

Comparing policy instruments in a dynamic  
environment with strategic firms:  
The case of Minnesota River phosphorus  
emissions.\*

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July 12, 2001

**Abstract**

This paper examines the strategic behavior of firms under emissions taxes and tradable emissions permits designed to mitigate phosphorus emissions. The Nash payoff to the regulator of the strategic game is determined for a sub-basin of the Minnesota River using econometric estimates of cost and benefit functions representative of the region. These payoffs are compared to determine the preferred policy instrument. Results show that emission permits yield lower deadweight losses than emissions taxes.

Environmental regulators are often imperfectly informed about a regulated firm's true abatement cost. In a dynamic environment, information asymmetry between the regulator and the firm implies that firms have an opportunity to exploit their advantage to undermine the goals of a regulator that seeks to maximize social welfare. In a static environment, the policy instrument that yields minimal welfare loss is dependant on the relative slopes of the marginal benefit and marginal cost curves. Weitzman (1974) showed that a quantity instrument (respectively a price instrument) is preferred if the marginal benefit curve is steeper than (respectively less steep than) marginal costs. In all of the subsequent work that compares price and quantity instruments in a *dynamic* setting, it is assumed that firms are non-strategic price takers.<sup>1</sup> It is the regulator who adopts sophisticated dynamic policy rules in order to induce a pliant, non-strategic polluting sector to achieve socially desirable outcomes. Though it has produced many important insights, it would appear that this approach runs

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\*Paper presented at the 2001 AAEA-CAES Annual Meeting, August 5-8, 2001 - Chicago. Preliminary draft. Please do not cite.

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<sup>1</sup>See Newell and Pizer (1998) and Baldursson and von der Fehr (1999) among others.

counter to Weitzman’s assumption about who holds the advantage in the interaction between regulator and polluters. If polluting firms have the informational advantage, it would seem natural to study a dynamic policy setting in which they are also more sophisticated than the regulator. Moledina, Coggins, and Polasky (2000) strengthen this insight by showing that in a dynamic environment, under most conditions, the firms’ strategic incentive to misrepresent costs allows permits to outperform taxes from an efficiency standpoint. This paper extends Moledina et al. (2000) empirically by comparing policy instruments to mitigate phosphorus emissions in the Minnesota River Basin.

We focus on a large sub-basin of the Minnesota River which contains two principal emitters of phosphorus: point sources with relatively high abatement costs and small farmers with relatively low abatement costs. The regulator has an accurate estimate of the benefits of phosphorus abatement in this region. However, she is unsure of the exact nature of the firms’ abatement costs.

The regulator’s uncertainty regarding the actual abatement cost function for the aggregate point and nonpoint source is essential for our model of strategic behavior. There are several sources of regulator uncertainty in our estimates of aggregate costs. The biophysical simulations and cost estimates for representative farm units may include measurement errors and biases, the conservative estimate on feedlot contributions may or may not be correct, and the “lumpy” investments necessary to achieve wastewater utility abatement make estimating an aggregate abatement cost function difficult for point sources.<sup>2</sup> We assume that these sources of uncertainty serve to shift the linear term in the polynomial abatement cost function in an additive manner by 5%. This in fact shifts the intercept for the marginal cost functions up by 5%. While this simplifying assumption about the extent of regulator uncertainty is debatable, when choosing limits for this assumption, care was taken to choose lower bounds.

The two policy instruments available to the regulator are emissions taxes and tradeable emissions permits. The strategic game proceeds as follows. For both policies the regulator chooses taxes or permit levels in the first period to reflect imperfect, ex-ante beliefs about the firms’ abatement cost functions. Following the first period, the regulator observes levels of abatement effort undertaken by both firms and then updates her beliefs about the cost function, choosing the second period’s tax or permit level at that time. The regulator’s updating rule follows Moledina et al. (2000) who assume that the regulator follows a mechanical but natural rule for updating the policy from one period to the next. Specifically, the regulator believes that the firms are non-strategic and will behave so that marginal cost equals the tax (in the case of emissions taxes) or the permit price (in the case of emissions permits). Having observed their behavior in period  $t$ , the regulator derives a new estimate of marginal costs and sets the policy in period  $t + 1$  so that marginal benefits equal the new expected marginal cost function. A key assumption is that the firms know this rule, and that their behavior in each period optimally anticipates the effect of their action

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<sup>2</sup>Dosi and Moretto (1993) discuss the uses of mathematical models to simulate nutrient flows for regulatory purposes.

on the policy in the following period. The regulator, then, is at a disadvantage in two respects. First, she is uncertain about the firm's abatement cost functions. Second, while the firm knows the regulator's dynamic rule, it is assumed that she does not anticipate the firms' manipulation of the rule.<sup>3</sup>

Knowing that the regulator will update the policy choice in the second period based on first period observations, firms choose their abatement efforts in both periods so as to minimize the total cost of abatement. Moledina et al. (2000) derive two main sets of results. The first concerns future taxes and emission levels in the tax case and the permit price in the emission permit case. On one hand, firms facing an emissions tax have a strategic incentive to overabate, pretending that their costs are low. The regulator, then, believing that the firms have low abatement costs, sets a relatively low tax. But overabatement is expensive, and the dynamic problem facing the firms requires balancing the desire to appear to have low costs against the desire to minimize actual abatement costs. On the other hand, firms facing a permit market have a strategic incentive to reveal a high permit price. The regulator, believing that the firms have high abatement costs, issues more permits in the next period.

Hence, in the two-period model with emissions taxes firms overabate in the first period and underabate in the second relative to non-strategic firms. The results for the permit case are both more complicated and less general. The complexity arises because firms have different incentives on how to manipulate permit prices depending on whether they are a buyer or a seller. In our model with two firms, we have a bilateral monopoly problem. This problem does not have a unique solution. It seems reasonable to expect that the point sources are price setters because of their small numbers: The Minnesota River Basin has 2 municipal wastewater treatment facilities and 92 feedlots compared to 430 farms. It also seems reasonable to assume that the point sources are net-buyers of permits because of their high pollution abatement costs relative to the non-point sources. Therefore, we solve the case when the point source is a monopsony permit buyer. In most cases, a price-setting firm has an incentive to set a high price because that leads to more permits in the next period. However, the buyer of permits wants the price to be low to reduce the cost of permit purchases. This effect can dampen the impulse to reveal a high first-period permit price. Depending on the strength of these two effects, the permit price can be set either above or below marginal abatement cost.

This paper compares welfare losses due to strategic behavior under the two policies. In the next section we provide a brief background of the Minnesota River Basin and motivate the problem. Section two describes the method used to econometrically estimate the abatement cost and benefit functions for the agents following Johansson (2000). Social benefits as a function of phosphorus abatement are developed from regional willingness-to-pay estimates (Johansson, 2000; Mathews et al, 2000). Section three outlines the model and presents the

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<sup>3</sup>While the regulator in this model is unsophisticated relative to the firms, there are several situations in which this may be a close reflection of reality. Polluters in this region will indeed lobby for a grandfathering provision wherein polluters might be able to affect their treatment under the anticipated regulatory policy in the future by modifying their current behaviour.

results. Here the functions estimated from section two are substituted into a dynamic programming simulation of the strategic game outlined in detail in Moledina et al. (2000) to compare policy outcomes. Section four concludes. In light of the EPA's proposed new Total Maximum Daily Loading (TMDL) rules, the results from this analysis will be useful to policymakers as they contemplate inclusive phosphorous management strategies.

## 1 Background and motivation

Under current TMDL proposals, states are now required to develop comprehensive management strategies for impaired water resources. These proposals are required to detail how nutrient emissions will be reduced to comply with federal water quality standards (Boyd, 2000). To a large extent, the regulation of pollution in the United States has mostly been of the command-and-control (CAC) form: explicit limits on the quantity of pollutant allowed or the processes and technology involved in production. This regulatory mechanism has typically focused on point sources of pollution, those that discharge pollution at a specific location (e.g., pipe or smokestack). However, command-and-control regulation has failed to adequately address the increasing levels of environmental damages resulting from agricultural, nonpoint pollution. Since 1960 agricultural intensity has increased substantially in the United States (wetland areas have decreased by 50+%, and the use of industrial fertilizers and pesticides have increased by approximately 200%) resulting in a 26% increase in output per unit input (CEQ, 1996). It should come as no surprise then that agricultural production currently contributes to 72% of impaired river areas, 57% of impaired lake areas, and 43% of the impaired estuarine areas assessed (USEPA, 1990 and 1994).

Furthermore, the potential to reach current water quality goals by regulating point sources alone is infeasible or has become prohibitively expensive. The question remains of how to regulate all sources of pollution efficiently. Hitherto, studies on environmental regulation and their costs have focused on point sources (e.g., electrical utilities - Swinton (1998), Coggins and Swinton (1996) and paper mills - O'Neil et al. (1983)) or nonpoint sources (e.g., nutrient emissions - Westra (1999), Morgan (1999), Fleming (1995)). The literature addressing simultaneous regulation of both point sources and nonpoint sources is quite thin. Notable exceptions include the literature on point/nonpoint trading (Johansson, 2000; Malik et al., 1993; Letson et al., 1993; Letson, 1992; Shortle, 1990) and examinations of the Dillon Reservoir and Tar-Pamlico trading programs (MPCA, 1996; Apogee Research, 1992; Harding, 1990; Elmore et al., 1985). This paper seeks to add to the theory and application of regulating point and nonpoint sources simultaneously.

Policies incorporating previously regulated point sources and unregulated nonpoint sources of nutrient emissions will be particularly important in agricultural river basins such as the Minnesota River, classified as one of America's most endangered rivers (American Rivers, 2000). Recently, the Minnesota Pollution Control Agency (MPCA) adopted the goal of reducing organic loading,

or biochemical oxygen demanding substances, by 40% (MPCA, 2000), which would in theory enable the Minnesota River to meet state water quality standards. To accomplish this, aggregate nonpoint phosphorus emissions have been targeted for more than a 40% reduction from current levels (MPCA, 2000).

The Minnesota River drains approximately 10 million acres in Central and Southern Minnesota before joining the Mississippi River in Saint Paul. Many of the 700,000 inhabitants and approximately 92% of the basin's area are involved in agricultural production, contributing about 50% of the state's corn and soybean production, more than 20% and 40% of beef and hog production respectively. Contributions of sediment, nitrogen, and phosphorus by the Minnesota River to the Mississippi River have been linked to severe eutrophication and hypoxia problems downstream (USEPA, 1997).

In this paper we use data gathered from the Sand Creek sub-watershed of the Lower Minnesota Basin. This region was chosen for several reasons. First, the Lower Minnesota is the largest contributor of phosphorus (p-load) to the Minnesota River. This contribution has been estimated to be between 17.2 % and 32.5% (Faeth, 1998; Mulla, 1998). Furthermore, the Sand Creek is one of the largest sub-basins of the Lower Minnesota Basin. It drains 14% of the Lower Minnesota watershed, or approximately 148,000 acres (MPCA, 1998). Its average phosphorus contribution is 115,000 lbs./year or 11% of the Lower Minnesota total load (MPCA, 1994). Of this, point source emissions account for approximately 35% of the total p-load while the remaining 65% comes from agricultural cropland emissions.

To simplify our analysis of possible strategic interaction by polluters in a dynamic regulatory environment we have decided to treat point and nonpoint sources in aggregate. The aggregate point source can be thought of a decision-making organization that is comprised of previously regulated polluters. The aggregate nonpoint source can be thought of as a decision-making organization that is comprised of previously *unregulated* polluters. As there is some prior knowledge of how to optimize production under regulation and because the aggregate point source organization has significantly fewer members we assume that the aggregate point source acts as the Stackelberg leader in the dynamic game. The Minnesota River then provides an excellent framework to examine strategic regulation of point and nonpoint phosphorus emissions for a region that will soon require substantial point and nonpoint source abatement policies.

## 2 On estimating benefits and costs

Before we calculate the Nash pay-offs to compare the two policy instruments, we require econometric estimates of the aggregate costs of abatement from nonpoint and point sources in addition the aggregate benefits. Also needed is the extent of regulatory uncertainty in abatement costs. As is typical in this literature, we assume abatement costs and benefits are quadratic (Leiby and Rubin, 2000; McKittrick, 1999; Kling and Rubin, 1997).

## 2.1 Nonpoint abatement costs

Following Johansson (2000 et al., 2001), Dalzell et al. (1999), and Gowda et al. (1998) soil data from STATSGO (NRCS, 1993) were used in conjunction with the biophysical soils model, ADAPT, to generate the effect of phosphorus BMPs on agricultural p-loads for Sand Creek soils.<sup>4</sup> The soils, distinguished land use, slope, tillage practice, and soil group, can then be thought of as representative farms on a per acre basis. Holding these representative farms constant, a variety of policy experiments can be conducted to determine the loading effects of different best management practices (BMPs). These simulations can be used to estimate baseline emissions of phosphorus from farms under a variety of climate conditions. These BMPs are a function of extensive and intensive management choices (Yiridoe and Weersink, 1998) and are linked to the abatement costs measured in forgone profits (Montgomery, 1972; Just and Zilberman, 1988; Malik et al., 1993).

Corresponding to varying degrees of desired phosphorus abatement are the horizontal sums of the least cost abatement efforts across Sand Creek’s 148,000 acres. These abatement levels and costs are used to derive the aggregate abatement costs for the entire watershed. A second degree polynomial functional form was estimated to represent the abatement cost,

$$C(q^l) = \alpha^l + d^l(q^l) + b^l(q^l)^2$$

where  $q^l$  is the abatement of the nonpoint source and  $\alpha^l$ ,  $d^l$ , and  $b^l$  are coefficients. Results are reported in Table 1. The coefficient estimates are consistent with the assumption of strict convexity and in line with previous work.

SUMMARY OUTPUT		Nonpoint Abatement Cost Function		
Ex-ante Emissions = 75,058 lbs. year <sup>-1</sup>				
Regression Statistics				
R Square	0.998817062			
F	Significance F			
2955.234407	5.69334E-11			
	Coefficients	Standard Error	t Stat	P-value
$\alpha^l$	20032.16355	10176.7398	1.968426425	0.089698971
$d^l$	-6.327539673	1.132515198	-5.58715652	0.000826999
$b^l$	0.000605045	2.67356E-05	22.63067331	8.32814E-08

Table 1: Aggregate nonpoint abatement costs.

<sup>4</sup>ADAPT (Agricultural Drainage and Pesticide Model) was selected due to its the ability to account for major surface and subsurface hydrologic processes including agricultural subsurface tile drainage systems, useful for the tile-drained soils of the Upper Midwest.

## 2.2 Point source abatement costs

The main point source contributors of phosphorus to the Sand Creek are wastewater treatment plants and feedlots. There are reliable sources documenting the annual contributions of the two wastewater treatment plants (MPCA, 2000; MPCA, 1994; Metropolitan Waste Control Commission, 1993). Documenting feedlot contributions is more difficult, calling into question categorizing feedlot contributions as point sources. Feedlots are considered point source contributors of phosphorus by the Minnesota Pollution Control Agency that has been compiling a list of licensed feedlots in Minnesota. The most current database lists 92 reported feedlots in the Sand Creek (MPCA, 1998), which contain approximately 14,903 animal units (1000 lbs. / animal). Using generic conversion ratios for beef cattle, this corresponds to an annual production of 583,601 pounds of phosphorus. A lower bound on the percentage of stored manure that annually enters the watershed is taken exogenously to be 5% of feedlot production (MPCA, 1999). The initial point source emissions sum to approximately 40,000 lbs/year, or 35% of the total Sand Creek load. This is consistent with earlier watershed estimates (MPCA, 2000). Similar to nonpoint sources, the aggregate point source abatement cost function is calculated as the horizontal sum of least cost abatement practices undertaken by the point sources to achieve a desired level of phosphorus abatement. As mentioned before, this cost is given as the difference between unconstrained profits and constrained profits. The point source cost function is therefore,

$$C(q^h) = \alpha^h + d^h(q^h) + b^h(q^h)^2$$

where  $q^h$  is the abatement of the point source and  $\alpha^h$ ,  $d^h$ , and  $b^h$  are coefficients. Results are reported in Table 2.

SUMMARY OUTPUT		Point Abatement Cost Function		
Ex-ante Emissions = 40,114 lbs. year <sup>-1</sup>				
<i>Regression Statistics</i>				
R Square	0.99814236			
<i>F</i>	<i>Significance F</i>			
4567.198957	6.11185E-24			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
$\alpha^h$	430701.1755	88799.13555	4.850285679	0.000150062
$d^h$	-103.948035	9.759454604	-10.65100861	6.09534E-09
$b^h$	0.007446797	0.000226219	32.91855899	7.73062E-17

Table 2: Aggregate point source abatement costs

## 2.3 Abatement benefits

A recent study has examined the benefits to phosphorus abatement in this region (Mathews et al., 2000). Combining revealed and stated preferences, Mathews et al. (2000) estimate random-effects probit model for phosphorus abatement in the Minnesota River similar to Loomis (1997). Using these estimates it is possible to estimate the mean willingness-to-pay for a 40% phosphorus abatement level and the marginal effect of water quality on willingness-to-pay. Calibrating these results to the Sand Creek (i.e., 3.5% of the total phosphorus load in the Minnesota River) it is possible to determine the total benefits to 3.5% of the regional population for a 40% reduction in Sand Creek emissions. Johansson (2000) estimates the marginal benefits under several broad assumptions to be<sup>5</sup>,

$$MB = 585 - 50.2024 \ln(q^h + q^l).$$

For the relevant range of efficient abatement choices the linear marginal benefits function,  $MB(q_t) = w - vq_t$  where  $w$  and  $v$  coefficients, is a sufficient approximation to the log-linear form for our purposes:

$$MB = 92.9899369 - 0.000874161 (q^h + q^l)$$

## 2.4 Regulator uncertainty

In this model of regulator-firm behavior, it is the regulator's uncertainty about the firms' abatement costs and the knowledge of the regulator's rule that introduces a strategic incentive for the firm to manipulate the regulator. As mentioned before, we assume that these sources of uncertainty serve to shift the linear term in the polynomial abatement cost function in an additive manner by 5%. This in fact shifts the intercept for the marginal cost functions up by 5%. While this simplifying assumption about the extent of regulator uncertainty is debatable, care was taken to be conservative. As more information becomes available, this variable will be improved.

## 3 Simulation: Model and results

There are two firms, one with high abatement costs and the other with low abatement costs, indexed by  $j = h, l$ . There are two time periods, indexed by  $t = 1, 2$ . Let  $\delta$  be the discount factor between periods. Initial emissions (without any costly abatement activity) by firm  $j$  in period  $t$  are  $e_t^j$ . Let abatement by firm  $j$  in period  $t$  be  $q_t^j$ . The abatement cost function for firm  $j$  is given by  $C^j(q_t^j, \theta)$ , where  $\theta$  is a realization of a random variable  $\Theta$ , which is known to the firms but not known by the regulator. We assume that the marginal abatement cost function for each firm is positive and increasing in abatement

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<sup>5</sup> Assume first that the marginal willingness-to-pay approaches zero as abatement approaches 100%. That is to say, that the benefits to abatement level off as 100% abatement is realized, consistent with the traditional assumptions of



( $C_q^j(q_t^j, \theta) > 0$  and  $C_{qq}^j(q_t^j, \theta) > 0$ ) and that  $C^j(0, \theta) = 0$ . We assume that increases in  $\theta$  result in higher total and marginal abatement cost at all levels of abatement:  $C_\theta^j(q_t^j, \theta) > 0$  and  $C_{q\theta}^j(q_t^j, \theta) > 0$ . The aggregate abatement cost function,  $C(q_t, \theta)$ , is the minimum cost of achieving aggregate abatement in period  $t$ , where aggregate abatement is  $q_t = q_t^h + q_t^l$ . Let  $C_q(q_t, \theta)$  represent the marginal aggregate abatement cost function, assumed to be continuous. Define  $E[C_q(q_t, \Theta)]$  as the *expected* marginal abatement cost function when information about the realization of the random variable  $\Theta$  is unknown. Benefits of abatement in period  $t$  are  $B(q_t)$ . We assume that the marginal benefits of abatement are positive but declining in aggregate abatement:  $B'(q_t) > 0$  and  $B''(q_t) < 0$ . To ensure an interior optimum, we assume that  $C_q(0, \theta) < B'(0)$  for all  $\theta$  in the support of  $\Theta$ .

Prior to the first period, the regulator chooses a type of policy, either emissions taxes or marketable emissions permits. In period 1, the regulator sets the level of emission taxes or the number of permits issued to each firm. Firms then choose period 1 abatement (and emissions trading). The regulator observes each firm's abatement level and, in the case of marketable emissions permits, the price of permits. She then updates her belief about  $\theta$  and, based upon the firms' behavior, infers that the value of the random variable  $\Theta$  is  $\theta^R$ . In the second period, the regulator again sets the level of emission taxes or the number of permits issued to each firm, this time using information gathered from observing first-period emissions and prices. Firms then choose period 2 abatement (and emissions trading).

The goal of each firm is to minimize the present value of costs (abatement plus regulatory costs). Firms are strategic in that they take account of how first-period actions may influence future regulatory policy.

The regulator's objective is to maximize the expected present value of net social benefits (i.e., minimize the sum of damages from pollution and abatement cost). In our model, the regulator is not strategic in the same way that firms are. In each period, the regulator sets marginal benefit equal to expected marginal cost and sets policy accordingly. The regulator uses a non-strategic updating of beliefs in period 2 that fails to account for the firms' strategic behavior.

For a detailed description of how the model is solved the reader is referred to Moledina et al (2000) and Appendix A of this paper. The results are presented in Table 3.

Variable	Full information efficient	Emission taxes		Emission permits	
		Non- strategic firms	Strategic firms	Non- strategic firms	Strategic firm: Buyer power
$q_1$	50,406.60	48,444.02	63,717.90	53,088.36	53,088.36
$q_2$	50,406.60	50,406.60	43,749.70	50,406.60	46,655.30
$p_1$	48.03	45.75	45.75	50.94	58.42
$p_2$	48.03	42.41	40.49	42.41	44.06
$a_1$	-	-	-	62,157.90	62,157.90
$a_2$	-	-	-	64,765.40	68,516.70
Welfare	5,064,477.41	5,060,637.02	4,684,558.41	5,057,308.05	4,800,101.41
Deadweight loss	0.00	3,840.40	379,919.00	7,169.36	264,376.00

Table 3: Numerical results from the two period game.

The results shown in Moledina et. al (2000) continue to hold when applied to the case of Minnesota Phosphorous emissions. With strategic firms, permits outperform taxes in terms of welfare. In the tax case, aggregate abatement is grossly inefficient in both periods. Firms overabate relative to the efficient amount in the first period to manipulate the regulator into believing that abatement costs are low. Firms then face a low second-period emissions tax and underabate in period two. The welfare losses from the combination of overabatement in period one and underabatement in period two under emissions taxes are generally greater than the welfare losses from underabatement in period two under emissions permits. It is interesting to note that the deadweight loss with taxes is only about 8% of welfare while with permits, the proportionate deadweight loss is 5%!

Again, with emission taxes in the first period, strategic firms abate more than is efficient in order to receive lower taxes in the next period. With emission permits, the buyer or point source makes a “take-it or leave-it” offer of price higher than the efficient permit price of \$48.03. This is done in order to manipulate the regulator into thinking that the firms are high-cost firms. The regulator obliges by issuing more permits in the next period,  $a_2 = 68,516.70$ .

## 4 Conclusions

When an environmental regulator does not have complete information about firms’ abatement costs, the firms can use this informational asymmetry to their advantage. Firms know that their behavior in a given time period is a signal of costs to the regulator, and that she takes this behavior into account when making policies in subsequent periods. We have explored the effects of this strategic behavior on the price-quantity comparison.

In the tradition of past studies that estimated the costs and benefits of pollution abatement, we assumed quadratic costs and benefits. We estimated the benefits and costs of phosphorus pollution abatement in the Sand Creek sub-watershed of the Lower Minnesota Basin following Johansson (2000). This

region was chosen for several reasons chief among them that it is the largest contributor of phosphorus (p-load) to the Minnesota River. These results were then used in a two-period simulation of a strategic game between a regulator and two aggregate sources of pollution, a point source and a nonpoint source.

When facing an emissions tax, we found that in a subgame-perfect equilibrium firms will overabate in the first period, face lower taxes in the second period, and underabate in the second period relative to the efficient outcome. When facing a permit market, firms have an incentive to bid up the price of permits in the first period, in order to obtain more permits in the second period. In our model, permits outperformed taxes in terms of efficiency.

There are a number of natural extensions to this work. Foremost would be to extend the simulation to multiple periods and see if the results still hold. Initial analytical work by Moledina et. al. (2000) show that these results continue to hold when the model is run over multiple periods. To sharpen the realism of the dynamic game, one could also consider the case in which the regulator knows she is going to be misled. In this case, both the regulator and the firms would be strategic players, resulting in a complicated dynamic solution concept.

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## APPENDIX

### A The tax environment

Recall from Section 2 that our estimated marginal benefit function was  $MB(q_t) = w - vq_t$ , firm  $j$ 's marginal abatement function is  $MC(q_t^j) = (d + \theta) + b^j q_t^j$ , and the regulators expected marginal cost function is  $E[MC(q_t)] = d + E[\theta] + (\frac{b^h b^l}{b^h + b^l})q_t$ . In the first period, the regulator chooses  $p_1$  so that marginal benefits and expected marginal costs are equal, which upon rearranging yields

$$p_1^* = \frac{vd + w\gamma}{v + \gamma}, \quad (1)$$

where  $\gamma = b^h b^l / (b^h + b^l)$ , is the slope of the aggregate marginal cost curve. The regulator expects an aggregate abatement level in the first period of  $q_1^*$ . After observing  $p_1$ , each firm  $j$  abates a quantity  $q_1^j$ . A non-strategic firm would choose  $q_1^j$  so that  $MC = p_1$ , or

$$q_1^{j**} = \frac{1}{b^j} \left( \frac{\gamma(w - d)}{(v + \gamma)} - \theta \right).$$

In the second period, the regulator observes each firm's  $q_1^j$ , and thus knows aggregate abatement  $q_1$ . She believes that the price-quantity pair she observes,

$(q_1, p_1^*)$ , is on the true marginal cost curve, so that  $p_1^* = (d + \theta^R) + \gamma q_1$ . This implies,

$$\theta^R = \gamma \left( \frac{w - d}{v + \gamma} - q_1 \right).$$

In the second period, the regulator, using the above relationship, the regulator chooses  $q_2$  to equalize marginal benefits and expected marginal costs:

$$MB(q_t) = w - vq_t = d + \theta^R + \left( \frac{b^h b^l}{b^h + b^l} \right) q_t = E[MC(q_t)].$$

Because the marginal costs are linear and the regulator knows the slope of the marginal cost function, the first-order conditions in the second period reduce to,

$$w - vq_2^* = d + \gamma \left( \frac{w - d}{v + \gamma} - q_1 \right) + \gamma q_2^*$$

which can be rearranged as

$$q_2^* = \frac{w - d}{v + \gamma} - \frac{\gamma}{v + \gamma} \left( \frac{w - d}{v + \gamma} - q_1 \right). \quad (2)$$

Using equation (2) and assuming the regulator sets a second-period price equal to the aggregate expected marginal cost, we obtain  $g(q_1)$ , the function used by the regulator to determine  $p_2$ :

$$p_2 = g(q_1 | p_1) = d + \gamma \left( \frac{w - d}{\gamma + v} - \frac{\gamma}{\gamma + v} \left( \frac{w - d}{v + \gamma} - q_1 \right) \right).$$

The  $j$ 'th firm takes  $q_1^{-j}$  as given and solves the dynamic programming problem of choosing a nonnegative  $q_1^j$  to minimize total costs, given by

$$TC = p_1(e^j - q_1^j) + (d + \theta)q_1^j + \frac{b^j}{2}q_1^{j^2} + \left\{ g(q_1^j + q_1^{j-} | p_1)(e^j - q_2^j) + (d + \theta)q_2^j + \frac{b^j}{2}q_2^{j^2} \right\}$$

subject to equations (2) and (1). The sub-game perfect Nash equilibrium is obtained by simultaneously solving this dynamic program in Mathematica for the two firms.

### A.1 The permit environment, high cost firm has market power

In the first period, the regulator chooses a target abatement level by setting marginal benefits equal to expected marginal costs. The result is  $q_1 =$

$(w - d) / (\gamma + v)$ , which means that the regulator distributes  $a_1 = e_1 - (w - d) / (\gamma + v)$  permits. To derive the relationship between the first period permit price observed by the regulator and the number of permits distributed by the regulator in the second period, we use the fact that in the first period she expects each firm to equate the permit price to marginal costs. Hence,

$$p_{a_1} = d + \theta^R + \gamma \left( \frac{w - d}{\gamma + v} \right) \quad (3)$$

and, thus,

$$\theta^R = p_{a_1} - \frac{dv + \gamma w}{\gamma + v}.$$

In the second period, the regulator equates marginal benefits with the new expected marginal cost,

$$w - vq_2 = d + \theta^R + \gamma q_2,$$

which, when solved for  $q_2$  using  $\theta^R$  from (3) yields the regulator's dynamic response function,

$$a_2 = h(p_{a_1} | a_1) = e_2 - \left( \frac{w(2\gamma + v) - d\gamma - p_{a_1}(\gamma + v)}{(\gamma + v)^2} \right).$$

In order to solve for a sub-game perfect equilibrium, we start in the second period. Since the high cost firm is the price setter, it solves for the seller's excess demand for permits in the second period. This is done by solving the seller's cost-minimization problem given  $p_{a_2}$ ,

$$\min_{q_2^l} (d^l + \theta)q_2^l + \frac{b^l}{2}(q_2^l)^2 + p_{a_2}(e^l - q_2^l - a_2^l).$$

From the fact that emissions must equal the number of permits, and from the solution to the above problem, we can rewrite  $p_{a_2}$  as a function of  $a_2$  and  $q_2^h$ , which can in turn be used in the buyers's cost minimization problem,

$$\min_{q_2^h} (d^h + \theta)q_2^h + \frac{b^h}{2}(q_2^h)^2 + p_{a_2}(a_2, q_2^h)(e^h - q_2^h - a_2^h).$$

The solution to this problem, along with the regulator's dynamic response function, yields optimal  $q_2^l$  as a function of  $p_{a_1}$ . We can also use the relationships derived thus far to link  $p_{a_1}$  and the optimal second-period price.

At this stage, we have the regulator's dynamic response function to the first-period price  $h(p_{a_1} | a_1)$ ; the seller's demand for permits as a function of the  $t$  period price,  $q_1^l(p_{a_t})$ ; the second-period price as a function of first-period permit



price,  $p_{a_2}(p_{a_1})$ ; and the number of permits in the second period as a function of first-period price,  $a_2(p_{a_1})$ . These results are substituted into the high cost firm's two period cost-minimization problem.

We are able to use the results from the above steps to reduce the high cost firm's problem to a univariate minimization problem in which the choice variable is  $p_{a_1}$ . All optimal values can be derived from the optimal value of  $p_{a_1}$ . As with the tax case, the model is solved in Mathematica using the equations developed here.