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Transaction Costs and Agricultural Nonpoint-Source Water Pollution Control Policies

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Mechanism design theory is used to develop the properties of optimal pollution control incentive schemes in the presence of adverse selection, moral hazard, and transaction costs. The model presented here shows (*a*) with no deadweight costs (transaction costs), first-best allocations are always possible; (*b*) in the presence of transaction costs (caused by raising taxes), only second-best allocations are feasible; and (*c*) the conditions under which the optimal incentive scheme implementing second-best allocations will be a nonlinear tax, a standard(s), or a combination of both taxes and standard(s).

Key words: asymmetric information, mechanism design, transaction costs

Introduction

Shortle and Dunn (hereafter S-D) examined the relative efficiency of alternative policies to control agricultural nonpoint-source (NPS) pollution. In their model, the regulatory agency cannot observe the amount of pollution runoff from a farm due to the high cost of undertaking this measurement: a distinguishing feature of NPS pollution. Moreover, in S-D the farmer knows his own profit function, but the regulator faces (prohibitively) high costs identifying all of the relevant parameters of the farmer's profit function; hence, there is asymmetric information between the regulator and the farmer. The regulator, however, is assumed to be able to monitor the farmer's input levels. Then, using a stochastic model of runoff, infers (imperfectly) the amount of pollution runoff from the farm.[1]

Shortle and Dunn showed, using a model of a single farm, that despite the lack of information in their model, the regulator can induce a farmer to choose an ex ante efficient level of polluting inputs. This can be done using an incentive scheme directed toward management practices in the form of a tax, a nonlinear function of the inputs used. The tax is equal to the expected environmental damages caused by the runoff.

In the S-D model, no transaction costs are incurred when implementing the regulatory policy. They clearly recognize this omission when summarizing their analysis (p. 674). "*[S]etting aside policy transaction costs*. . . allowing for both a differential information structure and a nonlinear damage cost function results in a situation in which only an appropriately specified management practice incentive is optimal" (emphasis added). However, despite our tendency to ignore them, such costs are likely to exist.

It is common practice to ignore the cost of implementing a policy in economic analysis and to focus attention on the (gross) efficiency implications of alternative regulatory instruments. The direct costs of raising funds and administering policies could be "netted

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[1] In an earlier article, Griffin and Bromley also examined the implications of using an estimated runoff function in design of policy to control agricultural pollution. S-D extend the Griffin and Bromley model to include a stochastic element in the runoff function, as well as asymmetric information between regulator and firm.

out" later in a policy analysis. In this article we show that the existence of transaction costs of implementing nonpoint pollution policy may be crucial in assessing the gross efficiency implications of the alternative regulations. Specifically, we model transaction costs of policy implementation as a proportional extra cost incurred when raising taxes. Then, contrary to S-D's results, the regulator is not able to devise an incentive scheme that induces a farmer to choose ex-ante efficient levels of a polluting input.[2]

In addition to the management practice incentive scheme just discussed, S-D examined the efficiency properties of implementing farm management standards.[3] They showed that an optimal management standard—where the same input vector is assigned to the firm irrespective of parameters of the profit function—never dominates an optimal tax structure in their model. In our model, we show that a tax scheme is not always superior and is (second-best) optimal only in special circumstances. We also show that, in general, the regulator's optimal regulatory policy is a mixture of taxes and one or more standards; in some cases it will consist solely of a standard. A distinguishing feature of our model is that the policy instrument choice is an endogenous one (Chambers).

Before proceeding, it is important that we clarify the scope and limitations of our analysis. First, the transaction costs we introduce are related only to those incurred by a government agency implementing a policy. As noted by Dahlman, externalities generally will not exist at all in the absence of suitably specified transaction costs. We maintain the existence of transaction costs which prohibit a fully decentralized resolution of the agricultural pollution problem.

Second, our model, as well as S-D's formal model, is that of a single farm. S-D acknowledge the importance of considering several farms—which may raise additional considerations of a second-best nature—but they do not resolve these issues, and neither do we. Considering multiple sources in the modeling of optimal incentive schemes for NPS pollution control remains an important topic for research.

Third, we are not very creative in our modeling of transaction costs. However, we are not interested in detailing specific transaction costs per se; rather we are focused on the implications of the existence of policy transaction costs for the analysis of agricultural NPS pollution regulation. To introduce transaction costs we simply append a constant proportional "social cost of funds" term that is meant to capture deadweight losses of distorting taxes and other costs associated with taxation. This approach provides a proxy for the detailed specification of policy transaction costs.

Our article is related to two strands of literature. One regards the problem of regulating agricultural NPS pollution when there is an inability to monitor farm emissions, uncertainty, and adverse selection (asymmetric information regarding the profit function). We follow Griffin and Bromley and S-D in modeling these problems. While the approach to incorporating policy transaction costs into the analysis is not new, having been developed for regulating a public firm, its implications for agricultural NPS pollution regulation have not been described previously (Fudenberg and Tirole; Russell and Shogren). The other strand

[2]For the class of transaction costs considered in this study, first-best allocations cannot be achieved by any policy, because policy costs must be netted out. In this case, efficiency comparisons among instruments are undertaken in a second-best setting, and hence, policies that achieve an efficient allocation in such a world would be second-best efficient. However, as a reviewer observed, different specifications of transaction costs might generate different policy implications. For instance, the (magnitude of) transaction costs associated with implementing a tax may be different from those associated with implementing a standard, or the policy implications associated with specific types of transaction costs may differ (e.g., do transaction costs that are independent of tax levels have the same implications as transaction costs that depend on tax levels).

[3]They also examined incentive schemes and standards directed to estimated runoff and found that these are almost never as good as a corresponding policy directed to management practices.

of literature concerns the design of second-best environmental policies in the presence of transaction costs, or when other distorting taxes exist in the economy.[4]

The Basic Problem

Our specification of the model closely follows that of Shortle and Dunn.[5] In the absence of regulation, a profit-maximizing farmer chooses an input $x \in R_+$ to maximize

$$\Pi(x,\theta) = E_w\{\tilde{\Pi}(x, w,\theta)\}.$$

Here, w, an ex post realization of a random variable that is unknown to the farmer at the time x, is chosen (for example, rainfall); E_w is the expectations operator (with respect to the random variable w); and θ is a scalar index of farmer profitability (called the farmer's "type") known to the farmer but not to the regulator. We refer to a farmer with profitability index equal to θ as a type-θ farmer. The parameter θ might be interpreted as an index of a farmer's managerial ability or an index of soil quality or a composite index of both. The expression $\tilde{\Pi}(x, w,\theta)$ is the profit a type-θ farmer receives when using x units of the input and the state of nature w occurs, and $\Pi(x,\theta)$ is the expected profit to a type-θ farmer's using x units of the input. From the regulator's perspective, θ is a random variable with density function $k(\theta)$, the support of θ is $\Theta = [\underline{\theta}, \overline{\theta}]$, and $\int_\Theta k(\theta)\, d\theta = 1$. Hence, there is asymmetric information between the farmer and the regulator concerning the value of θ.

> *Assumption 1*: (i) $k(\theta) > 0$ for all $\theta \in \Theta$; (ii) for all w, $\tilde{\Pi}$ is strictly concave and thrice continuously differentiable in x and θ; and (iii) $\Pi_{x\theta}(\cdot) \geq 0$.[6]

Assumption 1 part (i) guarantees there is no division by zero later in the text, and part (ii) guarantees that expected profits Π are strictly concave in x and θ. Assumption 1 part (iii) says that marginal profits increase with higher values of θ: in other words, the shadow value of the input is nondecreasing in θ, or similarly, the higher the value of θ; the more efficient is the farmer. The implications and importance of Assumption 1 part (iii) will be discussed in the subsequent discussion on truthtelling.

The regulator's understanding of the relationship between runoff r and the input x is represented by a stochastic runoff function, $g: R^3 \to R$, with $r = g(x, w, \varepsilon)$. Here, ε is a random variable representing the regulator's uncertainty about actual runoff. The agency's joint density for ε and w is given by $f(w, \varepsilon)$. The expected runoff generated by the input x is

$$\bar{r}(x) = \int g(x, w, e) f(w, e) dw\, de.$$

Runoff causes water quality damage, $D(r)$; we assume that D is convex and twice continuously differentiable in r. The expected damage caused by the vector x is

[4]For example, Lee and Misolek show that optimal emission taxes generally will not equal marginal pollution damages when the revenue collected can reduce deadweight losses elsewhere in the economy. We extend this analysis to the NPS setting.

[5]The major difference is that we view the farmer as having only one (polluting) input. This assumption is made only to keep the notation simple. Assuming that x is multidimensional and will leave our results unchanged; in this case, all operations performed on x are vector operations.

$$\overline{D}(x) = \int D(g(x, w, \varepsilon))f(w, \varepsilon)dw\, d\varepsilon.$$

Given knowledge of θ and no transaction costs, the *first-best* (ex ante efficient) choice of x maximizes

$$\Pi(x, \theta) - \overline{D}(x),$$

and solves the following first-order condition:

$$\Pi_x(x, \theta) - \overline{D}'(x) = 0,$$

where Π_x is the partial derivative of the farmer's profit with respect to input x, and $\overline{D}'(x)$ is the derivative of expected damages with respect to input x. The first-best problem can be viewed as one in which the regulator observes the farmer's private information costlessly and requires the farmer to choose the socially optimal input bundle or else be assessed an extremely large fine.[7]

Direct Revelation Incentive Schemes Regulating Input Use

When the regulator does not observe θ the knife-edged instrument just described is unavailable. In what follows, we assume both asymmetric information over θ and the presence of transaction costs and develop the properties of optimal incentive schemes. Currently there are two general approaches to choosing such incentive schemes (leading to equivalent optimal allocations): nonlinear pricing techniques (Maskin and Riley; Chambers; Lee) and truthful direct revelation (TDR) mechanisms (Guesnerie and Laffont; Laffont and Tirole).[8] This article follows the TDR mechanism approach.[9]

One of the distinguishing features of a direct revelation mechanism is that an "agent" (farmer) announces his private information (efficiency parameters) to a "principal" (the regulator). See Myerson (1989) for a general discussion of direct revelation mechanisms. In the *direct revelation mechanism* (incentive scheme) considered here, the regulator announces a contract schedule $\{t, x\}$ that maps farmer types into tax and input levels. After observing the incentive scheme the farmer reports a type to the government. The government observes the farmer's reported type, denoted $\hat{\theta}$, and pursuant to the announced contract schedule, offers him the contract $(t(\hat{\theta}), x(\hat{\theta}))$.

Typically the mechanism design literature focuses its attention on the class of mechanisms that maximize social welfare and are both truthful and voluntary. The mechanism is truthful if it is optimal for the farmer to report $\hat{\theta}$ truthfully (i.e., report $\hat{\theta} = \theta$), and the

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[7]This type of instrument is often referred to as a *knife-edged* instrument.

[8]Guesnerie and Laffont show that nonlinear pricing rules and truthful direct revelation mechanisms are equivalent resource allocation devices (Proposition 1, p. 335).

[9]The information requirements for implementing a direct-revelation scheme are potentially demanding. For instance, to implement the direct revelation tax scheme considered here, the government must know the structure of the profit function and the distribution of θ.

Several authors have shown that nothing is lost when modeling a mechanism as a TDR mechanism (see Dasgupta, Hammond, and Maskin; Holmstrom; Myerson 1989). This observation—called the *revelation principle*—says that for any equilibrium of any general mechanism there exists an equivalent direct-revelation mechanism that involves truth telling.

mechanism is voluntary if the farmer is better off choosing a contract (voluntarily) than not choosing one. As for social welfare, recall that a major difference between S-D's model and the model presented here is that we assume the regulator incurs transaction costs when raising tax revenues. We model the effect of transaction costs on net tax revenues by assuming the regulator realizes only λ cents from each dollar the farmer is taxed, $0 < \lambda \leq 1$. If λ is equal to one, then there are no transaction costs. For a given θ, the expected profit to the farmer is $\Pi(x, \theta) - t$ and the expected net social cost is $\lambda t - \overline{D}(x)$. Hence, the net social welfare associated with a type-θ farmer is

$$B(x(\theta), t(\theta), \theta) = \Pi(x(\theta), \theta) - \overline{D}(x(\theta)) - (1-\lambda)t(\theta),$$

where λ is equal to one in the S-D case. Given that Π is strictly concave in x and $\overline{D}$ is convex in x, it follows that $B(\cdot\cdot)$ is strictly concave in x.

Let $\pi(\hat{\theta}, \theta) = \Pi(x(\hat{\theta}), \theta) - t(\hat{\theta})$. Given the social welfare function B, truth telling is ensured if the following *incentive compatibility* constraint is introduced:

$$\text{(1)} \qquad \theta \in \arg\max_{\hat{\theta}} \{\pi(\hat{\theta}, \theta)\}, \quad \forall \theta, \hat{\theta} \in \Theta.$$

Voluntary participaton is ensured if the following *individual rationality* constraint is introduced:

$$\text{(2)} \qquad \pi(\hat{\theta}, \theta) \geq \overline{\pi}, \quad \forall \theta, \hat{\theta} \in \Theta,$$

where, without loss of generality, we set $\overline{\pi}$ equal to 0.[10]

The regulator's *second-best* problem (SB) is to choose $\{x(\theta), t(\theta)\}$ to solve

$$\max_{\{x(\theta), t(\theta)\}} \left\{ \int_{\underline{\theta}}^{\overline{\theta}} B(x(\theta), t(\theta), \theta) k(\theta)\, d\theta \right\}$$
$$\text{s.t.} \qquad (1) \text{ and } (2).$$

(SB) is a standard problem in the literature on designing mechanisms under private (asymmetric) information (Guesnerie and Laffont; Chambers). Typically, before actually solving this problem, the analyst transforms the incentive compatibility and individual rationality constraints into simpler forms.

Incentive Compatibility and Individual Rationality

Guesnerie and Laffont show that equation (1) will be satisfied if and only if:

$$\text{(3)} \qquad \pi_{\hat{\theta}}(\hat{\theta}, \theta)|_{\hat{\theta}=\theta} = \Pi_x(x(\hat{\theta}), \theta)x'(\hat{\theta}) - t'(\hat{\theta}) = 0,$$

and

[10] It is, of course, possible that the optimum involves driving the farmer out of business, but we do not consider this degenerate case further.

(4) $$x'(\hat{\theta}) \geq 0.$$

For a proof see Guesnerie and Laffont. Here, $\pi_{\hat{\theta}}(\cdot\cdot)|_{\hat{\theta}=\theta}$ is the partial derivative of π with respect to $\hat{\theta}$ (evaluated at $\hat{\theta} = \theta$) and is the first-order condition for truth telling, and $x'(\cdot)$ and $t'(\cdot)$ are the respective derivatives of the input and tax functions. Equation (3) says that the input and tax functions must be chosen so that the marginal benefit from lying a little—for example, reporting $\hat{\theta} = \theta^2 + d\theta$—is just offset by the marginal cost of lying a little; the marginal benefit is $\Pi_x x'$ and the marginal cost is t'. Equation (4) results from the assumption that $\Pi_{x\theta}$ is greater than or equal to zero and, as shown in Guesnerie and Laffont, comes from the second-order condition for truth telling. Given that profits are nondecreasing in θ, (4) says that a profitable (efficient) farmer should be allocated at least as much of the input as less profitable ones. Equation (4) is often called the *monotonicity condition.*

To see why truthful revelation requires a nondecreasing input function consider the farmer's marginal rate of substitution between x and t. By rearranging the terms in (3) this is

(5) $$\frac{dt}{dx} = \Pi_x(x, \theta).$$

The regulator can use its knowledge of Π to choose the incentive scheme as a function of the units of x used and does this by setting the change in the tax given a change in x equal to the marginal quasi-rent of the input.

Suppose for the moment that the farmer is one of two possible types: θ^2 or θ^1, $\theta^2 > \theta^1$. In figure 1, two isoprofit lines pass through contract A = (t_1, x_1). I^1 is an isoprofit line for the type-θ^1 profit line for the type-θ^2 farmer. By assumption the slope of I^2 is everywhere steeper than that of I^1. Note that profits increase in the southeast direction. A type-θ^2 farmer (or a type-θ^1 farmer) has isoprofit line I^2 (or I^1). To get a type-θ^2 farmer to report θ truthfully, the regulator needs to offer another contract somewhere to the right of A and above I^1; one such contract being the point B. At B the farmer is better off reporting θ^1. (If B were on I^2 then truthful reporting is still an optimal response, although it is not unique.) To keep the farmer from reporting type θ^1 when it is really θ^2, the regulator makes sure that two things happen. First, the marginal increase in t for the type-θ^2 farmer, given a marginal increase in x, is larger than the marginal increase in t that keeps a type-θ^1 farmer on I^1 (given the same marginal increase in x). Second, the marginal increase in t for the type-θ^2 farmer, given a marginal increase in x, is less than the marginal increase in t that keeps the type-θ^2 farmer on I^2.

If the input function violates (4) the tax scheme will not encourage truth telling by the farmer. To see this, assume that the contract targeted for the type-θ^2 farmer is to the left of A and below I^1—contract C, for example (i.e., the input function is decreasing in θ). Then the type-θ^1 farmer has no incentive to report θ truthfully. In this case, she would report $\hat{\theta} = \theta^2$ and receive contract C; placing her on the higher isoprofit curve I^1.

The individual rationality constraint requires that the tax scheme does not leave the farmer with negative profits. Since this must hold for all possible farmer types (2) must hold for each possible value of θ. This set of rationality constraints can be replaced by a single constraint. By (3) and the envelope theorem, truth telling implies

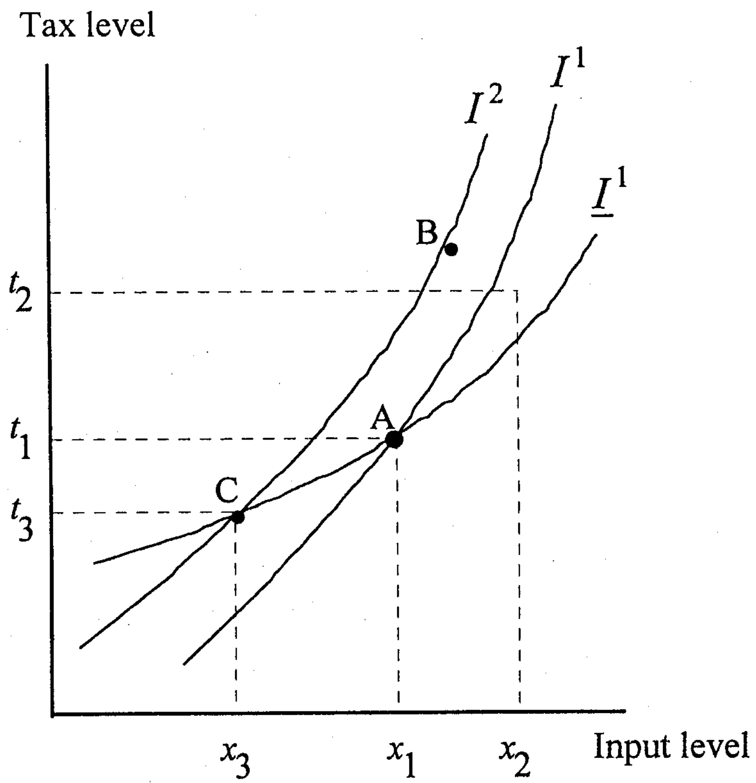

Figure 1. The monotonicity condition and truth telling

(6) $$\frac{d}{d\theta}\pi(\theta,\theta) = \Pi_x(x(\theta),\theta)x'(\theta) - t'(\theta) + \Pi_\theta(x(\theta),\theta) = \Pi_\theta(x(\theta),\theta).$$

By assumption, $\Pi_\theta(x(\theta),\theta) \geq 0$. So it follows that $\pi(\theta,\theta)$ is increasing in θ and (2) holds as long as:

(7) $$\pi(\underline{\theta},\underline{\theta}) = 0.$$[11]

[11]The farmer can always say that he is a type-$\underline{\theta}$ farmer and get
$$\pi(\underline{\theta},\theta) = \Pi(x(\underline{\theta}),\theta) - t(\theta) \geq \Pi(x(\underline{\theta}),\underline{\theta}) - t(\underline{\theta}) = \pi(\underline{\theta},\underline{\theta}) = 0.$$

Optimal Incentive Schemes under Asymmetric Information and Transaction Costs

In this section we develop the regulator's optimal incentive scheme given transaction costs and asymmetric information over the farmer's type. We proceed by first setting up the regulator's optimization problem. Then we develop the optimal input function and end with a characterization of the optimal tax function.

It can be shown that the second-best problem can be rewritten as an optimal control problem with the slope of the input function, $x'(\theta)$, being the control variable. Specifically, the second-best problem (SB) is equivalent to the following optimal control problem:

$$\max_{\{x(\theta)\}} \left\{ \int_{\underline{\theta}}^{\overline{\theta}} W(x(\theta),\theta)k(\theta)\,d\theta + \Pi(x(\underline{\theta}),\underline{\theta}) \right\}$$

$$\text{s.t.} \qquad x'(\theta) = \varphi(\theta),$$

$$\varphi(\theta) \geq 0,$$

$$\pi(\underline{\theta},) = 0,$$

$$t(\theta) \text{ satisfies (4), and } x(\theta) \geq 0;$$

where

$$W(x(\theta),\theta) = \lambda\Pi(x(\theta),\theta) + Z(\theta,\lambda)\Pi_\theta(x(\theta),\theta) - \overline{D}(x(\theta)),$$

and

$$Z(\theta,\lambda) = (1-\lambda)\left[\frac{1-K(\theta)}{k(\theta)}\right].$$

For a proof see Guesnerie and Laffont, p. 360. The expression $W(x,\theta)$ is the expected net social benefit of using x units of the input and $\lambda\Pi(\cdot\cdot) + Z(\cdot\cdot)\Pi_\theta(\cdot\cdot)$ is another representation of farmer profits. Finally, the term $(1-K(\theta))/k(\theta)$ is the inverse of the *hazard rate*: the probability that the farmer's type belongs to $[\theta, \theta + d\theta]$ given that his type is not less than θ.

Assumption 2: $W(x,\theta)$ is strictly concave in x.

Assumption 2 ensures that the optimal input function is unique.

The Hamiltonian associated with the above optimal control problem is

$$H = W(x(\theta),\theta)k(\theta) + [\mu(\theta) + \gamma(\theta)]\varphi(\theta)k(\theta).$$

The costate variable, $\mu(\theta)$, represents the marginal expected net benefit to society of using $x(\theta)k(\theta)$ units of the polluting input. The multiplier function $\gamma(\theta)$ is the expected marginal net benefit of relaxing the incentive compatibility constraint. The necessary conditions for an optimum include

$$(8) \qquad -H_x = -W_x(x(\theta),\theta)k(\theta) = \mu'(\theta),$$

(9) $$H_\varphi = [\mu(\theta) + \gamma(\theta)]k(\theta) = 0,$$

(10) $$H_\mu = H_\gamma = \varphi(\theta)k(\theta),$$

(11) $$\mu(\theta)\varphi(\theta) = \gamma(\theta)\varphi(\theta) = 0,$$

and the transversality condition:

(12) $$\mu(\bar{\theta}) = 0.$$

Choosing the Optimal Input Function

We construct the optimal input function in two steps. In the first step we solve the above optimal control problem while ignoring the monotonicity constraint on {x}, equation (4). This step gives us the *unrestricted input function,* denoted $\{x^{**}\}$. In the second step we inspect the unrestricted input function to see if there are any subintervals of Θ over which (4) is violated. Among other things, we show that if $x^{**'}(\theta) \geq 0$ for all θ, then the optimal input function, denoted $\{x^*\}$, is identical to $\{x^{**}\}$. The second step (discussed shortly) is required if there are any intervals of $\{x^{**'}\}$ over which equation (4) is violated.

The First Step in Choosing an Optimal Input Function. Given that $\varphi(\theta) = x'(\theta)$ is the control, if the monotonicity constraint is ignored the necessary condition (9) becomes $H_\varphi = \mu(\theta)k(\theta) = 0$, or $\mu(\theta) = 0$. So, integrating (8) between $\underline{\theta}$ and θ and using (12) gives

(13) $$\mu(\bar{\theta}) - \mu(\theta) = \int_{\theta}^{\bar{\theta}} W_x(x^{**}(s), s)k(s)ds = 0,$$

where

(14) $$W_x(x^{**}(\theta),\theta) = \lambda\Pi_x(x^{**}(\theta),\theta) + Z(\theta,\lambda)\Pi_{\theta x}(x^{**}(\theta),\theta) - \bar{D}'(x^{**}(\theta)).$$

Equation (13) says that the unrestricted input function must be chosen so that the expected marginal benefit from using $x^{**}(\theta)$ units of input is equal to the expected marginal damage it causes. Given that W is strictly concave in x, the input profile satisfying (13) is unique. Equation (13) holds only if $W_x(x(\theta),\theta) = 0$ for all θ in $[\underline{\theta},\bar{\theta}]$. Hence, the regulator must choose the unrestricted input function so that $W_x(x,\theta) = 0$ for all $\theta \in [\underline{\theta},\bar{\theta}]$.

After choosing the unrestricted input function $\{x^{**'}\}$ the regulator checks to see if there are any subintervals of Θ over which $\{x^{**'}\}$ violates the monotonicity constraint, (4). To see how the unrestricted input function behaves, we take the total derivative of (14) with respect to θ and isolate the $x^{**'}(\theta)$ term by itself:

(15) $$x^{**'}(\theta) = -\frac{(\lambda + Z_\theta)\Pi_{x\theta} + Z\Pi_{\theta x\theta}}{\lambda\Pi_{xx} - \bar{D}'' + Z\Pi_{\theta xx}}.$$

The denominator in (15) is simply the second derivative of the Hamiltonian with respect to x and is negative by Assumption 2. So $\{x^{**'}\}$ is nonnegative only if $(\lambda + Z_\theta)\Pi_{x\theta}$

$+Z\Pi_{\theta x\theta} \geq 0$. Given that there are no restrictions imposed on Z and $\Pi_{\theta x\theta}$, it is impossible to tell whether $\{x^{**}\}$ is decreasing (or increasing) over Θ, or increasing over some subintervals of Θ and constant or decreasing over others.

Before discussing the second step, we make the following four observations. First, in S-D the regulator incurs zero transaction costs, that is, $\lambda = 1$. With zero transactions costs, (15) is given by:

$$x^{**\prime}(\theta) = -\frac{\Pi_{x\theta}}{\Pi_{xx} - \bar{D}''} \geq 0, \quad \forall \theta \in \Theta.$$

With zero transaction costs ($\lambda = 1$) the monotonicity condition is satisfied over the entire domain of x, implying that the monotonicity condition can be ignored. If so, then the optimal input function is equivalent to the unrestricted input function. Also, by (14) the input function satisfies the condition for efficiency (when $\lambda = 1$). Moreover, when $\lambda = 1$ and $\Pi_{x\theta} > 0$, the monotonicity condition implies that each possible report of the farmer's type is assigned a different input level, so an input standard cannot be optimal. These results accord with those of S-D.

Second, as suggested in the previous paragraph, even if $\lambda < 1$, if the unrestricted input function is increasing over its entire domain, then the optimal input function and the unrestricted input function are equivalent. Sufficient conditions for a nondecreasing unrestricted input function are

$$[\lambda + Z_\theta(\theta,\lambda)]\Pi_{x\theta}(x(\theta),\theta) + Z(\theta,\lambda)\Pi_{\theta x\theta}(x(\theta),\theta) \geq 0, \quad \forall \theta \in \Theta.$$

Third, in the presence of transaction costs, ex ante efficient pollution levels cannot be attained. Ex ante efficiency requires that input levels be chosen so that marginal profits are equal to marginal damages ($\Pi_x = \bar{D}'$). By (14) this condition will never hold when λ is less than 1.

Finally, if the unrestricted input function is everywhere decreasing, then the optimal function must be a constant function. In other words, the optimal incentive scheme is a standard. To understand this claim recall that the unrestricted input function must satisfy the following (for all $\theta \in \Theta$):

$$\mu(\theta) = \int_{\underline{\theta}}^{\theta} \mu'(s)ds = \int_{\underline{\theta}}^{\theta} W_x(x(s),s)ds = 0.$$

Given that $x' = \varphi$, equation (11) can be rewritten as:

$$\varphi(\theta)\mu(\theta) = x^{*\prime}(\theta)\left[\int_{\underline{\theta}}^{\theta} W_x(x^*(s),s)ds\right] = 0.$$

Since the (unrestricted) input function satisfying $\mu(\theta) = 0$ is unique, if it is strictly decreasing then it cannot be the optimal input function, $\{x^*\} \neq \{x^{**}\}$. Given that the bracketed term is equal to zero only if $x^* = x^{**}$, the term $\varphi(\theta)\mu(\theta)$ is equal to zero only if $x^{*\prime}$ is the zero function, implying $x^*(\theta) = \bar{x}$ for all $\theta \in [\underline{\theta}, \theta]$; the regulator implements a standard.

The Second Step in Choosing an Optimal Input Function. If the unrestricted input function is increasing on some subintervals of Θ and decreasing on others, then the optimal input function will be a connected function composed of (*a*) (increasing) portions of the unrestricted input function and (*b*) constant functions (line segments). The subintervals over which the optimal input function is constant is equivalent to a standard. The regulator will choose standards for some, but not necessarily for all, farmer types. The second step *involves* determining exactly when farmer types will be regulated using standards (bunched).

Guesnerie and Laffont observed the unrestricted input function might assume a myriad of potential shapes. However, for a discussion on how to choose the optimal input function when the monotonicity constraint is violated we direct the reader's attention to figure 2. In figure 2 the unrestricted input function is represented by the curve abcdefg. This unrestricted input function is increasing on the intervals $[\underline{\theta}, \theta_2]$ and $[\theta_4, \bar{\theta}]$ and decreasing on the interval $[\theta_2, \theta_4]$. In this case, the optimal input function will include an interval like $[\theta_1, \theta_5]$ where the value of the optimal input function is equal to a constant value x°, for all θ in $[\theta_1, \theta_5]$. A farmer reporting any type in this subinterval will be allowed to use x° units of the input; thus, the optimal regulatory scheme is a standard in this interval. The optimal input function x^*, then, would look something like the heavy curve abdfg: increasing from $\underline{\theta}$ to θ_i, constant between $[\theta_1, \theta_5]$, and increasing from θ_5 to $\bar{\theta}$ to.

The constant function is determined by choosing the values x°, θ_1, and θ_5 to solve the following problem:

$$\int_{\theta 7}^{\theta_5} W_x(x^\circ, \theta) k(\theta) d\theta = 0,$$

$$x^\circ = x^{**}(\theta_3); \; x^\circ = x^{**}(\theta_5).$$

Here we have three equations and three unknowns x°, θ_7, and θ_5. The top equation says that the parameters are chosen so the expected marginal net benefit of input usage (conditioned on θ being between θ_7 and θ_5) is zero. For complete details on choosing these values see Guesnerie and Laffont or Fudenberg and Tirole (pp. 303–6).

The Optimal Price Function

Once the optimal input function has been chosen, determining the optimal tax function is straightforward. First integrate (7) between $\underline{\theta}$ and θ to obtain the following:

$$\pi(\theta, \theta) - \pi(\underline{\theta}, \underline{\theta}) = \int_{\underline{\theta}}^{\theta} \Pi_\theta (x(s), s) ds.$$

Since $\pi(\underline{\theta}, \underline{\theta}) = 0$, we have

$$\pi(\theta, \theta) = \int_{\underline{\theta}}^{\theta} \Pi_\theta (x(s), s) ds = \Pi(x(\theta), \theta - t(\theta).$$

Substituting x^* for x and solving for t, we get the optimal input tax function:

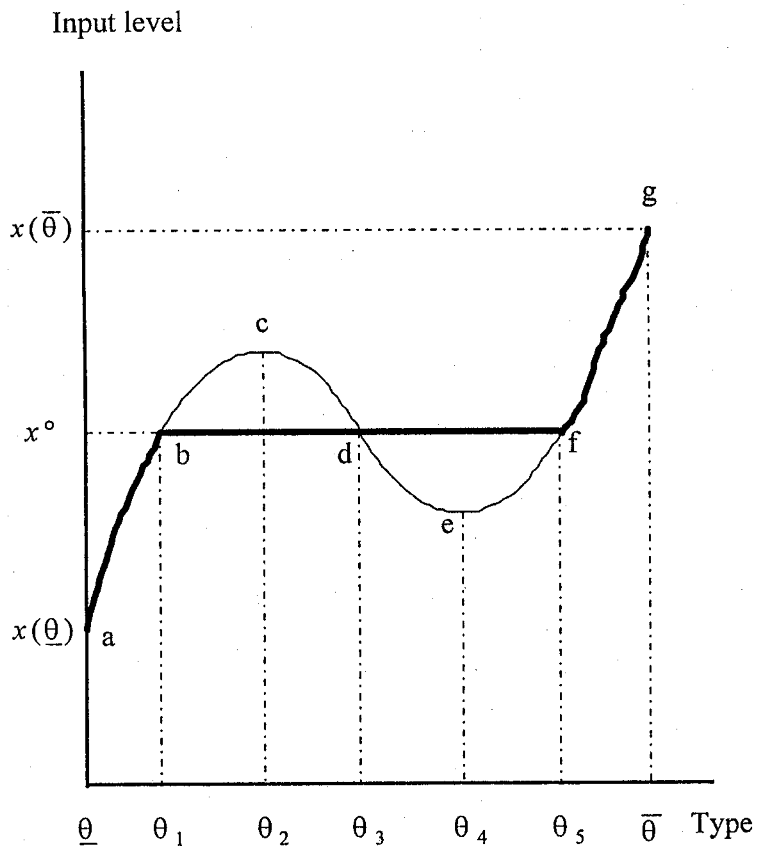

Figure 2. Choosing the optimal input function

$$t^*(\theta) = \Pi(x^*(\theta),\theta) - \int_{\underline{\theta}}^{\theta} \Pi_\theta(x^*(s),s)ds.$$

The optimal tax is equal to the farmer's true profit less $\int \Pi_\theta(\cdot)ds$. The integral component of the tax results from the farmer's private information and is the minimum amount she must be paid to reveal her true θ. A farmer who reports a true type equal to the lower bound of possible types makes zero profits. If the true type is interior to Θ then the farmer earns an additional "information rent" and the value of that rent is equal to the minimum amount he must be paid to reveal his true type. To interpret this result, observe that the farmer's total profits increase at a rate equal to $\Pi_\theta(\cdot)$. The potential gain to a farmer with $\theta = \theta^\circ - \Delta$ (with $\Delta > 0$) from choosing the contract designed for a type-θ° farmer is approximately equal to $\Pi_\theta(\cdot)\Delta$. To induce truthful revelation of θ, the approximate difference in the amount the farmer is taxed, $t'(\cdot)\Delta$, must just offset the potential benefit of misrepresenting his true θ.

Conclusion

In this article we reconsider the single-farm model of Shortle and Dunn and demonstrate that their results depend critically on an implicit assumption that there are no transaction costs involved in tax implementation. When such transaction costs are introduced to the model, we show that it is no longer possible to achieve the ex ante efficient level of agricultural pollution. Moreover, in some cases, the optimal regulatory policy consists of management standards.

Shortle and Dunn also consider the problem of controlling pollution from multiple polluters. An extension of our approach to this case involves some complications that await further research. In particular, in this case the contract and, hence, the payoffs to any one farmer will depend on the messages and true types of all of them. We must then consider the type of equilibrium notion most appropriate to the model. However, this line of research is promising for providing insight into how the regulation of heterogeneous emitters would be altered when the regulator can receive information from firms about their types.

In our article, as well as in that by Shortle and Dunn, it is assumed that, while the farmer has private information regarding her profit function, the regulator could monitor the inputs used. Thus, while there is adverse selection, there is no moral hazard. A number of papers in the NPS literature have considered the moral hazard problem (e.g., Segerson; Xepapadeas). Preliminary work on the case where both forms of asymmetric information are present has been recently undertaken by Laffont.

In general, the problem of controlling NPS pollution is a vexing one for policy makers because of the diversity of informational deficiencies involved. Yet, the problem is an important one to investigate, given that NPS pollution remains a major source of environmental degradation. While the practical application of the kinds of incentive schemes we derive here has yet to be demonstrated, the derivation of their properties and the parameters they depend on is a vital prerequisite to their implementation.

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