Second-Best Tax Policies to Reduce Nonpoint Source Pollution

Douglas M. Larson, Gloria E. Helfand, and Brett W. House

Control of nonpoint source pollution often requires regulation of inputs, but first-best solutions are unattainable. Because inputs are monitored by different agencies and regulatory coordination can be costly, it may be more practical to regulate single inputs. A cost-effectiveness approach to determining the best single-input tax policy is developed and applied to the question of reducing nitrate leaching from lettuce production in California. Water is the best single input to regulate, and efficiency losses from this second-best approach appear not to be great. Conditions for the welfare ranking of policies to be invariant to heterogeneity in production or leaching are identified.

Key words: nonpoint source pollution, tax policies, nitrate leaching, lettuce production, Salinas Valley.

Because point sources of pollution have been aggressively regulated over the last two decades, reducing pollution from nonpoint sources is perhaps the major remaining challenge for clean water policy in the United States. Nonpoint source water pollution has historically been more difficult to regulate because the pollution is by definition diffuse in origin and often involves water moving and mixing over large areas. Traditional approaches based on regulating individual sources are not easily implemented without enormous expenditures on monitoring.

Several authors discuss ways to reduce nonpoint pollution based on relatively easily observed factors such as input use or ambient water quality. Holterman, and Griffin and Bromley show that properly designed taxes on inputs can achieve a first-best solution when the individual firm's pollution generation is not directly observable, though regulation is more complex because all inputs that contribute to the externality must be addressed.[1] Shortle and Dunn show that if damage is nonlinear and stochastic, and farmers have better information about control costs than regulators, price-based incentives on inputs generally outperform quantity controls. Segerson demonstrates that taxes based on ambient water quality can achieve an efficient level of nonpoint pollution, with a uniform tax appropriate for heterogeneous farmers only when marginal benefits of abating pollution are constant. Cabe and Herriges consider the information and monitoring costs required to implement an ambient quality tax and show the tradeoff between these costs and the design of the tax mechanism.

Input-based, first-best solutions depend on having detailed information on input usage and on the ability to regulate all inputs contributing to pollution simultaneously. Often, however, inputs to farm production are monitored or regulated by different federal or state agencies. For instance, pesticide use is regulated by the federal Environmental Protection Agency, while fertilizer controls may be based in state departments of agriculture. Irrigation water may be regulated by local or state water agencies, or by

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[1] For this to have empirical content in the real world, one must be able to observe (and regulate) each agent's use of inputs at little or no cost, and the pollution function must be known. Knowledge of these make it unnecessary to observe pollution directly since it can be inferred directly from known information.

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the federal Bureau of Reclamation. Coordination of tax instruments among all the regulatory bodies to get taxes "right" can be difficult at best. It is worth considering whether less-efficient but simpler regulatory instruments can achieve substantially the same pollution reduction goals, and at what higher cost.

In this paper a systematic approach to the evaluation of second-best policies for nonpoint pollution reduction is developed. Input taxation is the focus, since inputs are frequently observable and, as noted above, it is possible to attain first-best solutions to the welfare maximization problem by suitable regulation of all inputs.[2] However, because it is costly to observe input usage and to implement tax mechanisms, the policy choice may be which input to regulate. The answer will depend on which policy causes the smallest loss in economic welfare to achieve a given reduction in nonpoint pollution. Input taxes have been used in the United States—for instance, Wisconsin and Iowa have taxed fertilizer—and in Europe, though primarily for financing nonpoint pollution control programs rather than to provide disincentives to their use (Thompson, Hahn).

A cost-effectiveness approach, or "efficiency without optimality" in the language of Baumol and Oates, is often the most useful framework for this type of comparison since marginal damages from pollution are typically not well known. The comparison of policies to meet a given pollution reduction can be made without considering the question of which specific pollution level is socially optimal. Since pollution production is external to the markets for agricultural inputs and output, the social cost of achieving a given reduction in pollution can be thought of as the social surplus (producer's and consumer's surplus plus tax revenues) foregone to achieve that goal. A policy creating incentives for individual agents to consider the social cost of pollution is, effectively, an intervention in the market, and it reduces social surplus by an amount usually measured as deadweight loss. The most cost-effective policy is that which has the smallest deadweight loss in achieving the stated policy goal.

The case study that motivates this analysis is lettuce production in the Salinas Valley of California. In this region nitrate leaching into groundwater from agricultural fertilizers is one of the major nonpoint pollution problems. Nitrate leaching depends on the amounts of both nitrogen fertilizer and water used in crop production, among other things, and a first-best solution to the nitrate problem would require regulation of both inputs simultaneously. However, coordination of policies for multiple inputs is often cumbersome and costly because each is subject to somewhat different regulatory processes and institutions.

The paper briefly develops the welfare-theoretic approach to comparing second-best, single-tax policies using a crop yield and pollution production model. Marginal and cumulative conditions for identifying the most cost-effective single-input (second-best) tax policy are given. The approach is illustrated using several models of lettuce production and nitrate pollution estimated using data generated from a version of the Erosion Productivity Index Calculator (EPIC) calibrated for lettuce production in the Salinas Valley. For each of these models the question of which single input to regulate, nitrogen or water, is evaluated, and the social welfare cost from use of the second-best regulations is also calculated. Possible effects on the policy choice of heterogeneity in production or leaching due to factors such as soil quality are also briefly considered. In particular, conditions under which the ranking of policies at the field level will be invariant to an index of field heterogeneity are noted.

Model

The model is first developed at the level of an individual field that can be taken as homogeneous with respect to soil quality and other factors that influence yield and nitrate leaching. The conditions determining the smallest deadweight loss tax policy are developed; then, the question of how robust the rankings at the field level might be as field characteristics are allowed to vary is briefly taken up.

Crop production and pollution functions are $y = f(\mathbf{x}, z)$ and $a = g(\mathbf{x}, z)$, respectively, where $\mathbf{x} = (x_1, \ldots, x_n)$ is an n-vector of inputs, z is an index of soil quality (the source of heterogeneity across farms to be taken up later), y is crop yield,[3] and a

[2] The symmetry between price and quantity controls as policy instruments for identical firms under certainty means that results obtained under input taxes carry over to policies involving corresponding quantity restrictions on input use.

[3] For convenience, a single crop is considered. This is probably the most realistic scenario for lettuce in the Salinas Valley, which dominates other crops in terms of short-run profit; typically one observes repeated cropping of lettuce with little rotation to other crops in the area. The principles of the analysis generalize readily to substitution among crops based on relative prices, though separate leaching functions and production functions are needed for each crop.

is the level of pollution produced. The marginal products $f_i \equiv \partial f/\partial x_i$ are assumed nonnegative, while $g_i > 0$ for polluting inputs and $g_i < (=) 0$ for abating (neutral) inputs.

In the absence of regulation of nonpoint pollution, individual farmers (who are taken to be identical) are presumed to maximize their private profits, $\pi \equiv pf(\mathbf{x}, z) - \mathbf{wx}$, where p is output price and $\mathbf{w}$ is an n-vector of input prices. Assuming second-order conditions are satisfied, let the input demand vector which maximizes profits be $\mathbf{x}(\mathbf{w}, p, z) = [x_1(\mathbf{w}, p, z), \ldots, x_n(\mathbf{w}, p, z)]$, with the unintended consequence of each farmer's decisions being pollution level $a(\mathbf{x}^*, z)$. The supply of input i to the farmer is $x_i^s(\mathbf{v}, w_i)$ for all inputs x_i, $i = 1, \ldots, n$, where $\mathbf{v}$ is the input prices faced by suppliers of input i and w_i is their output price. This allows for possible feedback from market-level decisions by all farmers on input price, with perfectly elastic supply as one limiting case.

Suppose that initially the markets for output and all inputs are in equilibrium with prices p^0 and input prices w_j^0 for all j.[4] The regulatory authority institutes a tax t_i per unit of input i as a measure to reduce pollution from a^0 to $a^1 < a^0$. This policy tool creates a difference between the supply and demand price of input i, given by

$$(1) \qquad t_i \equiv w_i^d(x_i^t, \overline{\mathbf{w}}_i, p, z) - w_i^s(\mathbf{v}, x_i^t)$$

where $w_i^d(x_i^t, \overline{\mathbf{w}}_i, p)$ and $w_i^s(\mathbf{v}, x_i^t)$ are the inverse demand and inverse supply functions for input i, respectively, $x_i^t \equiv x_i^d(w_i^s + t_i, \overline{\mathbf{w}}, p, z) \equiv x_i^s(\mathbf{v}, w_i^s)$ is the resulting quantity in the market corresponding to t_i, and $\overline{\mathbf{w}}_i$ is the complement of w_i in $\mathbf{w}$. By the second-order conditions for profit maximization, the input demand and output supply functions are strictly monotonic in all prices whenever quantity is positive so that the inverse functions are well defined in the positive orthant.

By the envelope theorem, changes in economic welfare to producers resulting from the policy-induced change in w_i can be analyzed in the market for input i (Just, Hueth, and Schmitz). The tax t_i creates a deadweight loss given by

$$(2) \qquad DWL_i = \int_{x_i^t}^{x_i^0} \left\{ w_i^d(r, \overline{\mathbf{w}}_i, p, z) - w_i^s(\mathbf{v}, r) \right\} dr$$

[4] The analysis can incorporate constraints or distortions in one or more input markets if desired, but this is beyond the scope of the present treatment.

where the variable of integration is quantity of input i. This does not account for the environmental benefits to society from reducing pollution, which will be equal for all policies in the cost-effectiveness analysis. Implicitly, too, the comparisons of expressions such as equation (2) for different policies presume that the transaction (enforcement, monitoring, administration) costs are roughly comparable for each, and that there are no substantial differences in the social benefit of tax revenues raised by each policy.

Marginal and Cumulative Deadweight Loss from Input Taxation

Deadweight loss and pollution are parametrically related through the policy maker's choice of tax policy t_i, which changes relative prices in the system of input demands and in turn affects the input mix, yield, and nitrate leached.

Consider first the effects of t_i on deadweight loss. As t_i increases it induces a reduction in the quantity sold x_i^t, which in turn increases deadweight loss. Marginal deadweight loss caused can be expressed as $dDWL_i = (\partial DWL_i/\partial x_i)dx_i$, or

$$(3) \qquad dDWL_i = -t_i \cdot dx_i$$

since $\partial DWL_i/\partial x_i^t = -\{w_i^d(x_i^t) - w_i^s(x_i^t)\} = -t_i$ by Leibniz's Theorem. (Inessential arguments of inverse demand and supply are suppressed.) Incremental deadweight loss is positive since $dx_i < 0$ for an increase in w_i^d.

Now to link the pollution resulting from this increase in w_i^d to the change in deadweight loss, note that the effect of the resulting change dx_i in usage of input i on the amount of pollution produced is

$$(4) \quad da = \left\{ \sum_j (\partial g/\partial x_j)(\partial x_j/\partial w_i^d)(\partial w_i^d/\partial x_i) \right\} dx_i, = (a/x_i)\left\{ \sum_j \omega_j \eta_{ji}/\eta_{ii} \right\} dx_i$$

where $\omega_j \equiv (\partial g/\partial x_j)(x_j/a)$ and $\eta_{ji} \equiv (\partial x_j/\partial w_i^d)(w_i^d/x_j)$ are the elasticities of pollution with respect to a change in input j and the demand elasticity of input j with respect to a change in w_i^d, and η_{ii} is input i's own-price elasticity. From equation (4), it can be seen that the term in braces is the elasticity of pollution production with respect to a change in x_i, defined as $\varepsilon_i^p \equiv$

$(da/dx_i)(x_i/a) = \sum_j \omega_j \eta_{ji}/\eta_{ii}$, as the tax policy induces optimal changes in all input usage. Using this in equation (4) and rearranging to solve for dx_i results in

$$(5) \quad dx_i = (x_i/\varepsilon_i^p)E_a$$

where $E_a \equiv da/a$ is the desired percentage reduction in pollution. Substituting equation (5) into equation (3) links the marginal deadweight loss to a given percentage reduction in pollution:[5]

$$(6) \quad dDWL_i = \{TR_i/\varepsilon_i^p\}E_a$$

where $TR_i \equiv t_i x_i$ is the revenue generated by the tax on input i.

Equation (6) expresses the marginal cost effectiveness of any single-input tax policy t_i. It accounts for the market surplus change (foregone producer's and consumer's surplus and government revenues) in a setting where both input supply and demand prices respond to changes in quantity. The "best" single-input tax at the margin is the one for which the left side of equation (6) is smallest, given that implementation and administration costs are comparable for all the tax policies being evaluated. The choice depends on two factors: marginal deadweight loss increases as tax revenues increase and decreases as the elasticity of pollution with respect to that input increases. The third factor, the size of the desired reduction in pollution, affects the magnitude of marginal deadweight loss but not the choice of best policy as the policies are compared for a given E_a (which presumably is small for marginal changes).

To get a cumulative deadweight loss estimate for nonmarginal pollution changes, a series of small reductions in a from its initial level, a_0, to its final level, a_1, are taken, and for each step, equation (6) gives the incremental deadweight loss. If there are m steps of $(a_1 - a_0)/m$ each, on the kth step the level of nonpoint pollution is $a_k = a_0(1 - k/m) + a_1(k/m)$, and the system of $n + 1$ equations $w_i^d(\mathbf{x^k}) = w_i^s(\mathbf{x^k}) + t_i^k$, $w_j^d(\mathbf{x^k}) = w_j^s(\mathbf{x^k})$ for $j \neq i$ and $a_k = g(\mathbf{x^k})$ solves for the $n + 1$ endogenous variables $\mathbf{x^k} = (x_1^k, \ldots, x_n^k)$ and t_i^k, provided the determinant of the Jacobian matrix for the system is nonvanishing. Using these values, an estimate of $dDWL_i^k$ for the kth step is obtained, and the numerical estimate of deadweight loss for tax policy t_i is simply $DWL_i \doteq \Sigma_k dDWL_i^k$.

The cumulative first-best deadweight loss estimate, DWL^*, is used to calculate the welfare losses associated with the different second-best policies. For this estimate, taxes t_i^* on all inputs i are chosen to minimize deadweight loss and satisfy $\partial DWL/\partial t_j = \partial DWL/\partial t_k$ for all pairs of inputs j and k. The second-order conditions for optimal choice by demanders and suppliers of inputs assure that the solution will represent a minimum of deadweight loss. On the kth iteration, the $2n$ equations consisting of $w_i^d(\mathbf{x^k}) = w_i^s(\mathbf{x^k}) + (t_i^*)^k$ for all inputs i, the pollution function $a_k = g(\mathbf{x^k})$, and the $n - 1$ conditions for optimal input choice $\partial DWL/\partial(t_i^*)^k = \partial DWL/\partial(t_g^*)^k$ for $g \neq i$ solve for the $2n$ endogenous variables $\mathbf{x^k}$ and $\mathbf{t^k} = [(t_1^*)k, \ldots, (t_n^*)^k]$.

An Empirical Application: Nitrate Leaching in the Salinas Valley

The Salinas Valley in California supports a wide variety of fresh vegetable and fruit production, including lettuce, broccoli, cauliflower, artichokes, and strawberries. A moderate year-round climate and intensive cultivation practices mean that two crops, and sometimes more, can be grown. The amount of fertilizer taken up by plants, as opposed to leaching through the root zone, depends on several factors but is heavily influenced by frequency and duration of irrigation and the amount of fertilizer applied.

As part of work designed to better understand the physical, biological, chemical, and hydrological processes at work in Salinas Valley agriculture, the Erosion Productivity Impact Calculator (EPIC) model was calibrated for use in predicting crop cultivation practices, crop yields for lettuce, and nitrate leaching in the Salinas Valley. EPIC is a comprehensive computer model developed to simulate agricultural crop production, including leaching of salts and nitrates with the potential to affect ground and surface water quality (Sharpley and Williams). It determines crop production and pollution runoff for a given set of farm management practices and technology, by processing the interactions among weather, hydrology, erosion, plant growth, and soil and can be used for different crops, rotations, cultural practices, tillage, and irrigation and fertilization regimes. A large data base of soil and weather parameters

[5] Taxing one input may not lead to a reduction in pollution. In equation (4), η_{ji} is positive for substitute inputs; ω_j is positive for polluting inputs. If a farmer's response to an input tax is to substitute to other inputs that also contribute to pollution, then the single input-tax could have the perverse effect of increasing pollution.

for most of the United States allows it to be used for site-specific applications. These parameters can be changed to simulate different field conditions.

EPIC was calibrated to Salinas lettuce growing conditions for spring and summer 1990 double-crop production (Jackson et al.). A data set was generated from 756 runs of EPIC using 35 levels of water and 20 levels of nitrogen use in various combinations, ranging from 30 to 230 kg/hectare of nitrogen and 200 to 1,600 mm/hectare of water, with the resulting lettuce yield and nitrate leached per acre also recorded. Observations were generated for input levels above and below the "baseline" input management practice, applications of 750 mm/ha of water and 180 kg/ha of nitrogen, respectively, per crop season. These data "points" were used to estimate lettuce production functions and a nitrate leaching function, conditional on the harvesting and irrigation technologies actually used in 1990, as well as the 1990 climate pattern. The use of such conditional functions is probably reasonable in this analysis because, within the range of alternatives considered, major changes in technology or uses of capital and labor are thought to be unlikely.

Water is applied six times in equal quantities throughout the crop season, and nitrogen is applied three times in unequal quantities. The same application schedules were used for all scenarios because, according to farm advisors and growers in this region, for input use in the vicinity of baseline" practices, farmers would use roughly the same proportion of inputs for each application. This is especially true if irrigation and fertilization are applied via a drip-line system.

Crop yield and nitrate pollution runoff functions were estimated using the ordinary least squares and nonlinear least squares algorithms in SHAZAM version 6.2. Three different yield functions and one pollution function were estimated. The specifications for yield were

(Mitscherlich-Baule)

$$Y = \beta_0[1 - \exp(\beta_1 + \beta_2 N)][1 - \exp(\beta_3 + \beta_4 W)] + \varepsilon,$$

(quadratic)

$$Y = \beta_0 + \beta_1 N + \beta_2 W + \beta_3 N \cdot W + \beta_4 N^2 + \beta_5 W^2 + \varepsilon,$$

(square-root)

$$Y = \beta_0 + \beta_1 N + \beta_2 W + \beta_3 N \cdot W + \beta_4 N^{0.5} + \beta_5 W^{0.5} + \varepsilon,$$

where Y, N, and W represent lettuce yield, nitrogen applied, and water applied, respectively, and ε is the disturbance term. The nitrate pollution function used is a restricted version of the quadratic and square-root functions with statistically insignificant second-order terms omitted, explaining nitrate leached (NO_3) as

(nitrate pollution)

$$NO_3 = \beta_0 + \beta_1 N + \beta_2 W + \beta_3 N \cdot W + \varepsilon.$$

Results of the production and nitrate pollution function estimation are given in table 1. All of the production functions are highly significant with coefficient estimates generally significant at the 1% confidence level, and goodness of fit ranging from 0.65 (quadratic) to 0.82 (Mitscherlich-Baule) for the lettuce yield functions and equal to 0.96 for the nitrate pollution function. Chi-squared tests for model significance against the alternative of no relationship are highly significant.

Estimating the Welfare Costs of Single-Input Taxation

Tax policies were designed to achieve a 20% reduction in estimated nitrate runoff per acre, from a baseline level of roughly 114 kilograms/hectare (kg/ha) to 91 kg/ha. Initial input prices were \$0.23 per millimeter per hectare (mm-ha) for water and \$0.70/kg for nitrogen fertilizer.[6] It was assumed that each input, nitrogen and water, was elastic in supply with $\varepsilon^s = 5.0$. Second-best tax policies involving taxation either of nitrogen alone or of water alone were determined to meet this goal, and the deadweight loss was calculated according to equation (8). These loss estimates were then compared to the minimum deadweight losses required to achieve nitrate reductions by regulating water and nitrate jointly. Results of these simulations, for the quadratic, square-root, and Mitscherlich-Baule lettuce yield functions, are presented in table 2.

The simulations show that taxing water use is the best in terms of deadweight loss per hectare. This result is robust across functional forms (figure 1). The efficiency loss from taxing only nitrogen is very high using the Mitscherlich-Baule yield function because it allows little substitu-

[6] The different production functions produce somewhat different optimal input choices under profit maximization and, thus, different estimated baseline levels of pollution. To ensure consistent comparisons of cost-effectiveness for pollution reduction across production functions, input prices were adjusted so that the same baseline input combination (750 mm of water and 180 kg of fertilizer per hectare) and pollution level (114 kg/hectare) was a profit maximum for each production function. In all cases, the needed adjustments to input prices were relatively minor, within plus or minus 20% of the actual prices.

Table 1. Estimation Results for Lettuce Production Functions and the Nitrate Pollution Function (Student's t-statistics in Parentheses)

Variable	Production Function: Mitscherlich	Production Function: Quadratic	Production Function: Square-root	Pollution Function
Intercept	3.26	2.52	0.629	–26.06
	(5.48)	(72.0)	(9.1)	(–6.80)
N-Intercept	–2.25			
	(–12.7)			
W-Intercept	1.25			
	(13.9)			
N	–2.44E-2	5.35E-4	–3.64E-3	–1.52E-1
	(–5.73)	(1.48)	(–8.5)	(–6.09)
W	–1.27E-2	1.51E-3	–3.09E-3	1.58E-1
	(–11.2)	(26.9)	(–46.7)	(40.77)
$N \cdot W$		2.00E-6	2.00E-6	3.63E-4
		(10.4)	(13.5)	(14.44)
N^2		–5.38E-6		
		(–4.63)		
W^2		–8.85E-7		
		(–31.66)		
$N^{0.5}$			5.94E-2	
			(6.5)	
$W^{0.5}$			1.70E-1	
			(47.4)	
Adj. R^2	0.82	0.65	0.80	0.96
F	3,152	277	582	5,634
χ^2 ($\beta = 0$)	5,460	4,974	5,380	4,324

Table 2. A Comparison of Deadweight Loss per Hectare to Reduce Nitrate Pollution for Alternative Tax Policies and Lettuce Yield Functions

	Level of Nitrates (kg/ha)	First-Best Taxes ($/ha)	Taxing *N* Only ($/ha)	Taxing *W* Only ($/ha)
Quadratic	114.00	0.000	0.000	0.000
	109.44	0.373	1.031	0.384
	104.88	1.410	3.951	1.447
	100.32	3.131	8.919	3.204
	95.76	5.565	16.139	5.680
	91.20	8.739	25.845	8.897
Square-Root	114.00	0.000	0.000	0.000
	109.44	0.339	0.683	0.354
	104.88	1.329	2.855	1.385
	100.32	3.062	7.083	3.180
	95.76	5.646	14.219	5.843
	91.20	9.200	25.589	9.486
Mitscherlich	114.00	0.000	0.000	0.000
	109.44	0.048	4.034	0.048
	104.88	0.196	21.762	0.199
	100.32	0.473	71.703	0.481
	95.76	0.916	192.165	0.933
	91.20	1.576	445.935	1.606

tion in production between inputs, and the pollution function is more elastic with respect to water use than nitrogen applications. Since the wrong input is being taxed, high nitrogen taxes are required to reduce pollution.

The efficiency loss (increase in deadweight loss) from regulating water alone is small relative to regulating both inputs optimally. This suggests that taxing water alone can achieve nitrate reductions nearly as effectively as first-best taxation. When the additional complexity and cost of getting the taxes on both inputs right" are considered, water taxes (or other measures to increase the marginal cost of water such as water marketing) may in fact be the best way to reduce nitrate runoff. This is similar to a result obtained by Weinberg, Kling, and Wilen.

The magnitude of lost quasi-rents from a water tax is modest in relation to the overall revenues from lettuce production (figure 2). With no taxes, estimated quasi-rents are in the vicinity of \$3,950–\$4,350/ha, depending on the yield function, and the reduction in quasi-rents associated with a 20% reduction in nitrate is approximately \$100/ha or less for the quadratic and square-root yield functions. The Mitscherlich-Baule predicts higher quasi-rent losses, but, as noted previously, this is due to extremely limited input substitution.

Another consideration is the tax bill generated by different tax policies. These can be determined from table 3, which reports input use patterns associated with the first- and second-best tax strategies for the square-root production function. A water-only tax of about \$0.21/mm-ha would achieve a 20% reduction, costing roughly \$138 in tax payments. The 20% nitrate reduction could also be achieved by a nitrogen-only tax of \$0.76/kg with associated tax bill of \$79, or by jointly taxing both inputs with associated tax bill of \$132. Interestingly, the tax bill for nitrogen-only taxation is lower even though higher deadweight loss results due to a greater percentage reduction in nitrogen use. In light of both the tax bill (a redistribution) and the estimates of production revenues, the efficiency losses from water-only regulation appear relatively insignificant.

Effects of Heterogeneity in Production and Pollution

The prescriptions for best single-input tax policy developed above implicitly assume homogeneous production and pollution relationships; that is, all farms have the same production technology, and the pollution that results from farmer decision is uniformly mixed. Substantial heterogeneity across farms in either relationship could change the recommendation about the least deadweight loss single-input tax policy. In this case, the preferred (smallest deadweight loss) policy in practice might be determined by the distribution of farms in different production or pollution classes, with the preferred policy having the smallest sum of deadweight losses across classes.

While generalizations are difficult in such a situation, and a complete analysis of the topic is beyond our scope here, one can develop simple rules about when the recommended second-best policy choice would not be sensitive to production or pollution heterogeneity. Assume the single heterogeneous characteristic is an index of soil quality (e.g., porosity) and, in keeping with the empirical analysis above, assume that the two main inputs that generate nitrate pollution, water and nitrogen applications,

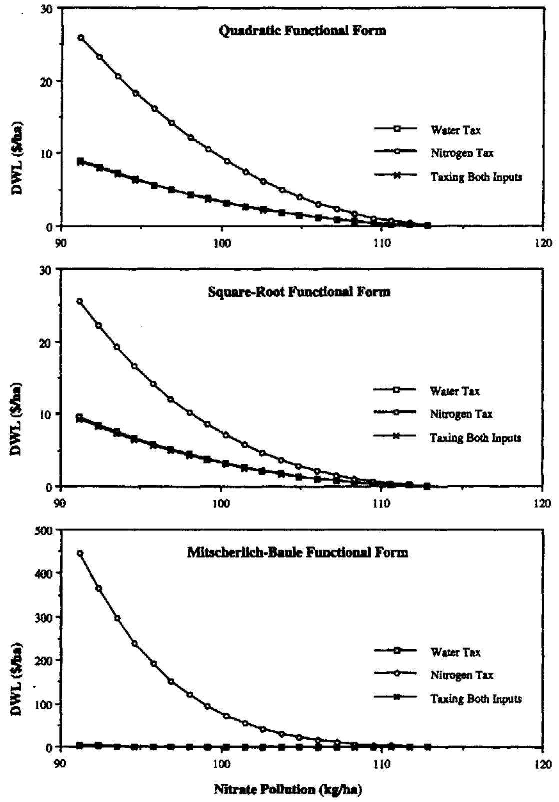

Figure 1. Deadweight loss associated with nitrate reductions

Table 3. Comparison of First- and Second-Best Tax Policies to Reduce Nitrate Pollution with Square-Root Lettuce Yield

First-Best: Taxing Water and Nitrogen Optimally

Level of Nitrates (kg/ha)	Water Tax ($/mm-ha)	Nitrogen Tax ($/kg)	Water Use (mm-ha)	Nitrogen Use (kg/ha)
114.00	0.000	0.000	750.00	180.00
109.44	0.027	0.014	733.74	173.17
104.88	0.060	0.029	716.44	166.31
100.32	0.096	0.045	698.63	159.68
95.76	0.137	0.061	680.30	153.31
91.20	0.183	0.076	661.45	147.22

Second Best Policies: Taxing Individual Inputs

	Taxing Nitrogen Only			Taxing Water Only		
Level of Nitrates (kg/ha)	Nitrogen Tax ($/kg)	Water Use (mm/ha)	Nitrogen Use (kg/ha)	Water Tax ($/mm-ha)	Water Use (mm/ha)	Nitrogen Use F(kg/ha)
114.00	0.000	750.00	180.00	0.000	750.00	180.00
109.44	0.083	737.21	166.60	0.033	733.00	174.59
104.88	0.191	723.71	152.07	0.071	715.04	169.14
100.32	0.331	709.91	136.79	0.113	696.68	163.83
95.76	0.514	695.77	120.67	0.159	677.93	158.66
91.20	0.764	681.25	103.60	0.209	658.79	153.63

have perfectly elastic supplies. (This is probably reasonable in a regional analysis such as for the Salinas Valley.) A first-order approximation to the cumulative deadweight loss due to a tax on input i is

$$(7) \quad DWL_i \doteq -\tfrac{1}{2} \cdot \Delta w_i^d \cdot \Delta x_i$$

since $t_i = \Delta w_i^d$ in this case. Now $\Delta w_i^d \doteq (dw_i^d/dx_i)\Delta x_i$, where dw_i^d/dx_i is the slope of the inverse demand function for input i; from the first-order condition for optimal input choice, this is $dw_i^d/dx_i = p\Sigma_j f_{ij}(\mathbf{x}, z)(\partial w_j/\partial x_i)dx_i$, where $f_{ij}(\mathbf{x}, z)$ are the cross-partial derivatives of the production function with respect to x_i and x_j. Since the tax policies are designed to achieve a given reduction in pollution Δa, one can write $\Delta a \doteq (da/dx_i)\Delta x_i$, or $\Delta x_i = \Delta a/(da/dx_i)$, where da/dx_i is the marginal change in pollution with x_i, given in equation (4). Using these expressions for Δw_i^d and Δx_i in equation (7),

$$(8) \quad DWL_i \doteq -\frac{dw_i^d/dx_i}{2(da/dx_i)^2}(\Delta a)^2.$$

From equation (8) it can be seen that the approximate total deadweight loss of a tax on input i relative to deadweight losses from other input taxes depends on the slope of inverse demand for input $i(dw_i^d/dx_i)$ and the marginal reduction in pollution with a small change in use of input i (da/dx_i). If, in comparing taxes on two inputs i and j, policy i is preferred for a reference level of soil quality z_0, then

$$(9) \quad \frac{-dw_i^d(\mathbf{x}, z_0)/dx_i}{[da(\mathbf{x}, z_0)/dx_i]^2} < \frac{-dw_j^d(\mathbf{x}, z_0)/dx_j}{[da(\mathbf{x}, z_0)/dx_j]^2}.$$

For a tax on input i to be best regardless of soil quality, as z varies, the inequality in equation (9) must be maintained. A sufficient condition for this is that $\partial DWL_i/\partial z < \partial DWL_j/\partial z$, which can also be expressed as

$$[\%\Delta(dw_i^d/dx_i) - \%\Delta(da/dx_i)^2] \cdot DWL_i < [\%\Delta(dw_j^d/dx_j) - \%\Delta(da/dx_j)^2] \cdot DWL_j$$

as the heterogeneity index z varies. If, as soil quality varies, the percent change in inverse demand slope for input i is less (or the percent change in marginal nitrate leaching with input i

is greater) than for other inputs, *ceteris paribus*, a tax on input i will continue to have smaller deadweight loss.

Conclusions

In this paper an approach is presented for evaluating second-best input taxation to achieve reductions in nonpoint source pollution. Input taxes introduce incentives to meet pollution reduction goals, and the resulting deadweight losses can be taken as the costs of meeting those goals. Administrative costs, political constraints, or diminishing marginal efficiency gains may make it impossible (or unnecessary) to regulate all polluting inputs in a first-best way. A useful way to evaluate which inputs to regulate is to consider the additional efficiency costs from intentionally suboptimal regulation.

The suggested approach can be used with information often available to agencies, namely a physical process model which yields estimates of pollution production and of crop yields. Such models are now available widely and can be calibrated to area-specific conditions. The question of which input(s) to tax to achieve reductions in nitrate pollution from fresh lettuce production in the Salinas Valley of California was evaluated using results of EPIC calibrated to local growing conditions. Water was found to be the best single input to tax, and the welfare cost of second-best regulation of water alone was not large. Results suggest that water market incentives could achieve nonpoint source reduction goals at relatively low efficiency costs.

Some limitations on generality should be noted. The welfare-theoretic framework does not explicitly consider policy transactions costs and compliance issues associated with the choice of second-best instruments. Neither is there any explicit consideration of the fact that the social value of a dollar of tax revenues may be less than unity. To the extent that these elements are likely to differ substantially across policy alternatives, the welfare evaluation framework should include them. For other crops than California produce, policy distortions (e.g., from commodity programs) may also be of special interest in light of their effects on tax policy coordination.

Several extensions are possible. One natural extension is to incorporate potentially observable differences between farms such as differences in soil types, which will affect both pollution generation and production. Uncertainty about the pollution and crop production functions could affect the choice of which input to regulate; for instance, a higher variance in the distribution of nitrate leaching could make one policy less attractive than an alternative with lower nitrate leaching variance but higher deadweight loss. It appears that EPIC can be a useful tool for considering heterogeneity of farms, but it is not clear at present whether EPIC can easily and realistically generate the dispersion of nonpoint pollution encountered in field conditions.

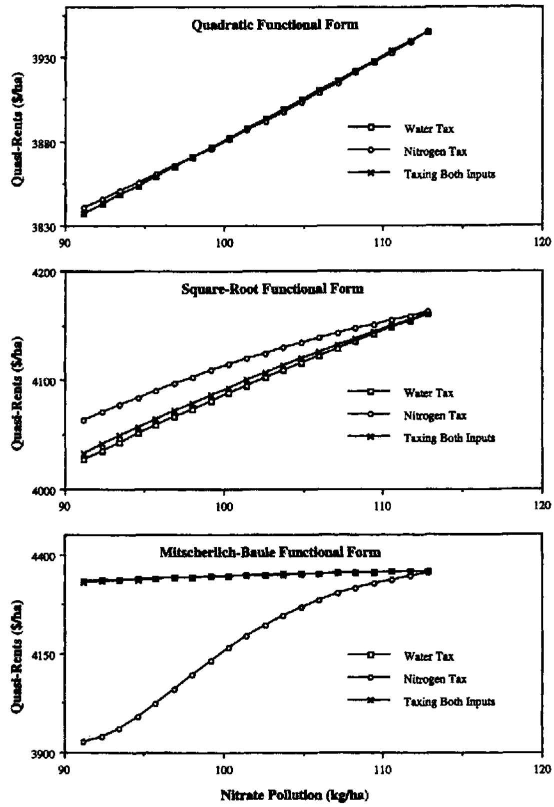

Figure 2. Quasi-rents associated with nitrate reductions

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Erratum

In the *AJAE* article by Harvey Lapan and Giancarlo Moschini, "Futures Hedging Under Price, Basis, and Production Risk," Volume 76, Number 3, August 1994, equations (53) and (54) were garbled at the typesetting stage. As the article's discussion following equation (54) suggests, these equations should have read as follows:

$$(53)\qquad p_{2,t}^r = \alpha_{21} + \sum_{j=2}^{6} \alpha_{2j} D_{j,t} + \alpha_{2F} p_{1,t-g} + \alpha_{2L} p_{2,t-1}^r + \varepsilon_{2,t}^r$$

$$(54)\qquad y_t^r = \alpha_{31} + \sum_{j=2}^{6} \alpha_{3j} D_{j,t} + \alpha_{3F} p_{1,t-g} + \alpha_{3L} y_{t-1}^r + \alpha_{3T} T_t + \varepsilon_{3,t}^r.$$