Beyond Optimal Linear Tax Mechanisms: An Experimental Examination of Damage-Based Ambient Taxes for Nonpoint Polluters

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1. Introduction

The regulation of nonpoint source water pollution from agriculture is a complex problem characterized by a multiplicity of polluters, informational asymmetries, complex fate and transport processes, and stochastic environmental factors. Taken together, these characteristics make regulatory policy based on individual firm emissions prohibitively costly. To circumvent this issue, economists, beginning with the seminal work of Segerson (1988), have devised economic incentive instruments that assign liabilities based on deviations between the observed ambient water quality level and a specified pollution threshold (Xepapadeas 1991; Horan, Shortle and Abler 1998, 2002; Hansen 1998, 2002).

In the special case of a linear damage function, the regulator can optimally set the parameters of Segerson's (1988) incentive scheme solely with information on the damage function. When the damage function is nonlinear, a depiction that likely represents many watersheds, Segerson's incentive scheme is firm-specific, and the regulator must acquire costly firm-specific data on factors such as input use, land management practice, and soil type.

Using a linear damage function setting, recent laboratory experimental economics efforts have investigated the ambient-based mechanisms proposed by Segerson, as well as some simple variants (Spraggon 2002, 2004; Poe et al. 2004; Vossler et al. 2005). Overall, five ambient pollution instruments have been tested. The overarching incentive scheme, the combined approach, imposes a tax (subsidy) on each unit of pollution in excess of (below) a pollution target coupled with a fixed penalty imposed whenever ambient pollution exceeds the target. Special cases include a tax/subsidy mechanism whereby the fixed penalty is omitted, a fixed penalty instrument whereby the marginal tax/subsidy is omitted, a tax-only scheme that implements a linear tax for pollution in excess of the target, and a subsidy-only scheme that implements a per-unit subsidy on each unit of pollution below the target.

Results from these investigations show that a subset of ambient-based regulatory instruments can produce near-efficient outcomes. Specifically, under noncooperative conditions, the tax/subsidy and tax-only instruments successfully realize the pollution target on average, whereas the other three instruments result in excess pollution. The explanation for the observed inefficiencies of the latter three instruments is that they result in multiple Nash equilibria, as opposed to the tax/subsidy and tax only policies, which result in unique equilibria. Under cooperative conditions, tax/subsidy and combined approach instruments result in gross overabatement whereas the tax-only and fixed penalty instruments perform reasonably well. The tax-only instrument, therefore appears to be the policy instrument with the potential to meet policy objectives in both cooperative (Spraggon 2002) and noncooperative (Poe et al. 2004) settings.

The current body of experimental economics research, however, is limited in two fundamental ways. First, each study has utilized an “optimal design” in which the threshold or “cutoff” pollution level for triggering the ambient-based tax/subsidy policy is set equal to the social optimum. The nature of such designs, however, does not enable the researcher to isolate the effect of the threshold and the effect of the specific tax/subsidy level, since the optimal tax/subsidy program and the threshold level are mutually reinforcing when set at the social optimum.

The second limitation of the current body of research is that it only investigates the limited case of a linear tax function. While the linear tax is appropriate for the case of a linear damage schedule, the application to real world situations may be limited. A more believable circumstance is that economic damages increase at an increasing rate as ambient pollution levels rise. Responding to the fact that Segerson's incentive scheme requires firm specific information in the case of a nonlinear damage function, Hansen (1998) and Shortle, Horan, and Abler (1998) introduced a damage-based tax whereby the regulator observes the ambient concentration and charges each polluting firm a tax equal to total damages. Under this liability scheme, the regulator need only know the damage function.

This paper describes a set of economics experiments that serve to address the limitations of past research by: (1) evaluating the effectiveness of an ambient-based tax mechanism under a broader, more realistic, range of conditions; and (2) testing the damage-based, nonlinear tax of Hansen (1998) and Horan, Shortle and Abler (1988).

The first set of experimental treatments expands on previous research efforts that assume a linear damage function by altering the regulator-designated tax cutoff and the marginal tax rate. As indicated previously, previous experiments implement the various schemes by setting the tax threshold equal to the socially optimal pollution level, and setting the marginal tax/subsidy rate and/or fixed penalty to theoretically induce the pollution target at minimum cost under noncooperative conditions. As such, it is impossible to determine whether subjects are making decisions based on the economic incentives that they are faced with or if instead they are responding only to the focal point provided by the threshold.

The importance of determining whether subjects are responding optimally to the tax or simply reacting to the focal point is not significant if the regulator is able to accurately identify the socially optimal level of pollution (and define the target accordingly). However, since the profit functions of producers are generally assumed to be not directly observable by the regulator, determining the social optimum is impossible even if the regulator has an understanding of the damage function. Without knowing the social optimum ex ante, it is therefore impossible for the regulator to consistently set the threshold equal to the social optimum.

Along with shifting the cutoff level, we also test the robustness of the results by varying the tax rate. Such exploration is critical because marginal damages and hence the optimal marginal tax are likely to vary across watersheds, and locations within a watershed, even if the same threshold ambient level applies, such as that specified in a TMDL. For example, a water resource that is used as a drinking water source will likely have higher marginal damage levels than a water resource that is used primarily for transportation.

Addressing the second fundamental limitation of past research outlined above, the second part of the paper discusses additional treatments that implement the damage-based tax of Hansen (1998) and Shortle, Horan, and Abler (1998) under a nonlinear damage function. As stated above, this is an important policy instrument to consider given the substantial reduction in the regulator's information burden (in comparison to Segerson's incentive scheme) when damages are nonlinear. Similar to the fixed penalty and combined instruments, the nonlinear tax also has multiple Nash Equilibria. This results from the fact that the tax paid by each firm is in part determined by the actions of all other firms. As Hansen states, "we cannot be confident that the system will actually settle down at the optimal Nash-equilibrium under the damage based tax mechanism as under Segerson's constant tax-rate mechanism" (p. 105). The experimental laboratory therefore represents an ideal testbed, to see how groups of subjects react under the nonlinear, damage-based tax.

The incidence of cooperation on the observed results indicates that instruments involving subsidies may be prone to inefficiencies when group communication can occur. As such, the set of experimental treatments reviewed in this paper relies exclusively on the tax-only instrument. While the theoretical literature considers only the competitive case, it seems very likely that communication will occur amongst a small group of homogeneous farmers. Taking into account the real world potential for communication, our experiments test the relative efficiencies of the tax only instrument under both cooperative and noncooperative settings.

2. Description of Economic Model

Our experiments are predicated on the model of nonpoint source pollution used by Segerson (1988) and others. In the experiment, each subject represents a firm that shares a common watershed with five other firms of identical structure. Each firm is a price-taker and generates revenues based producing y units of a commodity at a per-unit price P. A firm's production, however, also generates emissions, x, that have an effect on the level of total ambient pollution. To reduce emissions the firm can either reduce production or increase abatement effort, a, using some form of abatement technology. Specifically, each of the six firms faces the following cost function, where the capital letters represent parameters:

$$C(y,a) = Ay^2 + Ba^2 \quad (1)$$

Taking prices as given and assuming that firms receive fixed payments (costs)[1] regardless of their production choices, each firm faces the corresponding profit function:

$$\pi(y,a) = Py - \left(Ay^2 + Ba^2\right) + FP \quad (2)$$

After taking the appropriate first order conditions to equation (3), we see that each firm maximizes profits, absent any regulatory policy, by choosing $y = P/2A$ and $a = 0$.

The runoff function for each firm that results from its output and abatement decisions can be characterized by the equation:

$$r(y,a) = Gy^2 - Ha^{0.5} \quad (3)$$

Firm runoff is then delivered to the common water resource by the equation:

$$x(r) = J\,r \quad (4)$$

The variable x represents an individual firm's level of emissions to the common water resource. Since six homogenous firms are located along the common water resource, the total ambient pollution (X) can be defined simply as a sum of the individual emissions. Total pollution therefore takes on the following functional form.

$$X = \sum_{i=1}^{6} x_i \quad (5)$$

To solve the social planner's problem, we first define the social damage function by the general equation:

$$D(X) = QX^{\alpha} \quad (6)$$

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[1] The fixed payment is included primarily to prevent firms from going bankrupt when the ambient based mechanism is imposed, however, it could be thought of as revenue coming from land that is enrolled in a conservation program such as the CRP. Firms do not explicitly see this profit function and are not given any reference to the fixed payment.

Where Q and α are real numbers and X is the total pollution level. To define the damage function in terms of y and a, we can use equations (3), (4) and (5) and the fact that all firms are homogeneous to derive the equation:

$$D(y,a)=6*Q*J*(Gy^{2}-Ha^{0.5}) \tag{7}$$

The benefit function for the economy is defined as the sum of the profit functions from each of the six firms. Since all firms are homogeneous, the benefit function therefore becomes:

$$B(y,a)=6*(Py-\left(Ay^{2}+Ba^{2}\right)+FP) \tag{8}$$

The net benefit equation for the economy can now be defined in terms of y and a using equations (7) and (8).

$$NB(y,a)=6*(Py-\left(Ay^{2}+Ba^{2}\right)+FP)-6*Q*J*(Gy^{2}-Ha^{0.5}) \tag{9}$$

The net benefit function above assumes that firms have an infinite number of output and abatement choices available to them. To simplify the decision making process and to better represent the limited number of abatement choices available to real world firms, we restrict the number of output-abatement combinations to twelve. In so doing, we assume that each firm has a choice of twelve potential emissions levels and then uses the optimal combination of output and abatement effort to reach that level of emissions. Therefore, each firm solves the following constrained maximization problem (CPMP) for every level of x.

$$\begin{aligned}
\underset{\mathrm{a,y}}{\mathrm{Max}}:\ & \pi = Py-\left(Ay^{2}+Ba^{2}\right)+FP \\
s.t.\ \ & x \geq J*(Gy^{2}-Ha^{0.5}) \\
& y \geq 0 \\
& a \geq 0
\end{aligned} \tag{10}$$

The implications of imposing a discrete choice set on each firm can best be illustrated by introducing the parameters used in this analysis.

Parameter	Value
P	6
A	0.02
B	0.05
FP	350
G	1
H	20
J	4/9,000

Table 1: Values of parameters used in analysis

Using the values in Table 1, we see that the answer to the unconstrained optimization problem is $y^* = 150$ and $a^*=0$, thus yielding an optimized profit of $\pi^*=800$.

Now suppose that the firm would like to reduce its emissions to $x=9$. Substituting $x=9$ into the CPMP yields the solution $y^*=142.34$ and $a^*=0.23$. Substituting y^* and a^* back into the objective function yields $\pi^* = 798.82$. So to optimally reduce emissions from 10 units to 9 units, the firm would reduce output from 150 to 142.32 and would increase abatement effort from 0 to 0.23. By choosing any level positive of emissions, we could similarly use the CPMP to optimally define y^* and a^*. Note that it is possible for the firm to produce more than 10 units of emissions. To do this it would hold abatement effort at zero and increase output above 150. However, since 150 is the unconstrained profit maximizing level of production, emitting more than 10 units of emission is suboptimal and therefore results in lower profits.

Solving the CPMP for discrete values of x between one and twelve results in the following the table below, where y^* and a^* represent the optimal output and abatement respectively for the given value of x, and π^* represents the corresponding optimized profit.

x	y*	a*	π*
12	164.32	0.00	795.90
11	157.32	0.00	798.93
10	150.00	0.00	800.00
9	142.34	0.23	798.82
8	134.21	0.38	795.01
7	125.56	0.53	788.04
6	116.26	0.70	777.21
5	106.15	0.88	761.51
4	94.98	1.10	739.39
3	82.30	1.39	708.24
2	67.28	1.82	662.99
1	47.78	2.64	590.65

Table 2: Profit maximizing values of output and abatement for given values of emissions

In Segerson's model, the firm level decision variables are output and abatement. For our analysis, we assume that the firm picks the profit maximizing pair of output and abatement to achieve a certain level of emissions. The firm level decision variable therefore is its level of emissions. The benefit schedule for each firm is therefore given by the profit corresponding to each level of emissions in Table 1.

The social benefit function is defined simply by multiplying the x and π* values by six, since there are six firms operating along the water resource. To calculate the benefit corresponding to emission levels that are not a factor of six, we make the final assumption that the group of firms is optimally distributing profits. This implies that if emissions are 33 for example, then three firms are emitting six units and three firms are emitting five units. While there are many combinations of individual firm emissions that sum to 33, we are interested in the optimal distribution of emissions for the construction of the benefit function. In this way, our benefit function might be better described as a benefit frontier. Due to the concavity of profits as a function of emissions, the optimal social benefit will always be characterized by the smallest range of individual emissions that exactly meet the given total emissions amount (so in the example above, the concavity of the profit function implies that the combination 5,5,4,7,6,6 will yield a lower total profit than the combination 5,5,5,6,6,6 since the range (6-5) is less than (7-4)).

The social benefit function as we have constructed it is not continuously differentiable. Instead, the function has small "jumps" in multiples of six, corresponding to the changes in profit associated with the discreet individual emission quantities. The marginal benefit of an increase in total emissions is therefore defined as $\pi^*(X) - \pi^*(X-1)$.

To solve the social planner's problem, we find the level of total emissions where the marginal social benefit is equal to the marginal social cost. As an example, suppose that the damage function is $20X^1$, yielding a constant marginal social cost equal to 20. The marginal social benefit is declining in X and is equal to 22.1 for $X \in [25,30]$ and equal to 15.7 for $X \in [31,36]$. The social optimum is therefore equal to 30. Increasing pollution from 29 to 30 results in a net benefit of 22.1-20=2.21 and further increasing pollution from 30 to 31 would result in a negative net benefit of 15.7-20=-4.3.

At the social optimum of 30, each firm must emit five units to be on the frontier of the social benefit function. The regulator can achieve this level of emissions by imposing a tax based on the damage function of the ambient pollution concentration. For the linear damage case this is easy since the marginal damage associated with a one unit increase in individual emissions is constant. For the case of nonlinear damages, however, the marginal damage of a one unit increase in pollution depends on the level of total pollution.

Focusing on the case of the linear damage function that is equal to 20X, setting the marginal tax equal to the marginal damage of 20 results in each firm optimally choosing to emit five units. By increasing emissions from five to six units each firm will gain an increase in profit of 777.21 – 761.51 = 15.7 but it will incur the cost associated with the marginal tax of 20. Therefore it is in no firm's best interest to increase emissions above five units. Similarly, the firm could reduce its tax burden by 20 through a reduction in emissions of one unit. However, the decrease in profit of 761.51 - 739.39 = 22.12 implies that this would not be an optimal choice. Therefore, when faced with the marginal tax of 20, each the individual firm should optimally choose to emit five units. Since the six firms along the common water resource are homogenous, the tax will optimally result in emissions of 30, which is identical to the social optimum.

The tax policy described above is equivalent to setting the tax equal to the total damage level. The optimal marginal tax is equal to the marginal damage and therefore the tax levied for a given level of total emissions is equal to the total damage level when there is no tax cutoff level. This is identical to the tax structure recommended by both Hansen (1998) and Horan et. al. (1998) where the tax levied is identical to the total damage associated with a given level of total emissions. The benefit of the damage based tax is that it has the flexibility to accommodate the case of nonlinear damages. As such, the marginal tax rate for any level of total emissions is equal to the marginal damage.

While the structure of the damage based tax mechanism is simple, the potential complexity that it adds to firm level decision making is substantial. Whereas firms in the linear tax case did not need to consider the decisions of other firms, the nonlinear tax presents a case where the marginal tax faced by each firm is contingent on the decisions of others. Suppose that the damage function is increasing at an increasing rate, as might be expected for the case of water pollution. If a firm expects the total emissions from all other firms to be low, then the expected marginal tax rate will also be low and it will be optimal for that firm to increase emissions. Conversely, if the firm believes that total emissions from other firms will be high, then it expects to face a high marginal tax and should cut back emissions.

Up to this point, we have assumed that the total pollution in the common water resource is a simple sum of the amount emitted by each individual firm. In reality, however, the observed ambient pollution is likely to be influenced by numerous stochastic factors, such as weather events, which may influence the delivery of pollutants to the water resource. To account for this reality, the total pollution amount (X) is redefined by adding a random term (ε) and can be characterized by the equation below.

$$X = \sum_{i=1}^{6} x_i + \varepsilon \tag{10}$$

$$where: \varepsilon \sim U[-4,4]$$

Since the random term is distributed uniformly on the range negative four to positive four, the expected value of the random term will be zero. Although the random term is equal to zero on average, it can still have important effects on firm decision making when a tax cutoff is in place, as explained below.

Segerson (1988) introduces what she terms a “cutoff” level of ambient pollution. The choice of the cutoff is “somewhat arbitrary because it does not affect the socially optimal level of abatement undertaken.” (p.89) Segerson’s incentive scheme, however, includes both a tax and a subsidy, such that a tax is owed for ambient levels above the cutoff and a subsidy is paid for ambient levels below the cutoff. Thus the tax/subsidy instrument proposed by Segerson is symmetric. However, following the conclusions of Spraggon and Poe et. al., the incentive scheme employed in this analysis is a pure tax policy, where no subsidies are paid for ambient pollution levels below the cutoff.

The cutoff can potentially have important effects on the emission decisions of individual firms under the pure tax policy, due to the asymmetry created by the cutoff. For levels of ambient pollution below the cutoff, there is no incentive to further reduce pollution. Therefore, if the cutoff is placed above the socially optimal level of pollution, then it is unlikely that ambient pollution will achieve the social optimum.

The uncertainty created by the random term also has important implications for firm level decision making due in part to the asymmetry of the tax policy with the cutoff. For example, even if firms are able to reduce combined emissions below the cutoff, they may still face some positive tax liability because of the range of the random term. Analogously, when combined emissions are above the cutoff there is some positive probability of not being taxed as long as combined emissions are not more than one half the range of the random term above the cutoff.

Despite the asymmetries created by the tax only policy, the primary motivation towards eliminating subsidies arises from the potential for the tax only mechanism to reduce cooperative behavior . Spraggon warned of the potential inefficiencies resulting from cooperation and Vossler et. al. as well as Poe et. al. observed these predicted inefficiencies when subjects were allowed to communicate. By eliminating the subsidy below the cutoff, firms no longer have an incentive to cooperatively reduce emissions once combined emissions fall sufficiently far below the cutoff.

The tax only policy, along with an appropriate cutoff, has the potential for greatly improving efficiency given the prevalence of cooperative behavior. However, the outcomes predicted by the tax policy along with the cutoff can vary greatly depending on whether cooperation actually occurs. The ambient pollution mechanism theory assumes noncooperative behavior, and only notes that the potential for cooperation could have negative effects on the efficiency of the system. However, given that the proposed market has only a few (six) homogeneous firms, located along the same water resource some amount of communication seems likely.

Indeed, the amount of communication among farmers does vary, potentially depending on the type of farm, the overall size of the common water resource and the number of farms affected. While communication and cooperation may be the norm in one watershed, other areas may be characterized by farms with little or no contact with one another. It is therefore important to test the tax policy and associated cutoff levels under both cooperative and noncooperative scenarios. This is accomplished in the laboratory setting by allowing subjects to discuss strategies and comparing the observed results to the case where subjects are not allowed to communicate.

3. Experiment Design

All experimental treatments described in this paper were performed at the Cornell Laboratory for Experimental Economics & Decision Research using undergraduates at Cornell University during the Spring 2005 semester. The undergraduates were recruited from introductory courses in the fields of Economics and Applied Economics and Management. The majority of subjects had some experience participating in other experiments and all subjects had taken at least one course in economics.

Paralleling previous experimental analyses, each of our treatments utilized groups composed of six subjects, where the subjects represent a set of homogenous firms located along the same common water resource. Each treatment is tested using eight groups of six subjects, where four of the groups were allowed to communicate and four were not. The communication (cheap talk) sessions gave subjects the opportunity for costless, nonbinding communication at three separate points during the experiment. In each experiment session, two groups of six students participated under identical regulatory and communication conditions. Each subject faced the same profit function and had the same delivery rate of emissions to the common water resource.

The experiment consisted of twenty rounds split into two parts. In each round, subjects select one management decision from a list of twelve options described below. Part A of the experiment consists of the first five rounds of the experiment. In part A, the total pollution amount in each round had no affect on subject earnings. Note that no communication was allowed in any of the sessions for part A.

After the first five rounds were concluded, subjects were given additional instructions for part B. In part B of the experiment, subjects faced a tax per unit of total pollution above a defined cutoff level. The tax and cutoff vary for each treatment and will be explained in detail in the next section. Although part B consists of fifteen rounds, subjects are not told this until after the rounds have been completed.

In each round of the experiment, subjects choose a management decision from a list of twelve possibilities. Each of the twelve possibilities corresponds to a discrete level of emissions ranging from one unit to twelve units. As previously explained, we assume that the specific level of emissions is reached using the optimal combination of output and abatement. The management decision therefore jointly determines emissions, output, abatement and before tax profit (which is referred to as "earnings from production"). Each subject is given a "Management Decision Sheet" that provides the output[2], emissions and earnings from production for each of the twelve available options. An example of the "Management Decision Sheet" is provided below.

Management Decision	Your Earnings From Production	Your Emissions	Your Production
A	795.90	12	164.3
B	798.93	11	157.3
C	800.00	10	150.0
D	798.82	9	142.3
E	795.01	8	134.2
F	788.04	7	125.6
G	777.21	6	116.3
H	761.51	5	106.2
I	739.39	4	95.0
J	708.24	3	82.3
K	662.99	2	67.3
L	590.65	1	47.8

Table 3: Example of the "Management Decision Sheet" provided to subjects

In addition to the "Management Decision Sheet", subjects were also given a "Tax Calculation Sheet" for part B of the experiment. The "Tax Calculation Sheet" listed the tax payment associated with each level of total pollution and therefore varied depending on the particular treatment.

The experiments generally lasted slightly less than one hour and subjects earned an average of $20. The earnings from each round were denominated in "tokens" and were converted into dollars using an exchange rate. The exact exchange rate varied per treatment so as to keep the earnings per round roughly equivalent across treatments.

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[2] The abatement effort is not included on the "Management Decision Sheet" as the term abatement generally implies a reduction in emissions from a previous level and might therefore confuse subjects.

For each treatment, there are four testable hypotheses based on the observed levels of total pollution. The first hypothesis is that the aggregate emission from rounds 1-5, where no instrument was in place is equal to 60, which represents the case where all six subjects choose the profit maximizing emissions level of 10.

The next three hypotheses are that total pollution level is equal to the (1) group optimum (2) private optimum (3) social optimum. The group optimum is the level of emissions that maximizes the expected payout for the group of six subjects. Since the tax is applied evenly to all subjects, a reduction in emissions by one subject effectively reduces the expected tax of all subjects. Therefore substantial gains from cooperation can be realized depending on the level of the cutoff.

The private optimum is the level of emissions that we expect if each individual is independently seeking to maximize her expected payout. Given the fact that all subjects face homogenous profit functions and delivery ratios and that the tax is applied evenly, the private optimum also represents a symmetric Nash equilibrium outcome. For some of the treatments there may not be a pure strategy symmetric Nash equilibrium. For these treatments results are evaluated based on the symmetric mixed strategy Nash equilibrium. Finally, the social optimum is the level of emissions that maximizes social benefit (profit) plus social cost.

In addition to these four hypotheses based on aggregate group results, we also explore the individual firm level effects of each treatment. It is possible that a particular treatment could look socially optimal according to the aggregate level of emissions, however, this could be misleading if some of the individual firms were not behaving optimally. Since all firms are symmetric, an aggregate level of emissions that approaches the optimum and has very little variation in earnings across subjects would be a positive indication that the instrument is efficient. Likewise if either the aggregate emissions are significantly different from the social optimum or there is a wide variation in earnings across subjects, then the tax instrument is not efficient

4. Treatments Altering Tax and Cutoff

The first four treatments were designed to determine whether subjects respond optimally to the mix of tax and cutoff that they are faced with or if their decisions are based more on the focal point provided by the level of cutoff.

Treatment 1: The first treatment represents the baseline scenario, where the marginal tax rate was fixed at 20 and the cutoff was set at 30. This treatment parallels previous experimental analyses in that the cutoff is set equal to the social optimum and subjects are faced with a linear tax instrument that is set equal to marginal damages.

The existence of the random term implies that the group can maximize profits by eliminating the majority of its tax exposure. By calculating the earnings from production minus the expected tax rate, the group optimum can be shown to be 27. For this case we have a unique Nash equilibrium in mixed strategies, where every subject emits 5 units with probability 0.62 and 6 units with probability 0.38. This results in a private optimum of 32.3. It is important to note that there are other Nash equilibria that are not symmetric. In fact any time where a cutoff exists, we will have a range of asymmetric Nash outcomes (therefore with the exception of treatment 4, all of the treatments will have asymmetric Nash equilibria). Finally, assuming that the damage function is equal to 20X, the social optimum occurs at 30.

Treatment 2: In the second treatment the cutoff remained at 30, but the tax rate was changed to 20/6 = 3.33. The tax rate was chosen for two reasons. First the 3.33 tax rate is equivalent to the Pigouvian tax when the marginal damages are 20. While previous experiments have shown that the ambient tax can achieve a socially efficient level of pollution, they have not shown that the ambient based tax is more efficient than the traditional Pigouvian tax that charges firms according to their contribution to marginal damages. Accordingly, the results from the 3.33 tax rate can be directly compared to the results from the 20 tax rate for the case where the social optimum is 30.

The second reason for the 3.33 tax rate is to test how the ambient based mechanism works for a case where the marginal damage of pollution is low. We can therefore evaluate the results from the tax, assuming that it is based on a marginal damage of 3.33, to determine whether the size of the tax has an effect on the efficiency of the instrument.

With the tax rate of 3.33 and the cutoff at 30, the group optimum is 32. The unique pure strategy Nash equilibrium has every subject emitting 9 units such that the private optimum is 54. The social optimum for this case, assuming that marginal damage is 3.33, is also 54.

Treatment 3: For the third treatment we reduced the cutoff to 18 and, similar to the first treatment, used a tax rate of 20. By comparing this treatment with the first treatment, we can better understand the importance of the cutoff level in determining the efficiency of the observed results.

For this treatment the group optimum can be shown to be 17. The symmetric pure strategy Nash equilibrium pure strategy is for each subject to emit 5 units, meaning that the private optimum is 30. Finally the social optimum, similar to treatment 1, is 30.

Treatment 4: The fourth treatment involved eliminating the cutoff and maintaining the tax rate at 20. This allows for an important comparison of the efficiency of observed results when the focal point created by the cutoff is completely eliminated compared to treatments 1 and 3 where there was a positive cutoff.

The group optimum in this case is 6, which represents the low end of the decision space. The Nash equilibrium and private optimum are 5 units and 30 units respectively, which is identical to treatment 3 predictions. The social optimum of 30 is also identical to that in the first and third treatments.

The set of group, private and social optimum aggregate emissions conditions for treatments 1-4 are presented in table 4 below. These optima are tested using the mean aggregate emissions for rounds 11-20 of each treatment.

	Cutoff	**Tax**	**Group Optimum**	**Private Optimum**	**Social Optimum**
Treatment 1	30	20	27	32.3	30
Treatment 2	30	3.33	32	54	54
Treatment 3	18	20	17	30	30
Treatment 4	0	20	6	30	30

Table 4: Description of cutoff, tax and corresponding optima for treatments 1-4

The mean combined emissions across rounds 1-5 and rounds 11-20 are included in table 5 below for treatments 1-4. For each treatment we report separately the results for the four groups of six subjects that were not allowed to communicate and the four groups that were allowed to communicate. The statistic in parentheses under the mean statistic is the variance across the four groups that make up each treatment and communication type combination.

	No Communication		Communication	
	Rounds 1-5	Rounds 11-20	Rounds 1-5	Rounds 11-20
Treatment 1	59.80 (0.21)	35.35 (3.03)	58.25 (8.25)	27.03 (1.84)
Treatment 2	59.80 (3.07)	49.08 (15.22)	59.20 (4.16)	32.78 (16.9)
Treatment 3	60.25 (6.28)	30.00 (25.27)	58.45 (2.68)	18.55 (0.64)
Treatment 4	58.85 (11.56)	29.30 (75.13)	58.55 (1.48)	8.65 (3.72)

Table 5: Summary of average total emissions from treatments 1-4.

The aggregate group emissions presented in table 5 are compared to the group, private and social optimal using t values in tables 6 and 7.

	No Communication	**Communication**
	Pollution = 60	Pollution = 60
Treatment 1	-0.87 (0.4502)	-1.22 (0.3101)
Treatment 2	-0.23 (0.834)	-0.78 (0.49)
Treatment 3	0.20 (0.8546)	-1.89 (0.1544)
Treatment 4	-0.68 (0.5472)	-2.39 (0.097)

Table 6: Summary of t values from rounds 1-5.

Table 6 shows that for treatments 1-4, the average aggregate emissions generated across the first five rounds was not significantly different from 60. Note that there was no communication allowed in any of these scenarios. Table 5 breaks the results into the no communication/communication columns only for consistency with the results presented below.

	No Communication			Communication		
	Group Optimum	Private Optimum	Social Optimum	Group Optimum	Private Optimum	Social Optimum
Treatment 1	9.59 (0.0024)	3.50 (0.0394)	6.15 (0.0087)	0.04 (0.9729)	-7.77 (0.0044)	-4.38 (0.0220)
Treatment 2	8.75 (0.0031)	-2.53 (0.0858)	-2.53 (0.0858)	0.38 (0.7313)	-10.33 (0.0019)	-10.33 (0.0019)
Treatment 3	5.17 (0.014)	0.00 (1.0000)	0.00 (1.0000)	3.86 (0.0306)	-28.55 (0.0001)	-28.55 (0.0001)
Treatment 4	5.38 (0.0126)	-0.16 (0.8819)	-0.16 (0.8819)	2.75 (0.0708)	-22.15 (0.0002)	-22.15 (0.0002)

Table 7: Summary of t values from rounds 11-20 with p values in parentheses.

The four treatments evaluated in this section show distinct differences between the groups that were able to communicate and the groups that were not. Among the groups that could not communicate, all but treatment 1 were not significantly different from the private optimum.

The groups that could communicate, however, were all significantly different from the private optimum. In fact, only treatment 3 was significantly different from the group optimum. This, however, is primarily a result of the low variance observed for the groups in treatment 3 as the observed mean of 18.55 is only slightly above the group optimum of 18. Note, however, that group means were always slightly greater than the optimum. This suggests some amount of free riding on the part of individuals within the groups. It should also be noted that in every case, communication led to a result that was not socially optimal.

The objective of these four treatments was to determine whether subjects were able to optimally navigate the mix of tax and cutoffs. While the cutoff does influence the observed results, it does not have an effect independent of its impact on determining the private and group optimum. For treatments 3 and 4, the tax remained at 20 while the cutoff was reduced from 18 to 0. For both treatments, the private and social optimum was 30 the aggregate emissions when communication was not allowed were not significantly different from 30 in either case despite the change in cutoff.

Moreover, groups were able to optimally respond to the tax rate imposed. When the cutoff remained at 30 and the tax changed from 20 to 3.33 between treatments 1 and 2 group emissions in the no communication case had a corresponding increase such that treatment 2 emissions were not significantly different from the private optimum.

When groups could communicate, the reduced emissions observed can be better explained by the group optimal amount rather than on loss aversion. For instance, in treatment 2, groups responded optimally by generating emissions in excess of the cutoff despite the tax that they paid as a result.

While the aggregate group results illustrate some interesting points, they only tell half of the story. To get a true idea for the efficiency of each of the treatments, the variance in earnings is also important to consider. The standard deviation of average per round earnings of each subject for each treatment from rounds 11-20 is included in table 8 below.

	No Communication	**Communication**
Treatment 1	31.25	4.05
Treatment 2	16.29	13.14
Treatment 3	84.39	12.46
Treatment 4	127.61	35.46

Table 8: Standard deviation of average earnings across subjects for rounds 11-20.

The standard deviations of average per round earnings show two very interesting results. First, the standard deviation is much lower among groups that could communicate that in groups that could not. Secondly, the standard deviation appears to increase as the cutoff gets further from the social optimum. In both the no communication and communication groups the standard deviation increased between rounds 1,3 and 4 as the cutoff was reduced from 30 down to 18 and then down to 0. This interesting result suggests that the cutoff, while not necessarily affecting aggregate results, may have a significant impact on the variability of the economy.

5. Treatments Altering Damage Function

The second set of treatments was designed to evaluate the effectiveness of a damage based tax. The evaluation utilizes treatments 1 and 4 that were discussed previously in addition to treatments 5 and 6 that are explained below.

Treatment 5: In treatment 5, we test a nonlinear damage based tax with no cutoff, similar to that proposed in Hansen and Horan et. al. For this treatment the damage function employed is $D(X) = (1/3)*X^2$. Since the tax is based on the total economic damage from pollution, the damage function also represents the tax schedule. The intuition behind the choice of damage function is that when X=30, the marginal damage rate is (2/3)*30 = 20. Therefore the social optimum for the nonlinear damage tested in this treatment is identical to the social optimum in the first, third and fourth treatments.

This treatment is directly comparable to treatment 4, where we had no cutoff and a linear tax with a social optimum at 30. The group optimum of 12 in this treatmtent is higher than the corresponding group optimum of 6 in the linear case, since marginal reductions in pollution are less valuable in terms of tax avoidance as the pollution level drops. In this treatment, there is a pure strategy Nash equilibrium of 6 units, however even with the absence of the cutoff, this equilibrium is not unique since the expected tax depends on the decision of all other subjects. The results are tested based on the private optimum of 30. As explained in the previous paragraph, the social optimum for this case is 30.

Treatment 6: The final treatment is also based on the nonlinear damage based tax, however in this treatment we include a cutoff of 30. Hansen proposed the introduction of a cutoff so as to limit the effects of cooperation. The cutoff tested in this treatment is motivated by Hansen, but was designed for making a comparison with treatment 1, where we had a linear tax and a cutoff of 30.

For treatment 6, the group optimum is 27, which is identical to the group optimum in treatment 1. The Nash equilibrium is a mixed strategy where each subject optimally emits 5 with probability 0.69 and 6 with probability 0.31, so that the private optimum is 31.9. Notice that this is slightly lower than treatment 1 because of the constantly increasing tax rate. The social optimum for this last treatment is 30.

The set of group, private and social optimum aggregate emissions conditions for treatments 4,5,1 and 6 are presented in table 6 below. These optima are tested using the mean aggregate emissions for rounds 11-20 of each treatment.

	Cutoff	**Tax**	**Group Optimum**	**Private Optimum**	**Social Optimum**
Treatment 4	0	20	6	30	30
Treatment 5	0	$(1/3)X^2$	12	30	30
Treatment 1	30	20	27	32.3	30
Treatment 6	30	$(1/3)X^2$	27	31.9	30

Table 9: Description of cutoff, tax and corresponding optima for treatments 4,5,1,6.

The mean combined emissions across rounds 1-5 and rounds 11-20 are included in table 10 below for treatments 4,5,1 and 6.

	No Communication		Communication	
	Rounds 1-5	Rounds 11-20	Rounds 1-5	Rounds 11-20
Treatment 4	58.85 (11.56)	29.30 (75.13)	58.55 (1.48)	8.65 (3.72)
Treatment 5	60.30 (1.56)	34.45 (3.99)	59.05 (1.96)	13.30 (3.65)
Treatment 1	59.80 (0.21)	35.35 (3.03)	58.25 (8.25)	27.03 (1.84)
Treatment 6	58.35 (9.34)	31.50 (1.25)	60.70 (3.8)	27.60 (1.47)

Table 10: Summary of average total emissions from treatments 4,5,1,6.

Again we see a large distinction between the communicating groups and the no communication groups. We are primarily interested, however, in comparing the nonlinear results to the linear results. Tables 11 and 12 below present the hypothesis test results.

	No Communication	**Communication**
	Pollution = 60	Pollution = 60
Treatment 5	0.48 (0.6638)	-1.36 (0.2675)
Treatment 6	-1.08 (0.3594)	0.72 (0.5245)

Table 11: Summary of t values from rounds 1-5 for rounds 5 and 6

Identical to rounds 1-4, table 11 shows that the average aggregate emissions generated across the first five rounds in treatments 5 and 6 was not significantly different from 60.

	No Communication			**Communication**		
	Group Optimum	Private Optimum	Social Optimum	Group Optimum	Private Optimum	Social Optimum
Treatment 4	5.38 (0.0126)	-0.16 (0.8819)	-0.16 (0.8819)	2.75 (0.0708)	-22.15 (0.0002)	-22.15 (0.0002)
Treatment 5	22.48 (0.0002)	4.46 (0.021)	4.46 (0.0210)	1.36 (0.2666)	-17.49 (0.0004)	-17.49 (0.0004)
Treatment 1	9.59 (0.0024)	3.50 (0.0394)	6.15 (0.0087)	0.04 (0.9729)	-7.77 (0.0044)	-4.38 (0.0220)
Treatment 6	8.06 (0.0040)	-0.72 (0.5254)	2.69 (0.0746)	0.99 (0.3948)	-7.10 (0.0057)	-3.96 (0.0287)

Table 12: Summary of t values from rounds 11-20 with p values in parentheses.

Table 12 again shows the result that no communication groups tended toward the private optimum while the communicating groups tended towards the group optimum. Treatment 5, where subjects faced a nonlinear tax with no cutoff failed to yield either the private or social optimum. A possible explanation for this result is that this particular treatment represented the most computationally challenging for subjects.

When groups were able to communicate, results from all four groups were not significantly different from the group optimum.

	No Communication	**Communication**
Treatment 4	127.61	35.46
Treatment 5	48.51	18.01
Treatment 1	31.25	4.05
Treatment 6	37.42	17.94

Table 13: Standard deviation of average earnings across subjects for rounds 11-20.

Again, the difference in the standard deviations of subject earnings between the communication and no communication groups is readily apparent. An interesting result is the fact that the standard deviations in treatment 5 were significantly lower than the standard deviations in treatment 4. This suggests that the nonlinear tax may actually have some beneficial properties in terms of affecting firms more homogeneously.

The results from the second section seem to show that groups do tend to "settle down" near the Nash equilibrium, despite the fact that it is not unique. When groups were not able to communicate in treatment 6 and faced the nonlinear tax and cutoff of 30, they were able to achieve the optimal symmetric Nash equilibrium. Treatment 5, where the cutoff was removed, however, did not achieve the Nash solution. This could be a result of the multiple asymmetric Nash equilibria or it could be a result of the difficulty associated with calculating optimal strategies under the more confusing nonlinear tax scenario. Comparing treatments 4 and 5 reveals that the group emissions were not significantly different under the linear and nonlinear tax with no cutoff. This is a strong indication that the nonlinear damage based tax in and of itself does not have a major impact on individual decision making.

Under the nonlinear tax, the groups that were able to communicate moved towards the group optimal level of emissions with proficiency comparable to that of the groups that faced a linear tax. The earnings under the nonlinear tax also seemed to vary no more than the earnings under the linear tax rate when communication was possible.

6. Conclusion

The set of experiments outlined in this paper show that groups respond optimally to the ambient based tax instrument under a variety of tax and cutoff scenarios. Although the cutoff does affect the group and socially optimal levels of emissions, it does not have an impact on aggregate group behavior outside of these effects. The primary impact of altering the cutoff seems to be its impact on increasing the variability of earnings at the individual level when groups are not able to communicate.

The experiments also indicate that subjects do respond optimally to the nonlinear damage based tax as proposed by Hansen and Horan et. al. There was in fact less variability in earnings associated with the nonlinear tax, pointing to the fact that below the private optimum there is less incentive to reduce emissions and above the private optimum there is greater incentive to reduce emissions. Therefore as long as the cutoff is set to ensure that the private optimum is equal to the social optimum, the nonlinear damage based tax will effectively induce socially optimal behavior in the absence of communication. The problems posed by group cooperation are still present, though they are less severe than under the linear tax since there are fewer incentives to collude as group emissions decrease.

We therefore seem to have to competing issues. When the cutoff is set equal to the social optimum, the asymmetry caused by the cutoff in combination with the level of uncertainty implies that the Nash equilibrium level of emissions will be greater than the social optimum. Therefore when the cutoff is set below the social optimum groups were better able to achieve the social optimum on average. However, as the cutoff is reduced below the social optimum there is a corresponding increase in the level of variability observed in individual earnings. Additionally, when communication is available, the further the cutoff is below the social optimum the bigger the problem posed by the group cooperation in terms of moving the aggregate emissions away from the social optimum.

Since the social optimum generally cannot be determined ex ante without knowledge of firm level profit functions, setting the cutoff appears to be a risky endeavor. While our results show that eliminating the cutoff will not have a significant impact on aggregate emissions when firms do not communicate, there is potential for inefficiencies in the form of greater variability in earnings and greater problems posed by cooperative behavior.

In addition, the tax instrument is, by its nature, prone to cooperation due to the fact that each group member is taxed according to the emissions generated by each individual. Therefore a unit reduction in emissions has the potential of positively affecting the earnings of every member of the group in the form of tax avoided while only affecting the production based earnings for one of the group members.

In cases where groups could communicate, we observed both lower production and lower emissions. Since firms are price takers, the cooperative activity did not result in higher prices to consumers and therefore did not have a negative impact on consumer surplus. It is therefore interesting that firms are actually colluding to provide better water quality at no cost to the consumers in the watershed under the assumptions we have made. Additionally, when cooperation occurs groups are earning the highest amount possible given the powerful incentives created by the tax.

To the policy maker, the results of our analysis imply that when farms along a given water resource do not communicate, the ambient tax based on the economic damages created by the pollution can effectively induce socially optimal levels of emissions. This result is independent of the level at which the tax cutoff is set so long as the cutoff is sufficiently far below the social optimum. Although eliminating the cutoff seems an attractive solution due to its simplicity, there is a greater potential for inefficiencies at the individual farm level. As the cutoff deviates from the social optimum it appears that some farms are more likely to over abate to the benefit of other farms that abate less than the optimal amount. The variability effects of changes in the cutoff are reduced, however, when the tax is based on a nonlinear damage schedule.

Finally, when communication among farms is the norm it is likely that cooperation will have a significant impact on group emissions. This suggests that the magnitude of the tax should be reduced to reflect the nature of the communication. While the degree of communication is a difficult variable to quantify, it is likely that the potential for cooperation will exist when a relatively small number of homogenous farms are reacting to the proposed tax mechanism. The potential for cooperation need not be seen in a completely negative light, however, as it tends to result in lower pollution levels at no major cost to consumers given that farms are price takers. Alternatively, when cooperation is apparent the regulator may be able to significantly reduce tax rate so as to achieve the social optimum.

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