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The Welfare Sensitivity of Agri-Environmental Instruments

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Most economic studies of pollution control analyze policies that are optimal for a given set of underlying parameters. Less understood is how such policies perform when the underlying parameters change and policies are not adjusted in response, or what the benefits of adjustment are. We construct several measures of welfare sensitivity and use them to analyze the welfare impacts arising in a simulation of second-best, agri-environmental policies.

Key words: emissions standards, emissions taxes, environmental policy, input standards, input taxes, nonpoint pollution, policy adjustment

Introduction

The economic literature on the control of pollution from agriculture and other sources primarily assesses the performance of optimally designed policy instruments given a particular set of market, technological, and environmental conditions. In reality, the conditions under which instruments are designed can be expected to change, possibly quite frequently. Optimality therefore requires potentially frequent instrument adjustments in response to exogenous change, provided the adjustment costs (e.g., administrative costs) are not too great.[1] But even when adjustments are economically justified, the political costs of adjustment might be prohibitive because those who would be adversely affected would have incentives to lobby and apply political pressure to prevent adjustment. Adjustments may be economically and/or politically optimal if the welfare loss from nonadjustment is sufficiently large (relative to political and transactions costs).[2] Policy instruments for which this condition is not met may optimally be "sticky."[3]

Given adjustment may be costly, what are the opportunity costs of nonadjustment, and how do these costs vary by the type of instrument (taxes versus limits) and/or the

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[1] It may also be optimal to make adjustments as uncertainty about existing and probable future conditions is diminished (Zhao and Kling).

[2] In this context, economically optimal refers to the maximization of net social surplus, accounting for adjustment costs. Politically optimal refers to an outcome that optimizes the political benefits resulting from allocating economic benefits across society. (See, e.g., Gardner, and Rausser and Foster for discussions of political-economic models.)

[3] A number of studies assess the economic and/or political forces that could create costly adjustment. For instance, a large macroeconomic literature examines how price stickiness (nominal rigidities) could arise if the costs of frequently changing prices are significant (see Blanchard and Fischer, chapter 8, for an overview). Several recent studies investigate how instrument stickiness may be an equilibrium outcome of political-economic markets (e.g., Coate and Morris; Fernandez and Rodrik).

compliance measure (emissions versus polluting inputs)? These questions remain largely unaddressed in the environmental literature. Bohm and Russell examined the environmental (but not welfare) impacts of nonadjustment by analyzing how producers respond to exogenous change when instruments are sticky. Their primary focus was "the ease with which the system maintains the desired ambient standards as the economy changes," or the "flexibility" of environmental instruments (p. 416).

Expanding on this concept, we consider a related notion which we call "sensitivity." Sensitivity measures how exogenous change affects an instrument's economic performance given that instruments are not adjusted. Thus, sensitivity is closely related to an instrument's relative efficiency—particularly when adjustment costs are large.

We propose two categories of sensitivity. The first is pre-adjustment sensitivity, which measures changes in welfare (to society as a whole and to various groups) when instruments are not adjusted in response to exogenous change or shocks. Greater pre-adjustment sensitivity indicates greater welfare responsiveness to shocks. The desirability of greater sensitivity may be influenced by a variety of economic and political forces. For instance, when policy adjustments cannot easily occur, instruments that minimize welfare sensitivity to shocks might be desirable (e.g., to reduce the risk of increasing expected damages). Indeed, there may be a bias toward the status quo given uncertainty regarding the distribution of gains and losses which might result from a shock (Fernandez and Rodrik), such as when the type and direction of the shock cannot be determined a priori.

A related issue is the widely held belief that, since incentives provide producers with more flexibility than limits in responding to shocks, incentives will better enable producers to respond in ways designed to minimize adverse economic consequences or maximize economic gains. Similar beliefs are held with respect to instruments based on environmental performance measures or proxies relative to input-based instruments. We examine these beliefs and find they are not always supported.

The second type of sensitivity is post-adjustment sensitivity, which measures the welfare gains (or, for some groups, losses) of optimally adjusting an instrument relative to the case of non-adjustment (assuming costless adjustment). Greater post-adjustment sensitivity indicates greater welfare responsiveness to adjustment. If, for a particular instrument, welfare is not sensitive to adjustment, then there is little need for adjustment in response to a shock. Given costly adjustment, environmental managers may prefer instruments for which post-adjustment sensitivity is small. We examine several types of instruments and identify those for which the benefits from adjustment are small, and thus frequent adjustments may not be required.

Welfare sensitivity issues are particularly relevant in the nonpoint setting, where first-best instruments are generally too complex to be practical and the number of second-best instruments to consider may be large (Helfand and House; Shortle, Horan, and Abler).[4] If several instruments exhibit similar performance in terms of efficiency, then it may be worthwhile to examine sensitivity as a secondary indicator of performance. In this study, we simulate corn production and related environmental outcomes

[4] Efficient nonpoint pollution control instruments are highly complex. They are site-specific when producers have heterogeneous marginal environmental impacts, and are applied to each relevant production choice (Shortle, Horan, and Abler). In more realistic settings, instruments may be applied uniformly across heterogeneous producers and/or only based on a few inputs or on performance proxies such as estimated emissions. Instruments designed to provide maximum social welfare under these (uniformity and/or application basis) restrictions are often called "second-best" (Helfand and House).

to compare the performance of several second-best instruments, where performance is measured in terms of relative efficiency and welfare sensitivity to changes in key production, environmental, and market parameters.

Sensitivity Measures

We begin by defining pre- and post-adjustment sensitivity. Let expected social net benefits from corn production, *SNB*, be a function of a $(1 \times s)$ vector θ of productivity, market, and environmental parameters. *SNB* is the sum of expected net benefits to consumers, producers, resource owners, and those damaged by the externality. Let $\mathbf{t}$ be a $(1 \times m)$ vector of policy instruments chosen to maximize *SNB*, given θ and subject to producer responses, i.e.,

(1)
$$\mathbf{t}(\theta) \equiv \text{argmax } SNB(\theta, \mathbf{t})$$
$$\text{s.t.: } \underset{\mathbf{x}}{\text{Max}}\, PNB(\mathbf{x}, \theta, \mathbf{t}),$$

where *PNB* represents the private net benefits to producers and $\mathbf{x}$ is a vector of their input choices. With $\theta = \theta_0$, $SNB(\theta_0, \mathbf{t}(\theta_0))$ defines optimal expected social net benefits. Define $NB_i(\theta_0, \mathbf{t}(\theta_0))$ $(i = 1, \ldots, n)$ as expected net benefits to the ith group receiving economic benefits from production (i.e., consumers, producers, resource owners, or those damaged by the externality).

Consider an exogenous change in one or more of the individual parameters, θ_k. When the change occurs, producers take the new vector θ as given and adjust their input choices to maximize *PNB*. The policy vector $\mathbf{t}$ must also be adjusted to optimally account for the change.[5] If an optimal adjustment is made, then *SNB* and NB_i are adjusted optimally as well. At the margin, the optimal adjustment in *SNB* for a change in one or more parameters θ_{0k} is written as:[6]

(2)
$$dSNB = \sum_{k=1}^{s} \frac{\partial SNB}{\partial \theta_k}\Big|_{\mathbf{t}=\mathbf{t}(\theta_0)} d\theta_k + \sum_{k=1}^{s}\sum_{j=1}^{m} \frac{\partial SNB}{\partial t_j}\frac{\partial t_j}{\partial \theta_k}\, d\theta_k.$$

Adjustments for other welfare measures, NB_i, are analogous. The first term on the right-hand side (RHS) of (2) is the change in *SNB* holding all policy variables constant. The second RHS term is the welfare effect of adjusting $\mathbf{t}$ in response to the change in θ. Because policy adjustment costs are not modeled explicitly, the second term represents the maximum potential gain from adjusting $\mathbf{t}$.

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[5] The shocks are not assumed to follow a known random process. If this were the case, then the regulatory agency would optimally choose policy variables to maximize expected welfare given the random shocks (as opposed to adjusting policy variables in response to the shocks). There are many important analogies between the deterministic and stochastic cases. In both situations, policy values determined prior to the shock will be suboptimal given the realized shock. Thus, our notion of post-adjustment welfare sensitivity is analogous (at least for first-best instruments; see below) to the ex ante/ex post welfare differences introduced by Weitzman for the stochastic case (in expectation, these differences are the value of having perfect prior information about the shocks). Given the majority of models that examine policies addressing nonpoint problems assume deterministic, fixed parameters, we have chosen to focus on the deterministic case.

[6] Adjustment on the part of producers and/or policy makers can be modeled as a static or dynamic process depending on how adjustment costs enter into the model. Firms adjust over time if they face convex investment costs associated with quasi-fixed factors such as capital. Policy instruments are optimally adjusted over time if (*a*) firms adjust over time, and/or (*b*) the political costs or transactions costs associated with policy adjustment are convex. While dynamic aspects of adjustment may be of interest, they greatly complicate the analysis and can make it more difficult to gain important insights which can be obtained more easily from a static approach. Therefore, we adopt a static framework, following the approach taken by Bohm and Russell in their analysis of flexibility, and by Blanchard and Fischer (chapter 8) in their analysis of nominal rigidities.

Pre-Adjustment Sensitivity

Suppose **t** is not adjusted in response to changes in one or more θ_k. However, producers will adjust (to some degree, depending on the instruments in place), and so *SNB* and other welfare measures adjust accordingly. From equation (2), the welfare effects of producer adjustments can be written as a percentage change (with analogous expressions for other welfare measures):

$$(3) \qquad \frac{dSNB\,|_{\mathbf{t}=\mathbf{t}(\theta_0)}}{SNB} = \sum_{k=1}^{s} \varepsilon_{SNB,\theta_k} \frac{d\theta_k}{\theta_k},$$

where $\varepsilon_{SNB,\theta_k} = (\theta_k/SNB)(\partial SNB/\partial\theta_k|_{\mathbf{t}=\mathbf{t}(\theta_0)})$ is the elasticity of *SNB* with respect to θ_k, holding **t** constant ($\varepsilon_{SNB,\theta_k}$ may be positive or negative). Pre-adjustment sensitivity is measured by $|\varepsilon_{SNB,\theta_k}|$. The larger is $|\varepsilon_{SNB,\theta_k}|$, the greater the deviation in welfare from the status quo when there is a change in θ_k and **t** is held fixed.

Pre-adjustment sensitivity will generally differ for each affected group. For example, if θ_k is an environmental parameter that does not affect production, either directly or via environmental policy, then $\varepsilon_{PNB,\theta_k} = 0$. However, $\varepsilon_{SNB,\theta_k} \neq 0$ due to the impact of θ_k on expected damages.

Post-Adjustment Sensitivity

The second RHS term in (2) represents the welfare impacts of policy adjustment (absent any adjustment costs), given exogenous changes have already occurred. The associated percentage change in expected welfare (which is nonnegative for *SNB*, but may be positive or negative for other welfare measures) is:

$$(4) \qquad \frac{dSNB\,|_{\theta=\theta'}}{SNB} = \sum_{k=1}^{s}\sum_{j=1}^{m} \varepsilon_{SNB,t_j}\,\varepsilon_{t_j,\theta_k} \frac{d\theta_k}{\theta'_k},$$

where $\varepsilon_{SNB,t_j} = (\partial SNB/\partial t_j)(t_j/SNB)$; $\varepsilon_{t_j,\theta_k} = (\partial t_j/\partial\theta_k)(\theta'_k/t_j)$; and θ' is the new value of θ. Post-adjustment sensitivity is represented by

$$\eta_{SNB,\theta_k} = \sum_{j=1}^{m} \varepsilon_{SNB,t_j}\,\varepsilon_{t_j,\theta_k}.$$

If $|\eta_{SNB,\theta_k}|$ is large, then the efficiency gains from adjusting instruments may be significant, even in the presence of adjustment costs. However, if $|\eta_{SNB,\theta_k}|$ is small, then gains from adjustment might be small or even negative in the presence of adjustment costs.

Instruments associated with small values of $|\eta_{SNB,\theta_k}|$ are advantageous in that they may not require frequent adjustment, as the benefits of doing so are small. Two factors influence whether or not this is the case. First, gains or losses from adjustment might be small if expected welfare is not sensitive to changes in policy variables (i.e., $|\varepsilon_{SNB,t_j}|$ is small), even if policy variables are sensitive to parameter changes. Second, gains or losses from adjustment might be small if policy variables are not sensitive to parameter changes (i.e., $|\varepsilon_{t_j,\theta_k}|$ is small), even if expected welfare is sensitive to changes in policy variables. Unlike pre-adjustment sensitivity, η_{PNB,θ_k} will not generally vanish for changes in an environmental parameter which do not directly impact producer choices, because **t** is adjusted in response to all exogenous changes.

Below, it may be tempting to compare our results with those of Weitzman, who found incentives and limits do not perform equally when firms hold private information about control costs. As in Weitzman's analysis, there is asymmetric information in our model: firms have knowledge of the shock when making decisions while the government does not. But, in contrast to Weitzman's model, we cannot make similar welfare comparisons. Our post-adjustment sensitivity measures are elasticities; hence, they measure welfare differences relative to the post-adjustment optimum. If the policies being analyzed were first-best in the absence of asymmetric information (i.e., if the post-adjustment optimum were the same for each instrument, as is the case in Weitzman's model), then differences in the sensitivity measures would also provide insight into welfare differences. However, the instruments we consider are second-best, and ex post performance differs (if only slightly) for each instrument. Consequently, the post-adjustment measures we derive only measure differences in the proportional benefits and costs of optimal adjustment and not differences in relative efficiency. The sensitivity measures would have to be combined with information on ex post performance to gain a more accurate indication of welfare differences.

A Simulation Experiment

Little can be said theoretically about the sensitivity of different welfare measures under different types of second-best instruments. It should be possible to obtain policy-relevant insights by specifying the model in a realistic fashion. To this end, we have developed an experiment involving a large number of simulated watersheds. The use of simulated watersheds permits complete control over the design of the experiment and, by comparison to one or a small number of case studies of actual watersheds, increases our ability to investigate these issues for a variety of conditions. Although the watersheds are simulated, the relationships (i.e., functional specifications and parameter values) are representative of more realistic settings involving agricultural sources.

The simulation model has the same general structure as standard conceptual models of agricultural nonpoint pollution (e.g., Shortle, Horan, and Abler). Specifically, each watershed contains four nonpoint sources, where each source essentially represents classes of producers that vary according to cost structure and environmental impacts. These variations are taken to occur at a sub-watershed region level; thus, each source represents aggregate production within a region.

Producers in each watershed produce a single, identical agricultural commodity (corn) according to a constant-returns-to-scale, two-level constant elasticity of substitution (CES) technology (Sato). Corn production depends on a composite biological input and a composite mechanical input. The biological input is produced using land and fertilizer according to a constant-returns-to-scale CES technology. The mechanical input depends on labor and capital, but is not decomposed into these inputs because labor and capital prices are held fixed, and hence labor and capital are used in constant proportions. Production heterogeneity is created through input cost shares (see table 1), with Regions 1 and 2 using fertilizer more intensively on a per acre basis than Regions 3 and 4. Initial outputs and costs are identical across farms to reduce the impacts of scale effects among sources since heterogeneity does not occur along these lines. Aggregate revenue and costs for this sector are normalized to one. With all prices set equal to one initially, output equals revenue and inputs equal factor costs.

Table 1. Factor Cost Shares and Distribution of Uncertain Parameters

Region	Biological Cost Shares: Land	Biological Cost Shares: Fertilizer	Mechanical Cost Shares
Region 1	0.25	0.35	0.4
Region 2	0.25	0.35	0.4
Region 3	0.4	0.2	0.4
Region 4	0.4	0.2	0.4

Uncertain Parameters	Distribution	Mean	Variance	Sources and/or Justification for Parameter Ranges
Elasticity of demand	U(-1.2, -0.45)	-0.825	0.0469	Consistent with the domestic elasticity of demand for corn in the Corn Belt and Lake States. See Claassen and Horan (2001) for sources and derivation.
Elasticity of land supply	U(0.15, 0.45)	0.3	0.0075	See Claassen and Horan (2001) for sources and derivation.
Elasticity of substitution between composite inputs	U(0.1, 0.9)	0.5	0.0533	See Claassen and Horan (2001) for sources and derivation.
Elasticity of substitution between land and fertilizer	U(1.1, 1.4)	1.25	0.0250	See Claassen and Horan (2001) for sources and derivation.
Average per acre runoff:				
▸ Regions 1 and 3	U(0.2, 0.4)	0.3	0.0033	See Claassen and Horan (2001) for sources and derivation.
▸ Regions 2 and 4	U(0.1, 0.3)	0.2	0.0033	
Elasticity of per acre runoff	U(1, 2)	1.5	0.0833	See Claassen and Horan (2001) for sources and derivation.
Coefficient of variation: Ambient pollution (CVA)	U(0.1, 3)	1.55	0.7008	Koutsoyiannia (1999); Manguerra and Engel (1998)
Coefficient of variation: Runoff	U(0.1, CVA)	0.825[a]	0.1752[a]	Koutsoyiannia (1999); Manguerra and Engel (1998)
Runoff transport:				
▸ Regions 1 and 3	U(0.6, 0.9)	0.75	0.0075	Fisher et al. (1988); Smith, Schwarz, and Alexander (1997)
▸ Regions 2 and 4	U(0.01, 0.3)	0.155	0.0070	
Elasticity of damages	U(1.2, 2)	1.6	0.5333	The chosen bounds ensure an increasing, convex function.

[a] Denotes expected mean and variance, respectively.

Producers in each region operate in competitive markets, taking prices as given, although output and land prices are endogenous.[7] The output market is at the watershed level and output demand is a first-order approximation of actual demand. In contrast, land supply takes a constant elasticity form and is defined for each region.

Nonpoint emissions (runoff) per acre are influenced by fertilizer use per acre as well as a stochastic, weather-related term. Specifically, farm *i*'s runoff per acre, r_i/x_{i1} (where x_{i1} is land), is a second-order approximation of actual per acre runoff, which is taken to be an increasing, convex function of fertilizer use per acre, g_i, i.e, $r_i/x_{i1} = b_{1i}g_i + b_{2i}g_i^2 + v_ig_i$, where $g_i = x_{i2}/x_{i1}$, x_{i2} is fertilizer, and v_i is a random variable with zero mean. The specification for the random term is consistent with that of Just and Pope. In particular, a larger value of g_i (due to either more fertilizer or less land) results in a larger mean

[7] The geography of watersheds is characterized by diversity, varying greatly in size and economic importance. We assume a watershed of sufficient size and importance that changes in aggregate production have impacts on market price. The elasticity of demand is varied across watersheds to permit a range of price effects.

and variance of r_i/x_{i1}.[8] Regions 1 and 3 have larger initial average runoff per acre (i.e., $r_i/(x_{i1}g_i)$) and larger transport coefficients on average than other farms (table 1; see also the discussion of the Monte Carlo analysis below).

Runoff from each source is transported to a water body according to a stochastic process, although only a fraction of the runoff generated at each site becomes part of the ambient pollution concentration. The proportion of runoff transported is given by the constant transport coefficient, $\tilde{\omega}_i$. In aggregate, pollution transport and the resulting ambient pollution levels are reasonably represented by a first-order approximation (Roth and Jury) based on the sum of the transported runoff (loadings) from all sources, $a = (\psi + \delta)L$, where $L = \sum_{i=1}^{n} \tilde{\omega}_i r_i$ is loadings, ψ is a deterministic parameter, and δ is a random variable with zero mean. Thus, more loadings result in a greater mean and variance of a. Mean ambient pollution is normalized to equal one initially.

Finally, the resulting ambient pollution concentration creates economic damages, denoted D. Economic damages are a second-order approximation of actual damages, which is taken to be an increasing, convex function of a, i.e., $D = d_1a + d_2a^2$. D is calibrated by setting initial expected damages equal to 20% of initial net benefits (we use a slightly larger value than reported by Smith, as his value was only for groundwater damages and not damages that would arise due to surface runoff), and by choosing an elasticity of expected damages (table 1).[9]

The parameters used to calibrate the model for each watershed are drawn from a literature reporting a range of values. We address this parameter uncertainty through a Monte Carlo (sensitivity) analysis to obtain an ex post distribution of results (see Abler and Shortle; Davis and Espinoza). Specifically, the model is solved K times, taking many parameter values as randomly and independently distributed. Each iteration represents a single draw (sample) of all uncertain parameter values and, for each sample, parameter values (but not stochastic variables) are assumed known with certainty by both policy makers and producers. In effect, each sample represents an individual watershed. The results from each watershed are then used to form a distribution of results. For example, expected social net benefits in our sample are $\sum_{k=1}^{K} (\text{Max}_t\ SNB)/K$.

Uncertain parameter values are all assumed to be uniformly distributed according to reasonable bounds suggested by the literature. The parameters and their distributions are also reported in table 1 (the GAUSS v.3.2.38 random number generator is used in numerically solving the model). Source-specific values are allowed to differ for each Monte Carlo sample, although source-specific values of a particular parameter are all taken from the same distributions (unless specified otherwise).

The sample size K is chosen according to the procedure described by Abler, Rodríguez, and Shortle. If y is a welfare measure to be estimated by the Monte Carlo procedure, then K can be chosen such that, with 95% probability, the margin of error is no greater than e. The appropriate sample size is then computed as $K^* = (1.96/e)^2\sigma^2$, where σ^2 is the variance of the welfare samples. As we describe below, each welfare measure is computed

[8] Another source of uncertainty that may be important in the nonpoint case is uncertainty regarding the effectiveness of nonpoint controls (i.e., in terms of our model, the coefficients b_{1i} and b_{2i} would be uncertain) (Malik, Letson, and Crutchfield). This uncertainty may result from a lack of experience with nonpoint controls. While we do not model this type of uncertainty explicitly, we acknowledge it could be an important factor in the design and performance of nonpoint instruments. In particular, this type of uncertainty could be important when controls are being allocated among point and nonpoint sources within a watershed (Malik, Letson, and Crutchfield).

[9] Expected damages and related terms depending on stochastic elements are calculated using Gaussian quadrature (Miller and Rice; Preckel and DeVuyst). Since r_i and a are linear in the random variables and D is quadratic, each random variable only needs to be evaluated at two points to provide an exact measure of all relevant expected values.

as a percentage of the corresponding welfare measure in an unregulated, competitive equilibrium. In choosing K, we specified a 95% probability that expected net benefits be estimated with a margin of error $e \leq 0.4$ percentage points.[10] Our initial guess of K = 1,000 was more than adequate, and so this is our sample size.

We obtain results for first-best instruments (i.e., region-specific taxes or limits on land and fertilizer) and four second-best instruments designed to reduce nutrient runoff from agricultural production. Specifically, the second-best instruments we consider are uniformly applied taxes and limits based on fertilizer use, and uniformly applied taxes and limits based on estimated runoff (a performance proxy). These instruments have real-world analogues. Measures to regulate fertilizer use, primarily in the form of fertilizer quotas or taxes, are a common feature of policy proposals to reduce nutrient pollution, and have been implemented in some states in the United States and in Europe (Leuck; Ribaudo). Similarly, existing point/nonpoint trading programs in the United States involve point sources purchasing reductions in estimated emissions from agricultural nonpoint sources (Malik, Letson, and Crutchfield). In each case, uniformity of application may reduce policy transactions costs, although at an efficiency loss (Helfand and House).

Each instrument is designed to maximize expected economic surplus from production (consumer's surplus, plus firm quasi-rents, plus returns to landowners, minus expected damage costs from pollution), subject to producers' responses, and given initial parameter values. Next, each of the elasticities in table 1 is shocked along with technical efficiency parameters for land, fertilizer, and composite inputs. (Technical efficiency parameters for inputs are multiplicative and initially set equal to one.) The shocks represent a percentage increase in the relevant parameters. For each watershed, the shocks are independently and randomly drawn from a uniform distribution with bounds of 0 to 15%, although productivity shocks are the same for each producer to reflect technological change that becomes available to all producers. Producers have perfect information about the shocks and respond accordingly. These responses are used to calculate the welfare impacts of the shocks, given the initial policy variables. Finally, optimal instruments and associated outcomes are computed given the new parameter values.

We should note that all shocks except to environmental variables shift the marginal benefits of production (but do not shift marginal damages). Shocks to the elasticity of runoff shift only marginal damages in the case of input-based instruments, but shift both marginal benefits and marginal damages in the case of expected runoff-based instruments. Shocks to the elasticity of damages rotate marginal damages only (and do not impact marginal benefits).

Comparison on the Basis of Relative Efficiency

We first compare the five scenarios defined above on the basis of efficiency. *SNB* and other welfare measures are presented in table 2 as indices, with the base being the corresponding welfare measure in the unregulated, profit-maximizing solution. We use these indices because absolute measures are not particularly meaningful due to the experimental nature of the analysis.

[10] Across the different policy approaches we analyzed, the margin of error for consumer surplus averaged about 1/3 of a percentage point and the margin of error for expected damages averaged about 0.15 percentage points (each with little variation across policy approaches). The margin of error for landowner surplus was slightly larger at about 0.5 percentage points. However, since landowner surplus was not of much interest in the ensuing analysis, this larger margin of error does not concern us here.

Table 2. Comparison of Policies on the Basis of Relative Efficiency

	Welfare Measures (expressed as indices)			
Policy Instrument	Expected Social Net Benefits	Consumer Surplus	Expected Damages	Landowner Surplus
First-best taxes/limits	119.40[a]	75.35	5.90	41.27
	(5.81)[b]	(4.92)	(2.07)	(8.90)
Uniform fertilizer taxes	114.96	65.84	9.36	40.28
	(4.84)	(5.30)	(2.59)	(8.02)
Uniform estimated runoff taxes	116.88	67.88	7.98	40.07
	(5.31)	(5.37)	(2.49)	(8.16)
Uniform fertilizer limits	114.68	64.91	9.08	40.88
	(4.91)	(5.47)	(2.48)	(8.02)
Uniform estimated runoff limits	116.76	68.79	8.17	40.51
	(5.36)	(5.50)	(2.52)	(8.33)

[a] Sample mean, expressed as a percentage of competitive, unregulated levels.
[b] Values in parentheses are sample standard deviations.

As seen from table 2, first-best instruments increase *SNB* by 19.4% relative to unregulated levels, as measured by the sample average value of *SNB*. The second-best instruments are less efficient. In terms of *SNB*, uniform estimated runoff-based instruments outperform uniform fertilizer-based instruments for most random samples and on average for the samples. This result occurs because uniform estimated runoff-based instruments indirectly target more inputs than do fertilizer-based instruments, and encourage producers to evaluate the impacts of their choices on their own runoff relationship. Thus, uniform estimated runoff-based instruments transmit more site-specific information about environmental pressures relative to uniform fertilizer-based instruments, which can only inform producers about average (across farms) impacts of fertilizer on runoff. Even so, differences in the welfare gains achieved by the second-best instruments are small. Consequently, if transactions costs of estimated runoff-based instruments are even slightly larger than those for fertilizer-based instruments, then fertilizer-based instruments may actually be more efficient when these additional costs are taken into consideration.[11]

Instruments can also be compared on the basis of economic outcomes for different groups (with constant returns to scale, firm quasi-rents vanish). The welfare impacts of each instrument on consumers' surplus and expected damages are very similar to those described above for expected net benefits (table 2), although the proportional welfare loss to consumers and the environment from using second-best as opposed to first-best instruments is greater.

Pre-Adjustment Sensitivity

Sensitivity represents an additional dimension from which instrument choices can be made. This criterion may be particularly useful in situations like the present where the second-best instruments exhibit similar relative economic performance.

[11] Although they are not modeled explicitly, transactions costs (enforcement costs in particular) can vary considerably among various policy approaches, and thus could greatly affect the optimal choice of instrument (e.g., McCann and Easter; Stavins). In a broader context, transactions costs could affect the relative degree to which point and nonpoint sources within a watershed are targeted by environmental authorities (see, e.g., Malik, Letson, and Crutchfield). We are indebted to an anonymous reviewer for pointing this out.

Table 3. Definitions of Sensitivity Coefficients, Estimated by Equations (5) and (6)

Coefficient		Coefficients are defined as the pre-adjustment (post-adjustment) sensitivity of NB_i with respect to the:
Pre-Adjustment	Post-Adjustment	
$\varepsilon_{NB_i,d}$	$\eta_{NB_i,d}$	elasticity of demand
$\varepsilon_{NB_i,ls}$	$\eta_{NB_i,ls}$	elasticity of land supply
$\varepsilon_{NB_i,BM}$	$\eta_{NB_i,BM}$	Allen elasticity of substitution between biological and mechanical inputs
$\varepsilon_{NB_i,LF}$	$\eta_{NB_i,LF}$	Allen elasticity of substitution between land and fertilizer
$\varepsilon_{NB_i,B}$	$\eta_{NB_i,B}$	technical efficiency parameter for the biological input
$\varepsilon_{NB_i,M}$	$\eta_{NB_i,M}$	technical efficiency parameter for the mechanical input
$\varepsilon_{NB_i,F}$	$\eta_{NB_i,F}$	technical efficiency parameter for fertilizer
$\varepsilon_{NB_i,L}$	$\eta_{NB_i,L}$	technical efficiency parameter for land
$\varepsilon_{NB_i,r}$	$\eta_{NB_i,r}$	elasticity of runoff
$\varepsilon_{NB_i,D}$	$\eta_{NB_i,D}$	elasticity of damages

Note: NB_i may be set equal to expected net social benefits (*SNB*), consumer surplus (*CS*), expected damages (*ED*), or landowner surplus (*LS*).

In principle, the pre-adjustment sensitivity of expected social net benefits with respect to parameter θ_k, $|\varepsilon_{SNB,\theta_k}|$ ($\forall k$) can be derived from the simulation results using comparative statics. However, comparative statics are difficult to compute in this case due to the large number of welfare measures, parameters, and producer and market responses to consider (308 coefficients in all for the pre- and post-adjustment cases would have to be computed from each sample). Instead, we apply statistical procedures to the Monte Carlo samples to estimate the sensitivity measures.

Using the data from the Monte Carlo experiment, the sensitivity measures $|\varepsilon_{SNB,\theta_k}|$ ($\forall k$ and for each instrument) are estimated by applying ordinary least squares (OLS) to the following discrete form of equation (3), which represents a first-order approximation to the data-generating process:

$$(5) \qquad \frac{\Delta SNB|_{\mathbf{t}=\mathbf{t}(\theta_0)}}{SNB(\theta_0, \mathbf{t}(\theta_0))} = \beta_0 + \sum_{k=1}^{s} \beta_k \frac{\Delta\theta_k}{\theta_{k0}} + \zeta,$$

where $\Delta SNB|_{\mathbf{t}=\mathbf{t}(\theta_0)}/SNB = (SNB(\theta', \mathbf{t}(\theta_0)) - SNB(\theta_0, \mathbf{t}(\theta_0)))/SNB(\theta_0, \mathbf{t}(\theta_0))$ is the dependent variable; $\Delta\theta_k/\theta_{k0} = (\theta_k' - \theta_{k0})/\theta_{k0}$ represents the independent variables; $|\beta_k| = |\varepsilon_{SNB,\theta_k}|$ are the pre-adjustment sensitivity coefficients; and ζ is an i.i.d. random error term. Equations similar to (5) are used to estimate pre-adjustment sensitivity for consumer surplus, expected damages, and landowner surplus. Although the error terms would be correlated across equations, each equation can be estimated individually since the independent variables in each equation are identical (Greene).

A potential criticism of using econometrics to derive the sensitivity coefficients is that the effects of a shock in particular scenarios might be obscured (at best, the variation in the coefficients can be derived from the *t*-statistics). This criticism can be made for many econometric analyses. The alternative would be to simulate the impacts of a shock. This could be done for a particular set of values for model parameters and a particular type of shock. However, the number of permutations to consider is too extensive given

Table 4. Results of Estimation of Coefficients, Pre-Adjustment Sensitivity

Estimated Sensitivity Coefficient	Expected Social Net Benefits				Consumer Surplus			
	Fertilizer		Estimated Runoff		Fertilizer		Estimated Runoff	
	Tax	Limit	Tax	Limit	Tax	Limit	Tax	Limit
Constant	4×10^{-4} (0.07)	0.01 (1.25)	-6×10^{-4} (-0.10)	-0.01 (-1.07)	-0.004 (-0.44)	-0.01 (-0.86)	-0.002 (-0.19)	-0.02* (-1.91)
Market Parameters:								
$\varepsilon_{NB_i,d}$	0.66*** (24.50)	0.74*** (28.97)	0.72*** (27.61)	0.74*** (27.18)	1.12*** (25.27)	1.20*** (45.39)	1.21*** (29.79)	1.21*** (34.99)
$\varepsilon_{NB_i,ls}$	-0.05* (-1.89)	-0.04 (-1.58)	-0.06** (-2.22)	-0.09*** (-3.28)	0.04 (0.80)	0.05* (1.71)	0.03 (0.75)	0.01 (0.22)
Productivity Parameters:								
$\varepsilon_{NB_i,BM}$	0.03 (0.91)	0.05* (1.83)	0.03 (1.29)	0.07*** (2.79)	-0.02 (-0.49)	-0.07*** (-2.71)	-0.03 (-0.66)	-0.06* (-1.74)
$\varepsilon_{NB_i,LF}$	0.04 (1.34)	0.06** (2.13)	0.09*** (3.41)	0.08*** (2.88)	-0.10** (-2.25)	0.18*** (6.67)	0.06 (1.49)	0.19*** (5.44)
$\varepsilon_{NB_i,B}$	0.74*** (27.90)	0.76*** (30.01)	0.77*** (30.14)	0.74*** (27.28)	1.45*** (32.92)	1.61*** (61.39)	1.49*** (36.93)	1.56*** (45.44)
$\varepsilon_{NB_i,M}$	0.44*** (16.70)	0.45*** (17.69)	0.41*** (15.67)	0.47*** (17.74)	0.69*** (15.80)	0.59*** (22.34)	0.62*** (15.24)	0.62*** (18.29)
$\varepsilon_{NB_i,F}$	0.34*** (12.70)	0.34*** (13.01)	0.30*** (11.81)	0.36*** (13.34)	0.70*** (15.85)	0.69*** (25.21)	0.63*** (15.77)	0.73*** (21.35)
$\varepsilon_{NB_i,L}$	0.43*** (16.1)	0.43*** (15.80)	0.44*** (17.06)	0.45*** (16.45)	0.80*** (17.95)	0.93*** (33.34)	0.81*** (20.21)	0.92*** (26.77)
Environmental Parameters:								
$\varepsilon_{NB_i,r}$	0.07*** (2.62)	0.02 (0.73)	0.07*** (2.86)	0.08*** (2.98)	—	—	-0.02 (-0.43)	0.34*** (9.99)
$\varepsilon_{NB_i,D}$	0.06** (2.33)	0.04* (1.67)	0.09*** (3.37)	0.06** (2.21)	—	—	—	—
$\bar{R}^2$	0.67	0.72	0.71	0.69	0.71	0.89	0.76	0.83
F-Statistic (p-Value)	200.90 (0.00)	252.70 (0.00)	243.90 (0.00)	224.40 (0.00)	306.90 (0.00)	1,029.80 (0.00)	243.90 (0.00)	524.20 (0.00)

Notes: Single, double, and triple asterisks (*) denote significance at the 10%, 5%, and 1% levels, respectively. Numbers in parentheses are t-statistics (unless otherwise noted).

the inherent uncertainty in parameter values and the number of shocks to consider. Moreover, the econometric approach would appear to be an improvement over simulations in which results are based on one set of values for model parameters—usually the point estimates from econometric studies. This is because the econometric model yields the expected results over all uncertain parameter values, while the simulation approach would yield results based on the expected parameter values. By Jensen's inequality, the results will differ, with the expected results of the econometric technique being more representative of a range of situations.

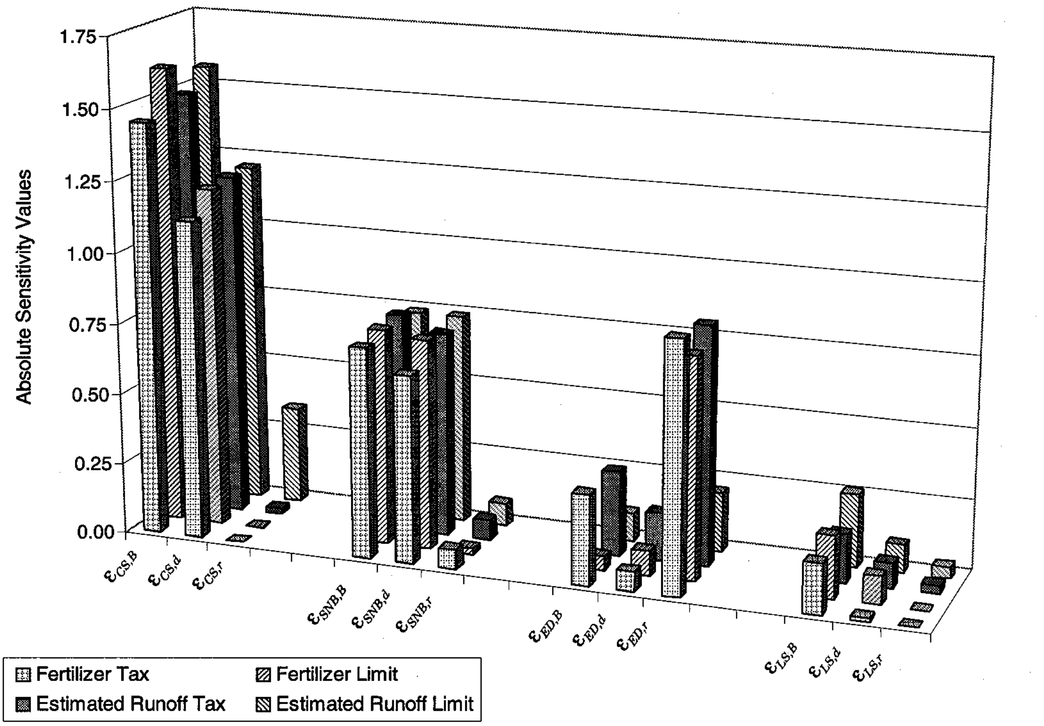
The sensitivity coefficients to be estimated in equation (5) are defined in table 3, and the results of the estimations are reported in table 4. The absolute value of each estimated coefficient measures welfare sensitivity for each instrument for a particular type of exogenous shock. The larger the absolute value associated with a particular instrument and shock, the more the associated welfare measure is likely to change in response to such a shock under that instrument.

Table 4. Extended

Estimated Sensitivity Coefficient	Expected Damages				Landowner Surplus			
	Fertilizer		Estimated Runoff		Fertilizer		Estimated Runoff	
	Tax	Limit	Tax	Limit	Tax	Limit	Tax	Limit
Constant	0.001 (0.09)	-0.02** (-2.40)	0.001 (0.06)	-0.02** (-2.09)	0.001 (0.17)	0.01 (0.70)	0.01 (0.93)	-0.001 (-0.13)
Market Parameters:								
$\varepsilon_{NB_i,d}$	0.07 (1.17)	-0.09** (-2.45)	0.17*** (3.07)	0.01 (0.13)	0.01 (0.53)	0.10*** (3.17)	0.09*** (3.44)	0.10*** (2.96)
$\varepsilon_{NB_i,ls}$	-0.01 (-0.17)	-0.005 (-0.13)	-0.05 (-0.83)	0.03 (0.63)	-0.19*** (-7.40)	-0.18*** (-5.21)	-0.21*** (-8.28)	-0.24*** (-7.09)
Productivity Parameters:								
$\varepsilon_{NB_i,BM}$	0.13** (1.97)	0.005 (0.13)	0.10* (1.71)	0.03 (0.66)	0.09*** (3.28)	0.14*** (4.20)	0.10*** (3.71)	0.19*** (5.47)
$\varepsilon_{NB_i,LF}$	-0.64*** (-10.31)	-0.02 (-0.60)	-0.40*** (-7.15)	0.08* (1.70)	0.22*** (8.40)	0.22*** (6.48)	0.27*** (10.00)	0.22*** (6.29)
$\varepsilon_{NB_i,B}$	-0.32*** (-5.14)	0.05 (1.37)	-0.30*** (-5.41)	0.10** (2.14)	-0.18*** (-7.00)	-0.22*** (-6.64)	-0.17*** (-6.54)	-0.26*** (-7.66)
$\varepsilon_{NB_i,M}$	0.33*** (5.37)	-0.02 (-0.67)	0.22*** (3.93)	-0.01 (-0.14)	0.15*** (5.70)	0.16*** (4.84)	0.11*** (4.44)	0.16*** (4.81)
$\varepsilon_{NB_i,F}$	-0.03 (-0.43)	0.01 (0.25)	-0.09* (-1.70)	0.02 (0.53)	-0.14*** (-5.32)	-0.11*** (-3.12)	-0.18*** (-7.11)	-0.11*** (-3.36)
$\varepsilon_{NB_i,L}$	-0.27*** (-4.38)	0.06* (1.65)	-0.20*** (-3.72)	-0.01 (-0.15)	-0.01 (-0.44)	-0.10*** (-2.76)	-0.03 (-0.98)	-0.09*** (-2.58)
Environmental Parameters:								
$\varepsilon_{NB_i,r}$	-0.88*** (-14.16)	-0.78*** (-20.34)	-0.84*** (-15.30)	0.21*** (4.68)	—	—	0.03 (1.06)	-0.04 (-1.25)
$\varepsilon_{NB_i,D}$	-0.69*** (-11.25)	-0.80*** (-20.37)	-0.77*** (-13.70)	-0.81*** (-17.57)	—	—	—	—
$\bar{R}^2$	0.34	0.45	0.36	0.25	0.20	0.15	0.24	0.19
F-Statistic (p-Value)	51.35 (0.00)	82.03 (0.00)	56.33 (0.00)	34.35 (0.00)	32.17 (0.00)	23.10 (0.00)	35.90 (0.00)	26.26 (0.00)

Because the results in table 4 are extensive, a limited number of representative results from table 4 are presented in figure 1. Specifically, we illustrate the effects of one market shock (the inverse elasticity of demand), one productivity shock (the technical efficiency of the composite biological input), and one environmental shock (the elasticity of runoff). The x-axis in figure 1 represents the pre-adjustment welfare sensitivity for each shock and for each welfare measure (with the sensitivity measures grouped along this axis by welfare measure). The y-axis indicates the instrument in place when the shock occurs. The absolute values of the sensitivity measures are given by the z-axis.

Several clear patterns emerge in figure 1 which are representative of the results in table 4. First, for a particular instrument and a particular type of shock, the absolute values of the sensitivity coefficients vary widely across welfare measures. All of the coefficients for expected net benefits have an absolute value of less than one (i.e., a 1% change in any one parameter results in a less than 1% change in expected net benefits), although there are substantial differences in coefficient values for different types of shocks, and combinations of shocks could certainly have substantial welfare impacts. The



Note: Illustrated here are the effects of one productivity shock (the technical efficiency of the composite biological input, B), one market shock (the inverse elasticity of demand, d), and one environmental shock (the elasticity of runoff, r), grouped along the x-axis by welfare measure.

Figure 1. Pre-adjustment sensitivity for selected shocks

coefficients have an absolute value of less than one because they reflect the aggregate impacts across individual groups (i.e., consumers, those damages by pollution, and landowners), which have some offsetting effects. Welfare sensitivity varies widely across different groups, and a particular shock could have significant impacts to one or more groups.

A second result indicates, for most of the different shocks, that neither the choice of instrument type (tax versus limit) nor choice of base (fertilizer versus estimated runoff) has much (statistical) bearing on the sensitivity of expected net benefits, consumer surplus, or landowner surplus.[12] These results may appear somewhat surprising because incentives (as opposed to limits) and instrument bases more closely tied to performance (such as estimated runoff) seemingly leave producers with a greater ability to adapt to exogenous change, suggesting differences in welfare sensitivity will exist. However, from our findings, greater freedom in making production choices does not imply significant differences in pre-adjustment sensitivity for these welfare measures.

For instance, consider a shock that increases the efficiency of the biological input. Regardless of instrument type or base, producers respond by substituting the mechanical input for biological inputs (because this reduces the producer's tax or the opportunity cost of a limit), and increasing output. As substitution away from biological inputs is not restricted under any particular instrument or base, proportional impacts of the shock

[12] Actual welfare impacts are determined by combining the sensitivity measures (which are essentially elasticities) with knowledge of the proportional size of the shock and also ex ante welfare levels. Hence, small differences in sensitivity could result in significant absolute welfare differences, depending on the size of the shock and also ex ante welfare.

on consumers and landowners do not depend on the base or instrument. Moreover, the impacts to expected net benefits are dominated by the impacts to consumers and/or landowners for most shocks (as opposed to any impacts to expected damages). This is because, in the optimum, expected damages are a relatively small component of expected net benefits.

Given these first two results, we find, for each instrument, demand and productivity shocks generally have the greatest impacts on consumers, while land supply shocks have the greatest impact on landowners (although landowner surplus is not very sensitive to any type of shock). It is not surprising that demand shocks heavily impact consumers or that land supply shocks have the greatest impact on landowners. But what may be somewhat surprising is that consumer surplus is even more sensitive to shocks to the efficiency of the composite "biological input" than it is to demand shocks.

Environmental policies target the biological input fertilizer (albeit to different degrees), making fertilizer use, and hence use of the "biological input," costly. However, an increase in the efficiency of fertilizer and/or land allows producers to substitute mechanical inputs for biological inputs, land for fertilizer, and also to increase output. The output effects are great due to the relatively large biological input factor share and the ease with which land is substituted for fertilizer. (In contrast, the output effects of exogenous mechanical shocks are proportionately smaller due to the relatively small mechanical input factor share.) Given inelastic demand, the large output effects significantly affect price and hence consumer surplus.

A final result emerging from figure 1 is that the sensitivity of expected damages to various types of shocks does not generally depend on the basis of application (i.e., fertilizer versus estimated runoff), but it does depend on whether taxes or limits are applied. This is not surprising given damages largely depend on the ratio of fertilizer and land inputs, and this ratio is likely to be affected in different ways depending on the instrument applied. Expected damages are not very sensitive to productivity and market shocks when limits are applied, but damages are somewhat sensitive to productivity shocks under a tax.[13] Thus, under a tax, producers respond to shocks in ways that create greater welfare sensitivity of expected damages than do producer responses under a limit. For shocks to the elasticity of runoff, we find a large difference in sensitivity between limits and taxes applied to estimated runoff, but not between limits and taxes applied to fertilizer. This is because, when fertilizer-based instruments are applied, shocks to environmental parameters affect expected damages directly with no other productivity effects (the same is true for shocks to the elasticity of damages regardless of instrument base).

Post-Adjustment Sensitivity

We now consider post-adjustment sensitivity to gain insight into potential costs and benefits from adjusting the different types of instruments in response to exogenous change. Post-adjustment sensitivity measures (η_{NB_i,t_i}) are estimated by applying OLS to the following discrete form of equation (4), which represents a first-order approximation to the data-generating process:

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[13] Under the current specification of a convex damage function, shocks having the same (different) qualitative impact on the mean and variance of ambient pollution would have reinforcing (offsetting) effects on the sensitivity of expected damages to the shock. The converse would be true if damages were instead concave. Under the current specification, a change in fertilizer use in one region has the same qualitative impact to the mean and variance of runoff and also ambient pollution, ceteris paribus. Thus, we might expect the sensitivity of damages to be larger than it would be under a concave specification.

Table 5. Results of Estimation of Coefficients, Post-Adjustment Sensitivity

Estimated Sensitivity Coefficient	Expected Social Net Benefits				Consumer Surplus			
	Fertilizer		Estimated Runoff		Fertilizer		Estimated Runoff	
	Tax	Limit	Tax	Limit	Tax	Limit	Tax	Limit
Constant	-1×10^{-4}***	-2×10^{-4}**	-1×10^{-4}***	-4×10^{-4}***	-0.002	0.003	0.00	-0.004*
	(-4.40)	(-2.35)	(-5.66)	(-3.80)	(-1.14)	(0.98)	(0.00)	(-1.84)
Market Parameters:								
$\eta_{NB_i,d}$	-4×10^{-4}***	-6×10^{-4}**	-3×10^{-4}***	-0.002***	-0.02***	0.05***	-0.02***	0.05***
	(-3.80)	(-2.00)	(-4.41)	(-3.90)	(-3.61)	(4.40)	(-6.50)	(5.00)
$\eta_{NB_i,ls}$	0.00	-6×10^{-4}*	0.00	0.001	0.01	0.01	0.003	-0.01
	(0.40)	(-1.92)	(0.30)	(1.10)	(1.20)	(0.99)	(0.80)	(-1.52)
Productivity Parameters:								
$\eta_{NB_i,BM}$	-2×10^{-4}**	-6×10^{-4}**	0.00	-0.003***	-0.02***	0.06***	-0.01**	0.06***
	(-2.24)	(-2.01)	(-0.40)	(-5.80)	(-3.23)	(5.10)	(-1.98)	(6.50)
$\eta_{NB_i,LF}$	0.001***	0.001***	-6×10^{-4}***	0.004***	0.08***	-0.12***	0.03***	-0.10***
	(10.90)	(4.61)	(7.90)	(9.07)	(13.40)	(-9.90)	(9.70)	(-11.40)
$\eta_{NB_i,B}$	7×10^{-4}***	0.003***	1×10^{-4}	0.004***	0.02***	-0.07***	-0.004	-0.06***
	(6.60)	(9.16)	(0.80)	(8.30)	(3.90)	(-6.30)	(-1.20)	(-6.70)
$\eta_{NB_i,M}$	-4×10^{-4}***	0.00	-3×10^{-4}***	-0.003***	-0.04***	0.06***	-0.02***	0.07***
	(-4.05)	(0.01)	(-4.25)	(-5.63)	(-7.90)	(5.70)	(-5.90)	(7.90)
$\eta_{NB_i,F}$	0.00	7×10^{-4}**	0.00	0.001**	-0.003	-0.01	-0.01	-0.01
	(0.40)	(2.37)	(-0.40)	(2.35)	(-0.60)	(-0.80)	(-1.57)	(-0.80)
$\eta_{NB_i,L}$	6×10^{-4}***	0.002***	2×10^{-4}**	0.003***	0.02***	-0.05***	0.004	-0.05***
	(5.70)	(4.90)	(2.36)	(6.70)	(3.80)	(-4.40)	(1.29)	(-5.60)
Environmental Parameters:								
$\eta_{NB_i,r}$	7×10^{-4}***	1×10^{-4}	0.002***	0.009***	0.04***	0.01	0.08***	-0.20***
	(6.40)	(0.20)	(21.20)	(20.30)	(7.90)	(0.90)	(25.10)	(-24.20)
$\eta_{NB_i,D}$	3×10^{-4}***	4×10^{-4}	6×10^{-4}***	-0.001***	0.02***	0.01	0.03***	0.03***
	(2.90)	(1.44)	(8.35)	(-2.89)	(3.40)	(0.70)	(9.20)	(3.20)
$\bar{R}^2$	0.20	0.13	0.39	0.39	0.26	0.19	0.47	0.47
F-Statistic	26.36	16.08	63.52	66.05	35.97	24.31	90.58	88.77
(p-Value)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Notes: Single, double, and triple asterisks (*) denote significance at the 10%, 5%, and 1% levels, respectively. Numbers in parentheses are t-statistics (unless otherwise noted).

(6)
$$\frac{\Delta SNB|_{\theta=\theta'}}{SNB(\theta', \mathbf{t}(\theta'))} = \alpha_0 + \sum_{k=1}^{s} \alpha_k \frac{\Delta\theta_k}{\theta'_k} + \xi,$$

where $\Delta SNB|_{\theta=\theta'}/SNB = (SNB(\theta', \mathbf{t}(\theta')) - SNB(\theta', \mathbf{t}(\theta_0)))/SNB(\theta', \mathbf{t}(\theta'))$ is the dependent variable; $\Delta\theta_k/\theta'_k = (\theta'_k - \theta_{k0})/\theta'_k$ represents the independent variables; $\alpha_k = \eta_{SNB,\theta_k}$ are the post-adjustment sensitivity coefficients; and ξ is an i.i.d. random error term. Equations similar to (6) are used to estimate post-adjustment sensitivity for consumer surplus, expected damages, and landowner surplus.

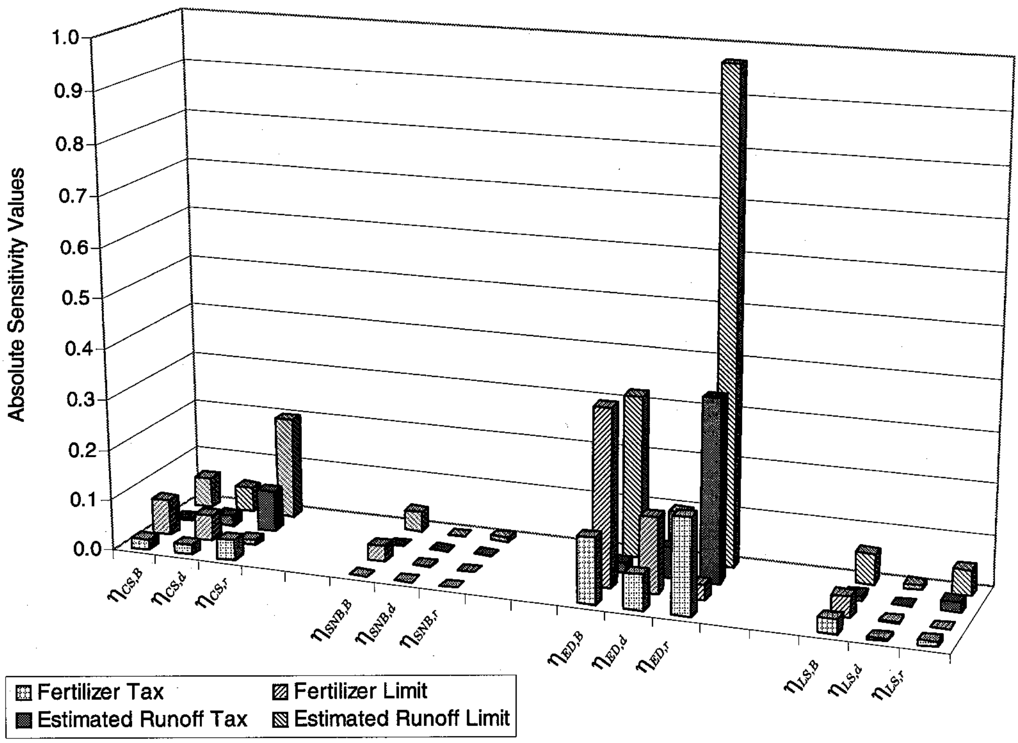
The results of the estimates are presented in table 5. The absolute value of each estimated coefficient measures welfare sensitivity for a particular instrument and type of exogenous shock. The larger the value, the more the associated welfare measure is likely to change in response to policy adjustment to the shock. In the case of expected social net benefits, a larger absolute value indicates adjustment yields a larger increase in efficiency. For other welfare measures, a larger absolute value only indicates greater

Table 5. Extended

Estimated Sensitivity Coefficient	Expected Damages				Landowner Surplus			
	Fertilizer		Estimated Runoff		Fertilizer		Estimated Runoff	
	Tax	Limit	Tax	Limit	Tax	Limit	Tax	Limit
Constant	-0.01**	0.02	-0.01	-0.01	0.002***	-0.002	0.002***	-0.002
	(-2.30)	(1.70)	(-1.47)	(-1.00)	(2.57)	(-1.21)	(3.13)	(-0.78)
Market Parameters:								
$\eta_{NB_i,d}$	-0.07***	0.15***	-0.06***	0.10***	-0.004	-0.003	0.001	-0.01
	(-2.60)	(3.10)	(-3.10)	(1.76)	(-1.18)	(-0.50)	(0.27)	(-0.87)
$\eta_{NB_i,ls}$	0.03	0.05	0.01	-0.04	-0.001	-0.01*	-0.003	0.01
	(1.20)	(0.90)	(0.60)	(-0.80)	(-0.14)	(-1.85)	(-1.20)	(0.94)
Productivity Parameters:								
$\eta_{NB_i,BM}$	-0.06**	0.22***	-0.01	0.32***	0.01**	-0.02***	0.002	-0.03***
	(-2.14)	(4.20)	(-0.40)	(5.50)	(2.11)	(-2.65)	(0.89)	(-4.36)
$\eta_{NB_i,LF}$	0.28***	-0.45***	0.13***	-0.39***	-0.03***	0.03***	-0.01***	0.04***
	(11.00)	(-8.80)	(6.70)	(-6.80)	(-7.59)	(4.67)	(-5.16)	(4.62)
$\eta_{NB_i,B}$	0.13***	-0.35***	0.02	-0.32***	-0.03***	0.04***	-0.01***	0.06***
	(5.10)	(-7.10)	(1.20)	(-5.70)	(-7.99)	(7.88)	(-4.80)	(7.79)
$\eta_{NB_i,M}$	-0.15***	0.24***	-0.07***	0.26***	0.004	-0.002	-0.002	-0.004
	(-5.70)	(4.90)	(-3.70)	(4.70)	(1.29)	(-0.36)	(-1.02)	(-0.49)
$\eta_{NB_i,F}$	-0.01	-0.07	-0.002	-0.004	-0.01**	0.01	-0.01***	0.02***
	(-0.50)	(-1.40)	(-0.14)	(-0.07)	(-2.32)	(1.91)	(-2.73)	(2.29)
$\eta_{NB_i,L}$	0.12***	-0.28***	0.04**	-0.27***	-0.02***	0.03***	-0.01***	0.03***
	(4.50)	(-5.30)	(2.17)	(-4.80)	(-5.23)	(4.30)	(-3.06)	(4.05)
Environmental Parameters:								
$\eta_{NB_i,r}$	0.19***	0.03	0.36***	-0.97***	-0.01***	0.001	-0.02***	0.05***
	(7.30)	(0.50)	(18.40)	(-17.40)	(-3.81)	(0.10)	(-9.21)	(6.60)
$\eta_{NB_i,D}$	0.09***	-0.01	0.15***	0.02	-0.01	0.01	-0.01***	-0.01
	(3.40)	(-0.30)	(7.50)	(0.40)	(-1.61)	(1.04)	(-2.84)	(-1.21)
$\bar{R}^2$	0.21	0.17	0.32	0.29	0.14	0.11	0.14	0.13
F-Statistic	27.04	22.00	47.75	42.66	17.39	12.78	16.99	15.33
(p-Value)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

welfare responsiveness when an adjustment occurs. Because the results in table 5 are extensive, figure 2 presents representative results analogous to those presented in figure 1 for the pre-adjustment case (note absolute values are presented).

First, consider the post-adjustment measures for expected social net benefits (figure 2; table 5). These measures are much smaller than their pre-adjustment counterparts (figure 1; table 4). Indeed, these measures are generally so small that it matters little to society whether any of the instruments are adjusted in response to the exogenous shocks. Moreover, while there may appear to be some differences across instruments (particularly between incentives and limits) in figure 2, the magnitude of the differences is either not statistically significant or is extremely small. This latter result mirrors the ex ante results, which should be expected given the small differences in ex ante sensitivities (for social welfare) across instruments and assuming the ex post optimal performance of the various instruments is similar (as it was in the ex ante case). For consumers and landowners, we also find small post-adjustment measures do not differ significantly across instruments.



Note: Illustrated here are the effects of one productivity shock (the technical efficiency of the composite biological input, B), one market shock (the inverse elasticity of demand, d), and one environmental shock (the elasticity of runoff, r), grouped along the x-axis by welfare measure.

Figure 2. Post-adjustment sensitivity for selected shocks

The primary reason we find small proportional benefits or costs of adjustment for society, consumers, and landowners lies with the motivation for adjusting the instruments. The instruments are optimally adjusted to reallocate pollution control costs and benefits after a shock. But, given the ex ante instruments in place, farmers already respond to shocks in ways chosen to maximize their own net private benefits (and also those to consumers and landowners).[14] Ex post, this leaves room for some adjustment in terms of reducing damages (more on this aspect is offered below). However, because damages are already significantly reduced under the ex ante policy (see table 2) and because moderate shocks (at least to individual parameters) do not make the externality much worse, it is not optimal to significantly alter control costs at this point to attain optimality. Hence, the proportional private benefits (or costs) of adjustment are generally small.

Now consider the post-adjustment measures for expected damages. Adjustments may have a significant proportional impact on expected damages (figure 2; table 5). Adjusting fertilizer taxes and limits or estimated runoff limits can create moderate proportional impacts to expected damages. These welfare impacts are greater under limits (except for the case of a fertilizer limit given a shock to the elasticity of runoff) because limits resulted in relatively small proportional impacts to damages in the pre-adjustment case,

[14] Note that farms can respond to adjustment of each policy instrument to some degree; in contrast to Weitzman's model, the limits we analyze do not constrain all relevant choices.

and hence there is greater room for adjustment ex post. Note the estimated coefficients (table 5) have opposite signs relative to the pre-adjustment case. The intuition for this is as follows: firms' responses are made without regard to expected damages. Thus, given exogenous shocks and fixed policy instruments, producer adjustments which are beneficial (detrimental) to the environment produce a greater reduction (increase) in expected damages than is optimal. The primary impact of policy adjustment is therefore to mitigate any excess increases or reductions in expected damages arising when policies are not adjusted.

Conclusion

Most economic studies of pollution control analyze policies that are optimal for a given set of underlying parameters. Less understood is how such policies perform when the underlying parameters change and policies are not adjusted in response, or what the benefits of adjustment are. We have constructed two measures of welfare sensitivity: (*a*) pre-adjustment sensitivity, which measures welfare changes when instruments are not adjusted to exogenous change, and (*b*) post-adjustment sensitivity, which measures the welfare gains (or losses) of optimally adjusting an instrument relative to the case of non-adjustment. We use these measures to analyze the welfare impacts arising in a simulation of second-best instruments designed to reduce agricultural nonpoint pollution.

Three results are worth highlighting. First, when exogenous shocks occur and policy variables remain fixed, welfare sensitivity in aggregate or to consumers or landowners does not depend significantly on whether incentives or regulations are used and whether they are applied to performance proxies or inputs. This result is in contrast to the widely held belief that taxes are better than standards and that performance measures or proxies are better than inputs due to the increased flexibility they provide producers to adapt to exogenous changes.

Second, optimally adjusting instruments after an exogenous shock does not have a great proportional impact on welfare in aggregate or to consumers or landowners. Thus, the proportional social benefits (or possibly costs to consumers or landowners) of adjusting policy instruments are small and may not outweigh the transactions costs of making policy changes. Once implemented, it may be optimal for instruments to remain fixed for a time.

Finally, the first two results may not hold in the case of expected damages. Limits are more effective at minimizing changes in expected damages after a shock occurs, provided these limits are not adjusted in response. Further, the primary impact of policy adjustment will be to mitigate any excess increases or reductions in expected damages arising when policies are not adjusted.

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