,\mu), L^* \le q^0(\mu)\right] = E_\mu\left[B_1(L^*,\mu)\middle|L^* \le q_0(\mu)\right]$ because when the standard is binding, the tax is also nonprohibitive in this case. Thus,

(34)
$$b_1 = S_2 E_\mu\left[B_1(L^*,\mu)\middle|L^* \le q^0(\mu)\right].$$

Similarly,

(35)
$$c_1 = E_\mu\left[C_1(q^r(\mu),\mu)\middle|\tau^* < B_1(0,\mu)\right]$$
$$= S_1 E_\mu\left[C_1(q_0(\mu),\mu)\middle|\tau^* < B_1(0,\mu), L^* > q^0(\mu)\right]$$
$$+S_2 E_\mu\left[C_1(L^*,\mu)\middle|L^* \le q^0(\mu)\right].$$

Comparing Equation (35) with Equation (34), and using Equation (14), we obtain

(36) $$b_1 < c_1.$$

Because b_1 and c_1 are the mean of marginal benefits and costs, evaluated at the application rates under the optimal restriction on land where the tax is nonprohibitive, Equation (36) suggests that the nonbinding standard is overly lax on land where the tax is nonprohibitive. To clarify, suppose there is one parcel of land where case (a) applies and the tax is nonprohibitive on the other $N-1$ parcels. If this parcel did not exist, expected marginal cost equals expected marginal benefit under both the tax and the standard, and the relative advantage of the tax is determined by the factors considered in Figures 2 through 7. But now an adjustment must be made for the one parcel where the restriction is not binding. Under the tax, expected marginal benefit continues to equal expected marginal costs across all land (see Equation 9). But under the uniform standard, expected marginal benefit equals expected marginal cost only on the $N-1$ parcels where the restriction is binding (see Equation 14). For the one parcel with the nonbinding restriction, marginal benefit equals zero, which implies that if marginal cost is positive on this parcel, expected marginal benefit is less than expected marginal cost across all tracts of land under the standard. It is this lack of equality between expected marginal benefit and expected marginal cost that results in the positive adjustment to $\Re$.

Now consider case (b). Suppose again that there is only one parcel of land for which the restriction is binding and the tax is prohibitive. Under the tax, expected marginal benefit equals expected marginal cost across the other $N-1$ parcels. By Equation (14), expected marginal benefit equals expected marginal cost under the standard across all N parcels, which implies that expected marginal cost will not equal expected marginal benefit across the $N-1$ parcels unless the standard is optimal on the parcel of land where the tax is prohibitive. Therefore, the tax has an advantage over the standard on the $N-1$ parcels, and the first term in the first set of braces in Equation (31) reflects the advantage.

The consequences of the inequality between the mean marginal cost and benefit on the $N-1$ parcels of land can be seen by using Equation (25) and showing that the first term in the first set of braces in Equation (31) equals

(37) $$\frac{1}{2}(b_1 - c_1)E_\mu\left[q^t(\mu) - q^r(\mu)\middle|\tau^* < B_1(0,\mu)\right].$$

Note that (37) is always positive when $b_1 \neq c_1$. Thus, in case (b), if $b_1 < c_1$, $E_\mu\left[q^t(\mu)\middle|\tau^* < B_1(0,\mu)\right] < E_\mu\left[q^r(\mu)\middle|\tau^* < B_1(0,\mu)\right]$. That is, average chemical use is less under the tax than under the restriction on the $N-1$ parcels of land where the chemical continues to be used under the tax. On these parcels, the uniform standard is, in some sense, too lax, driving expected marginal benefit below marginal cost. On the other hand, if $b_1 > c_1$, then $E_\mu\left[q^t(\mu)\middle|\tau^* < B_1(0,\mu)\right] > E_\mu\left[q^r(\mu)\middle|\tau^* < B_1(0,\mu)\right]$. That is, average chemical use is greater under the tax than under the restriction on the $N-1$ parcels of land where the chemical continues to be used under the tax. On these parcels, the uniform standard is too tight, driving expected marginal benefit above marginal cost. Of course, the reason why the standard is too tight on these $N-1$ parcels, is that on the one parcel, for which case (b) applies, marginal cost is greater than marginal benefit. That is, the standard is more restrictive than it otherwise would have to be because of the relatively high marginal cost on the one parcel. This does not imply, however, that the tax outperforms the standard on either the $N-1$ parcels or on the one parcel. The first term in the first set of braces in Equation (31) is simply one of four terms that determine the advantage of the tax on parcels of land where the tax is not prohibitive. The second braced term determines the advantage on the parcels where the tax is prohibitive.

The difference in deadweight loss from the two instruments on a parcel where the uniform tax is prohibitive is shown in Figure 8. The top panel of Figure 8 illustrates a situation in which the tax has an advantage over the standard. The standard has the advantage in the bottom panel. As drawn, chemical use is bound by the optimal standard in the upper panel and is not in the lower panel. So, in the upper panel, $q^r = L^*$, and in the lower panel, $q^r = q^0$. The deadweight loss from the prohibitive tax is denoted by area *A*. The deadweight loss from the standard is denoted by area *B*. Thus the advantage of the tax on this land is area $B - A$. But this area is exactly the difference shown in the second braced term in Equation (31). To see this note that area $(B + C)$ equals $q^r MC(.5q^r)$, and area $(A + C)$ equals $q^r MB(.5q^r)$, and the difference between the two areas is $(B + C) - (A + C) = (B - A)$.

On land where the tax is nonprohibitive, the standard tends to have an advantage when marginal costs are more sensitive to chemical use than marginal benefits. The opposite may be true on the land where the tax is prohibitive. In general, when the marginal cost is relatively high and more sensitive to chemical use than marginal benefit, as is drawn in the top panel of Figure 8, the prohibitive tax will tend to be favored over the standard. But, as shown in the bottom panel, the standard will tend to have an advantage when the marginal pollution cost is relatively small and insensitive to chemical use.

V. Efficiency Losses

Uniform policies are attractive because they are less costly to implement than site-specific policies. But site-specific policies may be a better choice if uniform policies lead to large efficiency losses. In this section, we identify the factors that determine the size of the losses from a uniform standard and a uniform tax.

By substituting (18) and (19) into (2), the difference between the optimal application rate $q^*(\mu)$ and the application rate under the optimal uniform standard $q^r(\mu)$ is

(38) $$q^*(\mu) - q^r(\mu) = \frac{b_1\beta_1(\mu) - c_1\alpha_1(\mu)}{c_2\alpha_2(\mu) - b_2\beta_2(\mu)}.$$

Substitute (35) into (18) and (19) and then substitute the results into (17) and collect terms:

(39) $$\ell_r = \frac{1}{2} E_\mu\left[\frac{1}{c_2\alpha_2(\mu) - b_2\beta_2(\mu)}\right]\left(\sigma_{mb}^{a2} + \sigma_{mc}^{a2} - 2v_{bc}^a + (c_1^a - b_1^a)^2\right) \geq 0,$$

where a superscript 'a' indicates that the parameters are defined for all land. This expression is always greater than zero because $v_{bc}^a = \gamma^a \sigma_{mb}^a \sigma_{mc}^a \leq \sigma_{mb}^a \sigma_{mc}^a$, where γ^a is the correlation coefficient between the marginal costs and marginal benefits of chemical use under the uniform standard.

The first thing to note from (39) is that, although spatial variability in pollution costs on its own has no effect on the relative efficiency of uniform taxes and standards, it clearly increases efficiency losses from a uniform standard. As shown in (39), spatial heterogeneity in marginal costs and benefits affects the efficiency loss equally. The larger the variability, the larger the loss. A positive correlation between marginal costs and benefits reduces the efficiency loss, whereas a negative correlation increases the loss. With a positive correlation, land with high marginal benefits also tends to have high marginal pollution costs. In this case, a uniform standard, which reduces chemical use by a greater amount on high-input land than would a tax, also reduces more pollution. The last term in (39) is the loss when the uniform standard does not constrain chemical use on low-input land. In this case, $b_1^a - c_1^a \neq 0$.

Expression (39) indicates that the efficiency loss from a uniform standard is reduced when either the mean marginal cost or benefit function is close to being vertical ($c_2^a \to +\infty$) or ($b_2^a \to -\infty$). Nearly vertical marginal curves imply that a large variation in marginal benefits or marginal costs results in a small variation in the optimal application rates on different types of land. In this case, a uniform standard can be specified that makes application rates on different types of land relatively close to the optimal application rates.

The efficiency loss from the uniform tax can be derived by substituting (31) and (39) into the relationship:

(40) $$\ell_t = \ell_r - \Re.$$

Specifically, when only the slope of the marginal cost and benefit functions varies across different types of land and all land still uses the chemical under the tax (i.e., $S = 1, c_1^a = c_1$), the efficiency loss from the uniform tax can be simplified to

(41) $$\ell_t = \frac{c_2^2 \sigma_{mb}^2 + b_2^2 \sigma_{mc}^2 - 2 b_2 c_2 \nu_{bc}}{2(c_2 - b_2) b_2^2} \geq 0 .$$

Expression (41) clearly indicates that spatial variations in marginal benefits and costs both affect the efficiency loss from the uniform tax. As in the case of the uniform standard, the larger the variability, the larger the efficiency loss; however, the effect of the correlation between marginal costs and marginal benefits is different. A positive correlation increases the efficiency loss from the uniform tax, whereas a negative correlation reduces the loss. This indicates that when a tax is used as an instrument, producers with high marginal benefits use more of the chemical. But with a positive correlation between marginal costs and benefits, land with high marginal benefits also have high marginal pollution costs. Thus, a positive correlation between marginal benefits and costs increase the efficiency loss from a uniform tax.

Expression (41) indicates that the efficiency loss from the tax is reduced as the mean marginal benefit function becomes steeper, because the denominator increases faster than the numerator. When the marginal benefit functions are nearly vertical, a large deviation from the optimal tax rates results in only a small derivation from the optimal application rates. In this situation, the efficiency loss from a uniform tax would be relatively small. In contrast to the case of the uniform standard, the efficiency loss from the uniform tax increases as the marginal cost functions become more vertical, because the denominator increases at a slower rate than the numerator. The intuitive explanation is that when marginal cost functions are close to vertical, a small variation in marginal benefits would result in a relatively large variation in the optimal tax rates on different types of land. In this case, a uniform tax would result in a large efficiency loss.

VI. Results

Spatial heterogeneity affects the deadweight loss from a uniform tax to control pollution differently than the deadweight loss from a uniform standard. A generalized application of

Weitzman's [18] framework is ideal to analyze the relative attractiveness of these two uniform policies. Spatial heterogeneity in marginal pollution costs from chemical use on its own has no effect on the advantage of a uniform tax over a uniform standard, but spatial heterogeneity in marginal benefits from chemical use can have significant effects. The relative advantage of a uniform tax increases when (a) marginal benefits are more sensitive to chemical use than marginal pollution costs on land where marginal benefits are high (and the tax is nonprohibitive); (b) marginal benefits are less sensitive than marginal costs on land where marginal benefits are low (and the tax is prohibitive); (c) marginal benefits are negatively correlated with marginal pollution costs; and (d) the variation in the slope of marginal benefits is small. Although spatial variability in pollution costs of chemical use does not affect the relative efficiency of uniform taxes and uniform standards, it clearly increases efficiency losses under both policies. The efficiency loss from a uniform standard is large when (a) spatial variability in marginal costs and benefits is large, (b) marginal costs and marginal benefits of chemical use are negatively correlated, and/or (c) both marginal costs and benefits are insensitive to chemical use. The efficiency loss from the uniform tax is large when (a) spatial variability in marginal costs and benefits is large, (b) marginal costs and marginal benefits are positively correlated, (c) marginal costs are very sensitive to chemical use, whereas marginal benefits are not.

What has been learned about the parameters affecting the relative efficiency of uniform taxes and uniform standards? Marginal pollution costs are likely to be high and fairly steep when the efficiency of agricultural chemical applications is low. Marginal costs are high because low efficiencies imply that much of the applied chemical is available to be lost to the environment. And marginal costs are steep because the environment is likely to receive a large proportion of any increase in chemical application. Marginal benefits are likely low and relatively flat (responsive to a tax) if application efficiency is low because much of the chemical is not utilized by the crop. The combination of steep marginal costs and flat marginal benefits suggests that Weitzman's term $-\dfrac{\sigma_{mb}^2(c_2+b_2)}{2b_2^2}$ may be negative, favoring the uniform standard.

If chemical application efficiencies are high, then marginal costs are likely low with fairly low slopes for the simple reason that a large proportion of the chemical is utilized by the crop and not lost to the environment. Marginal benefits are likely much higher and chemical demand is likely to be relatively unresponsive to an increase in price. The combination of flat marginal cost curves and steep marginal benefit curves would favor the uniform tax.

One factor that likely affects application efficiency is chemical price. For example, Babcock and Blackmer [2] show that, when the price of nitrogen fertilizer is low relative to its average value in production, then farmers have an incentive to apply “insurance nitrogen” to guard against years in which large amounts of soil-stored nutrient are lost. This type of behavior leads to low application efficiencies. At a higher fertilizer price, application efficiency would increase, particularly if more efficient application techniques became profitable to adopt.

Stavins [15] showed that the effect of correlation can dominate the effect of relative slopes. Varying chemical application efficiencies lead to a negative correlation between marginal costs and marginal benefits. On farms with low application efficiencies, marginal benefits are likely low and marginal costs high. On farms with high application efficiencies, marginal benefits are high and marginal costs are low. A negative correlation favors the uniform tax. Variability in application efficiencies may be the reason both Wu et al. [20] and Helfand and House [7] found that a uniform tax is more efficient than a uniform standard.

The other important factor that influences both the advantage of the uniform tax and the degree of deadweight loss from use of uniform policy instruments is the amount of variability in marginal costs and marginal benefits. Evidence provided by the 1992 National Resource Inventory survey data reveals large variations in land quality and environmental characteristics across farms. And a recent study by Hertel, Stiegert, and Vroomen [8] demonstrated that there is considerable variability in nitrogen application rates in U.S. corn production, even after accounting for land quality, crop rotation, and natural nitrogen sources. This spatial heterogeneity likely results in large variations in marginal costs and benefits of chemical use, which would magnify the expected loss from using the instrument with the comparative disadvantage. In addition, large variability likely magnifies the importance of accounting for land where the tax is prohibitive and where the optimal uniform restriction is nonbinding.

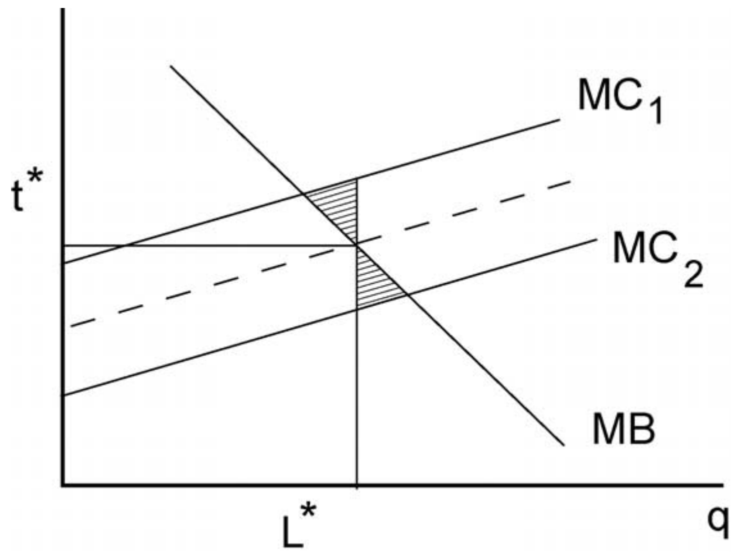

Figure 1. An Illustration of the equivalence between uniform taxes and uniform standards when marginal costs and marginal benefits are uncorrelated

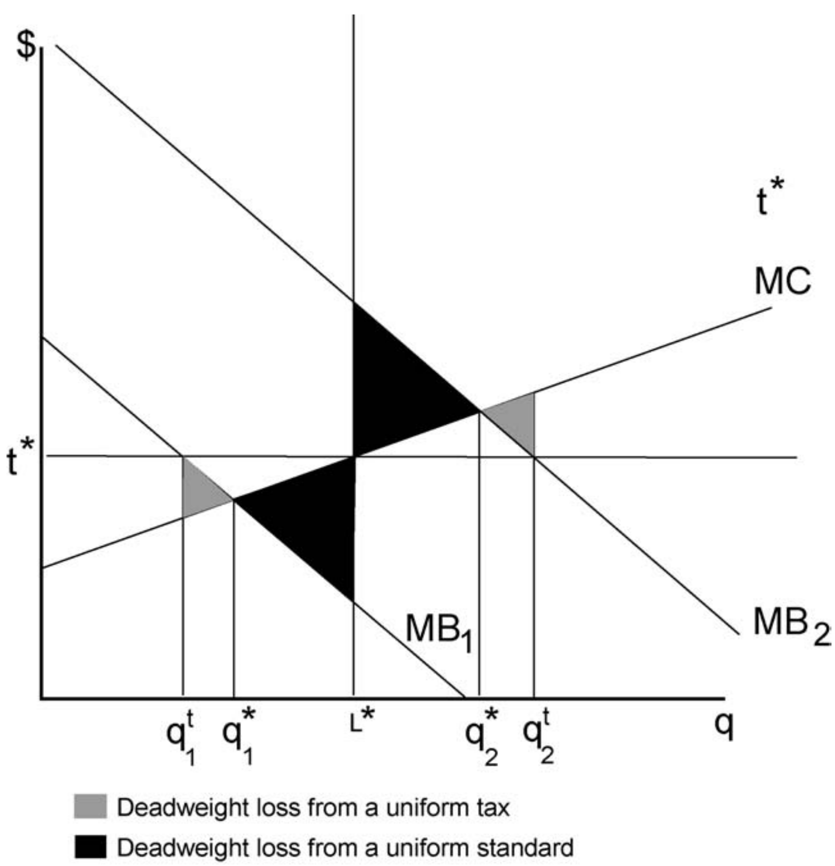

Figure 2. Deadweight losses from a uniform tax and a uniform standard

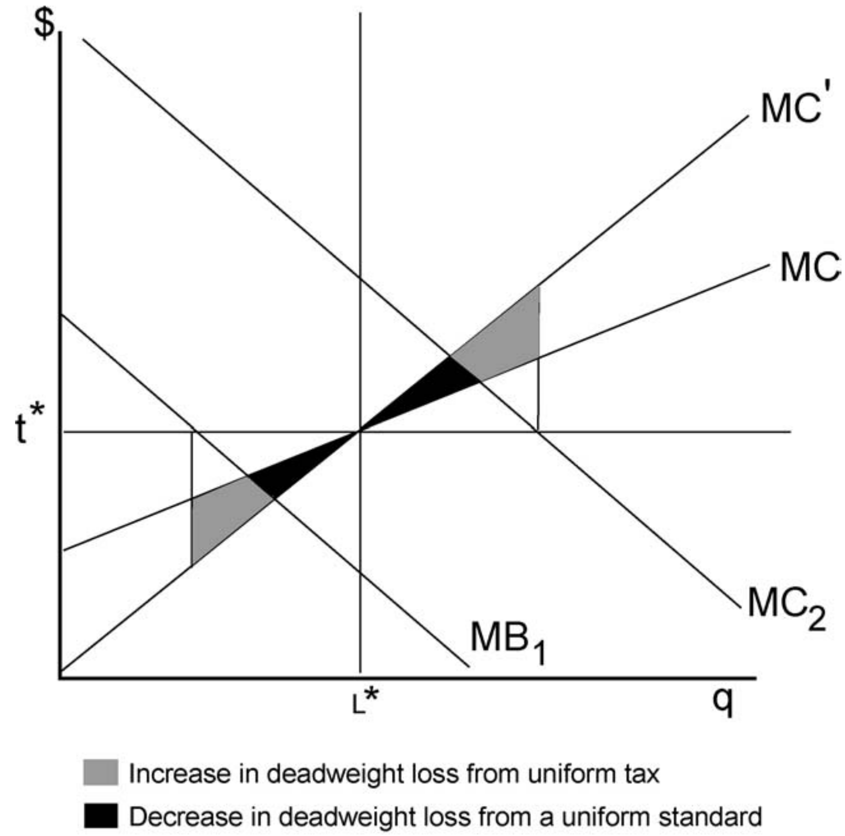

Figure 3. Effect of an increase in slope of marginal cost on relative advantage of a uniform tax

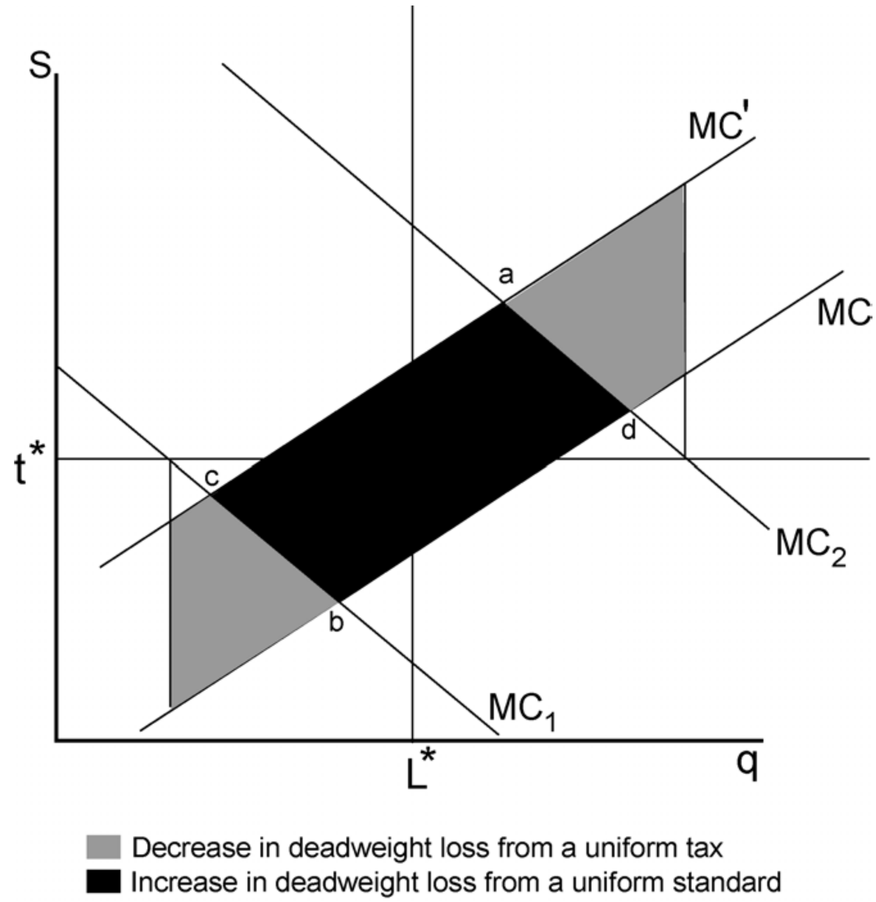

Figure 4. Effect of decreasing covariance between marginal cost and marginal benefit on the relative advantage of a uniform tax

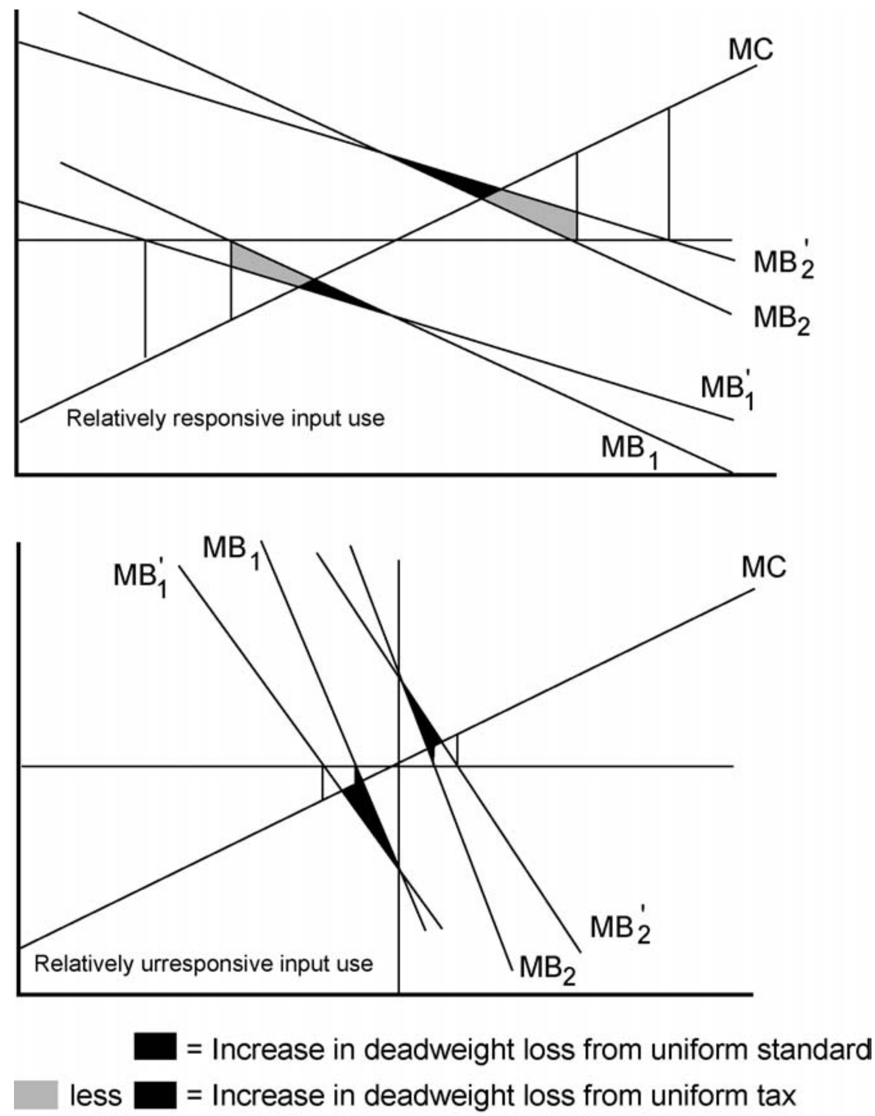

Figure 5. Effect of an increase in the average responsiveness of input use to a tax on the relative advantage of a uniform tax

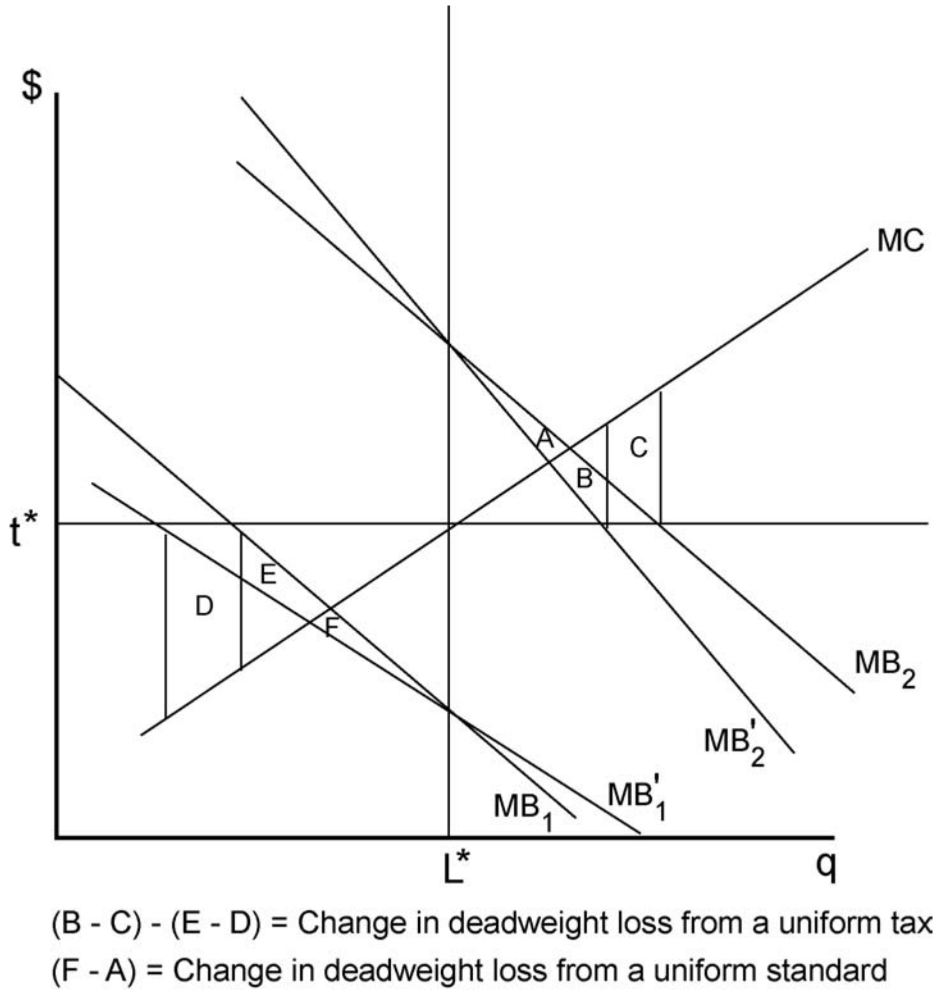

Figure 6. Effect of increasing the variance of the responsiveness of input use to a tax

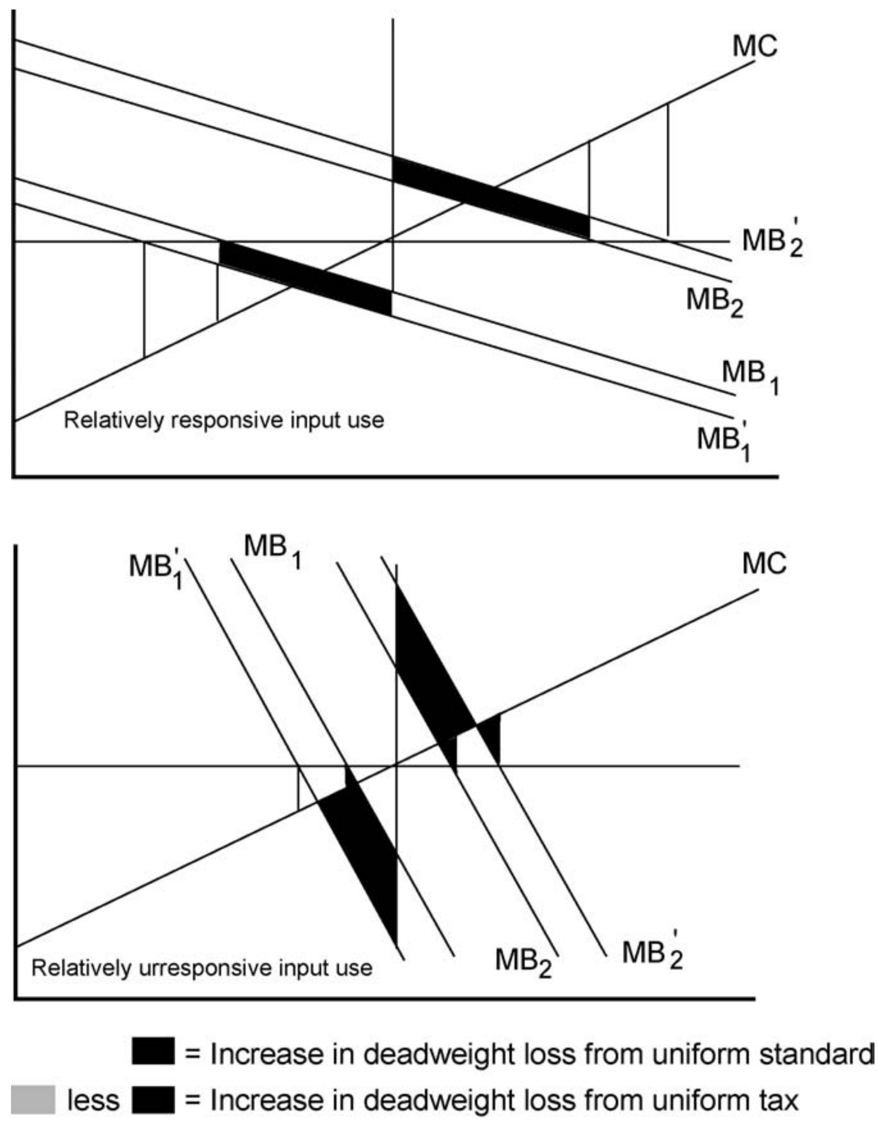

Figure 7. Effect of an increase in the variance of marginal benefits on the relative advantage of a uniform tax

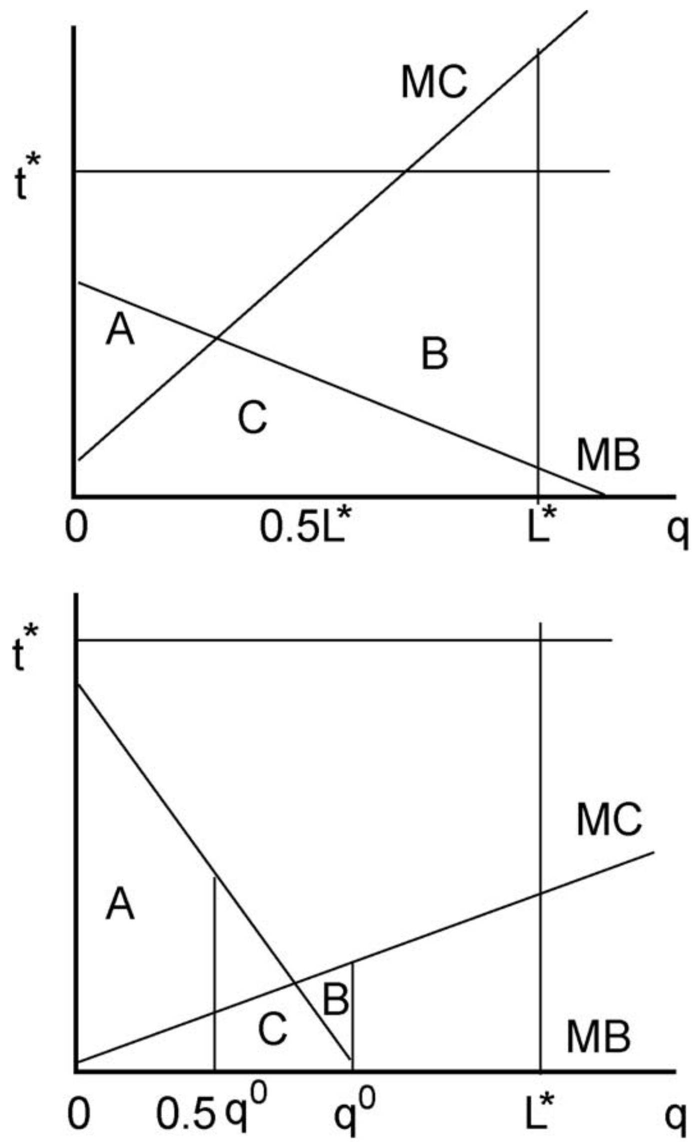

Figure 8. Deadweight loss from a uniform tax and a uniform standards on land where the tax is prohibitive

Table 1. Determinants of the Relative Efficiency of Uniform Taxes and Uniform Standards

Factors (x) affecting $\Re$	The sign of $\partial\Re/\partial x$
Average slope of marginal cost (c_2)	negative
Covariance between marginal cost and benefit (υ_{bc})	negative
Average input response to a tax ($1/b_2$)	negative if $\upsilon_{bc} \leq 0$ and $\lvert b_2 \rvert > 2c_2$; positive if $\upsilon_{bc} \geq 0$ and $\lvert b_2 \rvert < 2c_2$.
Variance of input response (σ_{sb}^2)	negative
Variance of marginal benefit (σ_{mb}^2)	negative if $c_2 > \lvert b_2 \rvert$; positive if $c_2 < \lvert b_2 \rvert$.

Note: Assuming that $S = 1$ and $b_1 = c_1$ in Equation (31).

ENDNOTE

[1] In this paper, control is assumed to be over chemical use. However, this model can also be applied to pollution from multiple point sources with heterogeneous technologies. In this case, q can be either an input or ambient pollution level.

REFERENCES

1. Adar, Z., and J. M. Griffin. “Uncertainty and the Choice of Pollution Control Instruments.” *J. Environ. Econom. Management* 3, 178-188 (1976).

2. Babcock, B. A., and A. M. Blackmer. "The Value of Reducing Temporal Input Nonuniformities." *J Agric. Resou. Econom.* 17, 335-347 (1992).

3. Dasgupta, P., P.J. Hammond, and E. Maskin. “ A Note on Imperfect Information and Optimal Pollution Control.” *Rev. Econm. Studies* 47, 857-860 (1980).

4. Griffin, R.C., and D.W. Bromley. “Agricultural Runoff as a Nonpoint Externality: A Theoretical Development.” *Amer. J. Agric. Econom.* 64, 547-552 (1982).

5. Groves, T. “Incentive in Teams.” *Econometrica* 41, 617-631 (1973).

6. Fishelson, G. “Emission Control Policies under Uncertainty.” *J Environ. Econom. Management* 3, 189-197 (1976).

7. Helfand, G.E., and B.W. House. “Regulating Nonpoint Source Pollution Under Heterogeneous Conditions.” *Amer. J. Agric. Econom.* 77, 1024-1032 (1995).

8. Hertel, T.W., K. Stiegert, and H. Vroomen. “Nitrogen-Land Substitution in Corn Production: A Reconciliation of Aggregate and Firm-Level Evidence.” *Amer. J. Agric. Econom.* 78, 30-40 (1996).

9. Johnson, S.L., R.M. Adams and G. M. Perry. “The On-Farm Costs Of Reducing Groundwater Pollution.” *Amer. J. Agric. Econom.* 73, 1063-1072 (1991).

10. Kwerel, E. “To Tell the Truth: Imperfect Information and Optimal Pollution Control.” *Rev. Econom. Studies* 44, 595-601 (1977).

11. Mapp, H.P., D.J. Bernardo, G. J. Sabbagh, S. Geleta and K. B. Watkins. “Economic And Environmental Impacts Of Limiting Nitrogen Use To Protect Water Quality: A Stochastic Regional Analysis.” *Amer. J. Agric. Econ.* 76, 889-903 (1994).

12. Roberts, M.J., and M. Spence. "Effluent Charges and Licenses under Uncertainty." *J. Public Econom.* 5, 193-208 (1976).

13. Segerson, K. "Uncertainty and Incentives for Nonpoint Pollution Control." *J. Environ. Econom. Management* 15, 87-98 (1988).

14. Shortle, J.S., and J.W. Dunn. "The Relative Efficiency of Agricultural Source Water Pollution Control Policies." *Amer. J. Agric. Econom.* 68, 668-77 (1986).

15. Stavins, R.N. "Correlated Uncertainty and Policy Instrument Choice." *J. Environ. Econom. Management* 30, 218-32 (1996).

16. Taylor, M.L., R.M. Adams, and S. F. Miller. "Farm-Level Response To Agricultural Effluent Control Strategies: The Case of the Willamette Valley." *J. Agric. Resour. Econom.* 17, 173-185 (1992).

17. Yohe, G. "Substitution and the Control of Pollution: A Comparison of Effluent Charges and Quantity Standards under Uncertainty." *J. Environ. Econom. Management* 3, 312-324 (1976).

18. Weitzman, M.L. "Prices vs. Quantities." *Rev. Econom. Studies* 41, 477-491 (1974).

19. Weitzman, M.L. "Optimal Rewards for Economic Regulation." *Amer. Econom. Rev.* 68, 683-91 (1978).

20. Wu, J.J., M.L. Teague, H.P. Mapp, and D.J. Bernardo. "An Empirical Analysis of the Relative Efficiency of Policy Instruments to Reduce Nitrate Water Pollution in the U.S. Southern High Plains." *Canad J. Agric. Econom.* 43, 403-420 (1995).