The Regulation of Nonpoint Emissions in the Laboratory: A Stress Test of the Ambient Tax Mechanism*

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Abstract

We investigate the ability of the damage based tax mechanism to induce socially optimal outcomes in a controlled laboratory environment which incorporates important aspects of nonpoint pollution problems. Our experimental setting combines a strictly convex damage function with uncertainty in measuring the ambient level of pollution, indefinitely repeated interactions among heterogeneous polluters, limited information on the regulator's side about the polluters' profit functions, and, in half of the experimental conditions, limited information on the polluters' side about the strategic environment. We additionally investigate whether the relative position of the social optimum in the polluters' emission space has an impact on the efficiency of the fiscal instrument. In almost all implemented conditions, the observed total pollution level is not significantly different from the socially optimal level but compliance at the individual level is rarely observed. Experimental conditions in which polluters have to dramatically reduce their emissions in order to comply with the fiscal instrument lead to higher efficiency levels than those where compliance implies less dramatic reductions. Our most striking result is that less information on the polluters' side is beneficial from a social point of view as the performance of the damage based tax mechanism is higher the less information polluters have about the strategic environment.

1 Introduction

Regulation of nonpoint emission problems such as pesticide, and nitrogen pollution of lakes and ground water is a major policy challenge. The emissions-based instruments that economists usually advocate for cost-effective pollution control are not feasible since individual emissions are unobservable. Among the policy instruments suggested by the theoretical literature on nonpoint management, the tax/subsidy schemes applied to ambient concentrations have drawn particular interest.[1]

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[1]Shortle and Horan (2001) provides an exhaustive review of the nonpoint source pollution control literature.

Segerson (1988) first proposed an ambient tax/subsidy scheme which implements an economically efficient allocation of pollution control among nonpoint sources. Under such a fiscal instrument, each polluter pays a marginal tax corresponding to total marginal environmental damage caused by changes in the ambient concentration. When the damage function is linear, the social optimum is implemented in dominant strategies and the correct specification of the mechanism only requires the regulator to have knowledge of the damage function.[2]

When the damage function is strictly convex, the regulator cannot introduce a linear ambient tax if he does not observe each polluter's profit function. Hansen (1998) proposed a damaged based version of the ambient tax that eliminates the need of additional information as the planning problem is decentralized to polluters. The damage based mechanism was independently introduced by Horan, Shortle, and Abler (1998) to handle the multiple dimensionality of polluters' choice set. Shifting the base of the mechanism from ambient concentrations to environmental damage weakens the solution concept since the social optimum is only implemented in non-dominant Nash strategies. A polluter's response to the mechanism therefore depends on its own expectations about the impact of its choices, the choices of others, and natural events on ambient conditions. Among others, Shortle and Horan (2001) have argued against this information burden on polluters as the typical private nonpoint polluter is a small business or household with limited technical information.

As far as we know, no real world implementation of an ambient tax/subsidy scheme to regulate nonpoint source pollution has been reported on till now.[3] The only available empirical evaluation of the ambient tax scheme has been carried out in the laboratory. Spraggon (2002a) investigates the ability of four variants of the ambient tax instrument to effectively control the nonpoint source pollution problem: a tax/subsidy scheme which combines a tax and a subsidy depending upon whether the total pollution level is above or below the optimal level; a tax scheme which involves only a tax if the optimal level is exceeded; a subsidy scheme which involves a subsidy and a bonus in case the total pollution level is below the optimal level; and a group fine scheme which involves a lump-sum fine if the total pollution level exceeds the optimal level. Contrary to the subsidy and group fine schemes, the two first variants of the fiscal scheme applied to ambient concentrations are effective in enforcing the socially optimal level, this result being robust to both uncertainty in measuring the ambient level of pollution and experience of the subjects with the environment. However, the data show that these schemes do not ensure individual compliance. As an extension of the previous study, Spraggon (2004) investigates the ability of the tax/subsidy and the group fine schemes to induce a group of heterogeneous polluters to choose a target pollution level. At the aggregate level, the group fine scheme is not effective in enforcing the socially optimal level whereas the tax/subsidy scheme is but there are significant reductions in efficiency when the group is composed of polluters who have different profit (cost) functions and maximal emission levels. Additional experimental evidence on the ability of the ambient tax mechanism to induce socially optimal outcomes in a nonpoint pollution context is provided by Cochard, Willinger, and Xepapadeas (2005), Alpizar, Requate, and Schram (2004), Poe, Schulze, Segerson, Suter, and Vossler (2004), Camacho and Requate (2004), and Vossler, Poe, Schulze, and Segerson (2004). Broadly speaking, the existing controlled laboratory experiments on the ambient tax/subsidy scheme conclude that though the polluters' emissions do not maximize the social net benefit,

[2]Social optimality in dominant strategies relies on the additional assumption that the ambient pollution is the sum of the individual emissions.

[3]Ribaudo, Horan, and Smith (1999) discuss several fiscal schemes sharing strong similarities with ambient taxes that have been introduced in the United States to regulate nonpoint source pollution.

a second-best level of social welfare is achieved as the observed total pollution level matches the specified target.[4]

In this paper, we investigate the ability of the damage based tax mechanism to induce socially optimal outcomes in a controlled laboratory environment which incorporates important aspects of nonpoint pollution problems. Indeed, and contrary to the previous laboratory studies which focused more on the internal validity of the experiment by considering 'stylized' environments, our experimental setting combines a strictly convex damage function with uncertainty in measuring the ambient level of pollution, repeated interactions among heterogeneous polluters without a well-defined last stage of interaction, limited information on the regulator's side about the polluters' profit functions, and, in half of the experimental conditions, limited information on the polluters' side about the strategic environment. The first aspect of our experimental design derives from the empirical observation that in many potential practical applications of the ambient tax mechanism (like pollution of lakes, streams and ground water reservoirs) damage functions are notoriously nonlinear–with sharply rising damage from concentrations above a critical level. By considering indefinitely repeated interactions among polluters, we evaluate the costs to the regulator of implementing the ambient tax/subsidy scheme when polluters have strong incentives to collude. The last aspect of our setting is particularly relevant for practical application of mechanisms based on ambient pollution concentrations as the solution of the planning problem under the damage based tax mechanism is decentralized to polluters.[5] More precisely, by comparing an experimental condition where polluters have no information about the other polluters' profit functions and maximal levels of emissions with an experimental condition where those characteristics are public knowledge, we investigate whether shifting the burden of information from regulators to polluters severely limits what the ambient tax scheme can accomplish in practice.

In our attempt to implement a setting which captures the uncertainties of naturally occurring environments, we also consider limited information on the regulator's side. Indeed, as the ambient tax/subsidy instrument, the damage based tax/subsidy scheme is defined as the damage minus some lump-sum subsidy, so that it results in a tax or a subsidy depending on whether the total damage is higher or lower than this lump-sum subsidy. Neglecting entry/exit problems, the "ideal" lump-sum subsidy is equal to the expected damage level at the social optimum, meaning that no taxes are collected from polluters and no subsidies are distributed to them in case of full compliance. Computation of the ideal lump-sum subsidy level requires perfect information on the regulator's side about the polluters' profit functions. In the more realistic case of imperfect information, the regulator would either under- or over-estimate the ideal lump-sum subsidy value. If the ideal lump-sum subsidy level is under-estimated then polluters pay taxes under full compliance whereas if the ideal lump-sum subsidy is over-estimated

[4]Auction-based mechanisms have also been put forward to regulate nonpoint source pollution. The experiments intended to test these instruments show that they have some ability to mitigate the ambient pollution problem as well (Cason, Gangadharan, and Duke, 2003; Cason and Gangadharan, 2004; Taylor, Sohngen, Randall, and Pushkarskaya, 2004; Cason and Gangadharan, 2005).

[5]Spraggon (2002b) also considers different information conditions in an experimental tax/subsidy setting with both homogeneous and heterogeneous profit functions, perfect observation of the ambient pollution level, and a finite time horizon. Due to the linearity of the setting, the social optimum is however implemented in dominant strategies. Information has no significant impact on the total pollution level but efficiency tends to increase with the level of information. Other less related experiments show that decreasing the subjects' level of information has no significant impact on behavior (Isaac and Walker, 1998; Marks and Croson, 1999), or decreases the degree of collusion, thereby increasing the frequency play of the static Nash equilibrium (e.g., Mason and Phillips, 1997 show that information has a greater impact on duopolies that have symmetric payoffs than on those with asymmetric payoffs, symmetric markets being more cooperative when payoffs are public knowledge whereas subject choices in asymmetric conditions are well explained by (static) Nash behavior no matter the amount of information available).

they get subsidies at the social optimum. We test the efficacy of the ambient tax mechanism in case of limited information on the regulator's side by comparing an experimental condition where the lump-sum subsidy is under-evaluated with an experimental condition where the lump-sum subsidy is over-evaluated.

Finally, in addition to evaluating what the ambient tax scheme can accomplish in informationally limited settings, we study whether the relative position of the social optimum in the polluters' emission space has an impact on the efficiency of the fiscal instrument. Considering this additional treatment variable is justified by the fact that reducing pollution to the socially optimal level might sometimes require a severe changing and other times only a small adjustment in the polluters' behavior. It should be noticed that existing laboratory studies on nonpoint management did not pay attention to this feature of the environment even though it led to strikingly dissimilar findings. Thus, while the ambient tax/subsidy mechanism reaches high efficiency levels in Spraggon's (2002a) experiment where the social optimum is relatively low in the polluters' emission space (thus requiring an important emission reduction with respect to the *laissez-faire* emission level), much lower efficiency levels are observed in Cochard, Willinger, and Xepapadeas's (2005) setting where the social optimum is relatively high in the polluters' emission space.[6] Related experimental evidence on public goods also shows the impact of the position of the equilibrium (the social optimum in the present study) on the participants' behavior. Roughly speaking, moving the equilibrium closer to the collusive outcome has been found to decrease collusion (see, e.g., Willinger and Ziegelmeyer, 2001). To study this issue, we evaluate the efficiency of the ambient tax/subsidy scheme both in experimental conditions where the social optimum is below the middle of the emission space and where it is above the middle of the emission space.

The remainder of the paper is structured as follows. Section 2 presents the decision setting for our experimental study. The experimental design is described in section 3. Section 4 is devoted to the results and section 5 concludes.

2 Theoretical background

We consider a stylized model of pollution in which a particular resource is damaged from nonpoint sources of emissions, where the damage function is nonlinear and where the polluters' profit functions are unknown to the environmental regulator. In the absence of any environmental control, emission levels are socially inefficient. As Hansen (1998) and Horan, Shortle, and Abler (1998) have shown, if the environmental regulator imposes a damage based tax mechanism, he implements the social optimum as a unique Nash equilibrium of the single-period interaction between polluters. First, we derive the Nash equilibrium emissions before and after the imposition of the damage based mechanism under the assumption that polluters only interact once. Second, we discuss the impact of polluters' knowledge about their strategic environment on the efficacy of the mechanism when polluters interact repeatedly.

2.1 Regulation of one-shot nonpoint emissions

A set $N = \{1, \ldots, n\}$ $(n \geq 2)$ of polluters emit pollutants to the same recipient and individual emissions cannot be observed by the environmental regulator (at least not at an acceptable cost). Environmental damage in the recipient is a function of the ambient pollution level at one given measuring point.

[6] The two experimental settings differ in additional aspects but we hypothesize that the relative position of the social optimum in the polluters' emission space is the one driving the dissimilarity in the results.

Each polluter $i \in N$ knows its own profit function which is defined as a function of emission levels that are a by-product of the polluter's production: $\pi_i(e_i) = \gamma_i - \alpha_i(e_i - e_i^{max})^2$ where $e_i \in [0, e_i^{max}]$ denotes the emissions of the ith polluter, e_i^{max} denotes polluter i's maximal amount of emissions, $\gamma_i > 0$ and $\alpha_i > 0$. In the absence of any environmental control, polluter $i \in N$ releases pollution up to e_i^{max} which we refer to as the uncontrolled level of emissions.

For simplicity, the ambient concentration of the pollutant is given by $\sum_{i\in N} e_i + \epsilon$, where ϵ is a stochastic environmental variable with null expectation. The economic costs of damages caused by pollution are given by $\left(\sum_{i\in N} e_i + \epsilon\right)^2$, meaning that damages from total emissions are a convex function of total emissions. We assume that the damage function is mutual knowledge.[7] The environmental regulator or social planner seeks to maximize total profit less expected environmental damages, i.e., he chooses the socially optimum emission level for each polluter such that the expected net profit is maximized. The expected net profit of resource allocation decisions by nonpoint sources is given by $\sum_{i\in N} \pi_i(e_i) - E\left[\left(\sum_{i\in N} e_i + \epsilon\right)^2\right]$ where E denotes the expectations operator over the stochastic environmental variable. Assuming that polluters and the environmental regulator are risk-neutral, the socially optimal level of emissions for each polluter is obtained by solving

$$\max_{\{e_1,\ldots,e_n\}} \quad \sum_{i\in N} \pi_i(e_i) - E\left[\left(\sum_{i\in N} e_i + \epsilon\right)^2\right]$$

which we refer to as the planning problem.

The environmental regulator has to design a mechanism that gives incentives to the polluters for optimal emission levels. As the damage function is nonlinear, an ambient tax scheme like the one suggested by Segerson (1988) would require knowledge of polluters' profit functions. Under the more reasonable assumption that the environmental regulator only knows the damage function and observes the concentration of ambient pollution, Hansen (1998) and Horan, Shortle, and Abler (1998) have shown that the environmental regulator has to impose a damage based tax mechanism on each polluter in order to implement the socially optimal level of emissions. After the mechanism has been introduced, polluter $i \in N$ chooses e_i so as to maximize $\pi_i(e_i) - E\left[\left(\sum_{i\in N} e_i + \epsilon\right)^2\right] + K$, where $K > 0$ is a lump-sum subsidy determined by the regulator. Assuming interior solution, Nash equilibrium first order conditions are given by $\alpha_i\left(e_i^* - e_i^{max}\right) + e_i^* + \sum_j e_j^* = 0$ leading to $e_i^* = (\alpha_i e_i^{max} - \sum_j e_j^*)/(1+\alpha_i)$, for $i, j \in N$ where $i \neq j$.[8] If $n = 2$, the Nash equilibrium emission of polluter $i \in N$ is thus given by $(\alpha_i e_i^{max}(1+\alpha_j) - \alpha_j e_j^{max})/(\alpha_i(1+\alpha_j)+\alpha_j)$ where $j \neq i$ whereas, for $n \geq 3$, e_i^* is given by

$$\frac{\alpha_i e_i^{max}\left(\frac{1}{(n-2)!}\sum_{\substack{k_{n-2}\in N\\ k_{n-2}\neq i}} \alpha_{k_{n-2}}\left(\sum_{k_{n-3}}\alpha_{k_{n-3}}\left(\cdots\left(\sum_{k_1}\alpha_{k_1}\left(1+\frac{\alpha_{k_0}}{n-1}\right)\right)\cdots\right)\right)\right) - \prod_{\substack{l\in N\\ l\neq i}}\alpha_l\left(\sum_{\substack{m\in N\\ m\neq i}} e_m^{max}\right)}{\alpha_i\left(\frac{1}{(n-2)!}\sum_{\substack{k_{n-2}\in N\\ k_{n-2}\neq i}} \alpha_{k_{n-2}}\left(\sum_{k_{n-3}}\alpha_{k_{n-3}}\left(\cdots\left(\sum_{k_1}\alpha_{k_1}\left(1+\frac{\alpha_{k_0}}{n-1}\right)\right)\cdots\right)\right)\right) + \prod_{\substack{l\in N\\ l\neq i}}\alpha_l}, \quad (1)$$

[7] As pointed out by Tomasi, Segerson, and Braden (1994), polluters are not likely to be informed of the damage function in naturally occurring environments. Therefore a necessary condition for the implementation of such a scheme is for the regulator to be able to estimate the damage function and then communicate it to the polluters.

[8] Due to our convexity assumptions, second order conditions are trivially satisfied.

where $k_{n-z} \in N \setminus \{k_{n-2}, \ldots, k_{n-z+1}, i\}$ $\forall z \in \{3, \ldots, n\}$.[9] Under the assumption that he knows the distribution of the polluters' profit functions, the regulator could determine the "ideal" level of the lump-sum subsidy K^* so that polluters would not incur expected taxes at the social optimum, i.e., $K^* = (\sum_i e_i^*)^2 + Var[\epsilon]$ where Var denotes the variance operator over the stochastic environmental variable.

The damage based mechanism is information efficient as the solution of the planning problem is decentralized to polluters. But the fact that the optimum is implemented as a Nash equilibrium entails that polluter i's response to the damage based mechanism will depend on its conjectures about the other polluters' emission choices. In other words, the consistency requirement in Nash equilibrium requires knowledge of other polluters' Nash equilibrium emissions for polluter i to determine its own Nash equilibrium strategy. Polluter i's conjectures about the profit and environmental types of all other polluters is however of no relevancy for the performance of the mechanism when polluters only interact once.[10]

The economics literature on nonpoint pollution control instruments has raised legitimate concerns about the performance of the damage based tax mechanism in the short run. For example, Hansen (1998) argues that the Nash equilibrium can only be the end point of the dynamic process of changing incentives and polluters reactions starting with the initial imposition of the mechanism. Unfortunately, the argument goes, some unreasonable assumptions have to hold for convergence to happen. The equilibrium approach is problematic as there is no sensible way to introduce a dynamic in the considered game while still preserving the rationality of the polluters. Either polluters are unaware that the game is being repeated and there is no meaningful dynamic[11] or they are aware of the repetitions and then the repeated game is itself a new game, entirely distinct from its components (see Bernheim, 1984, section 2a for a more elaborate discussion). In the next section, we consider a repeated version of the single-period game described above where polluters are aware of the repetitions.

2.2 Regulation of repeated nonpoint emissions

We start by defining the (fully) collusive outcome of the one-shot interaction between polluters, i.e., the outcome when polluters maximize the sum of their expected profits. The collusive outcome is obtained if each polluter $i \in N$ maximizes $\sum_{i \in N} \left[\pi_i(e_i) - E\left[\left(\sum_{i \in N} e_i + \epsilon\right)^2\right] + K\right]$, which leads to $e_i^C = (\alpha_i e_i^{max} - n \sum_j e_j^C)/(n + \alpha_i)$ for $i, j \in N$ where $i \neq j$ (assuming interior solution). If polluters collude, the damage based mechanism becomes inefficient as collusive emissions are lower than the individually optimal ones. Indeed, straightforward but tedious computations show that the Nash equilibrium emission minus the collusive emission of polluter $i \in N$ is given by $\alpha_i \alpha_j^2 (e_i^{max} + e_j^{max})/((\alpha_i(1 + \alpha_j) + \alpha_j)(\alpha_i(2 + \alpha_j) + 2\alpha_j))$ where $j \neq i$ if $n = 2$ whereas, for $n \geq 3$, $e_i^* - e_i^C$, is given by

[9] For example, if $n = 3$, $e_i^* = (\alpha_i e_i^{max}(\alpha_j + \alpha_k + \alpha_j \alpha_k) - \alpha_j \alpha_k (e_j^{max} + e_k^{max}))/(\alpha_i(\alpha_j + \alpha_k + \alpha_j \alpha_k) + \alpha_j \alpha_k)$ where $i, j, k \in N$, and i, j, k are all different.

[10] Indeed, sufficient epistemic conditions for Nash equilibrium assume that each player maximizes his payoff function given his conjectures (i.e. each player is rational), that each player knows his payoff function, and that each player *knows* the strategy choices of the others. Accordingly, common knowledge plays no role and as far as rationality and the payoff functions are concerned, not even mutual knowledge is needed. See Aumann and Brandenburger (1995) for formal details.

[11] This approach appears to presuppose some kind of bounded rationality on the part of polluters.

$$(n-1)\alpha_i \prod_{\substack{r\in N\\ r\neq i}} \alpha_r^2 \sum_{s\in N} e_s^{max} / \left(A(\alpha_1,\ldots,\alpha_n,n)\, B(\alpha_1,\ldots,\alpha_n,n)\right) \tag{2}$$

where

$$A(\alpha_1,\ldots,\alpha_n,n) = \alpha_i \left(\frac{1}{(n-2)!} \sum_{\substack{k_{n-2}\in N\\ k_{n-2}\neq i}} \alpha_{k_{n-2}} \left(\cdots \left(\sum_{k_1} \alpha_{k_1} \left(1 + \frac{\alpha_{k_0}}{n-1}\right)\right) \cdots \right)\right) + \prod_{\substack{l\in N\\ l\neq i}} \alpha_l,$$

$$B(\alpha_1,\ldots,\alpha_n,n) = \alpha_i \left(\frac{1}{(n-2)!} \sum_{\substack{k_{n-2}\in N\\ k_{n-2}\neq i}} \alpha_{k_{n-2}} \left(\cdots \left(\sum_{k_1} \alpha_{k_1} \left(n + \frac{\alpha_{k_0}}{n-1}\right)\right) \cdots \right)\right) + n \prod_{\substack{l\in N\\ l\neq i}} \alpha_l$$

and $k_{n-z} \in N \setminus \{k_{n-2},\ldots,k_{n-z+1},i\}$ $\forall z \in \{3,\ldots,n\}$. As made clear by the *folk-theorem* literature, collusion can arise when polluters interact repeatedly provided there is a 'sufficient' degree of uncertainty over when interactions will cease. In the following, we first evaluate the performance of the damage based tax mechanism under infinitely repeated interactions among polluters, and then we discuss the impact of polluters' knowledge about their strategic environment on the efficacy of the mechanism.[12]

Let us assume that the set of polluters play the single-period game infinitely often in a stationary and time separable environment. After each period of play t, polluters observe the damage caused by ambient pollution. The stochastic environmental variables ϵ_t are independently and identically distributed. Polluter $i \in N$ maximizes $\sum_{t=0}^{\infty} \beta^t \left(\pi_i(e_{it}) - E\left[\left(\sum_{i\in N} e_{it} + \epsilon_t\right)^2\right] + K\right)$ where $\beta < 1$ denotes the polluters' common discount factor. Under the assumption that polluters' profit functions are common knowledge, Green and Porter (1984) provide a theoretical analysis of an equivalent repeated game with imperfect public monitoring. They exhibit a specific symmetric equilibrium where polluters emit at the collusive level as long as the realized damage is below a certain threshold, but revert to the individually optimal emission for a fixed number of periods when it increases above the threshold.[13] Because of the stochastic component in ambient pollution, periodic switches to the individually optimal emission occur on the equilibrium path. The collusive outcome is therefore not supported by the equilibrium even though the performance of the damage based mechanism is greatly reduced. Fudenberg, Levine, and Maskin (1994) conduct a general theoretical analysis of repeated games in which players observe a public outcome that imperfectly signals the actions played. They show that the equilibrium considered by Green and Porter (1984) does not support the collusive outcome only because it is symmetric and that polluters can coordinate on the collusive outcome once one admits asymmetric equilibria. In conclusion, infinitely repeated interactions among polluters have the potential to render the damage based tax mechanism inefficient.[14]

[12]Hansen (1998) extends the damage based mechanism in order to reduce the polluters' incentives to collude. This is achieved by adding a cut-off level to the mechanism so that reducing the damage below the social target no longer results in reduced tax payments. However the computation of the adequate cut-off level requires that the regulator has complete information, in particular regarding the polluters' profit functions.

[13]Collusion is sustainable if and only if polluters put sufficient weight on future profits, i.e., if their discount factor is not too small.

[14] Notice that collusion, which reduces the performance of the fiscal instrument, can be sustained under infinitely repeated

Even after the implementation of the fiscal instrument, polluters can achieve high profits through some type of tacitly collusive signalling behavior. For tacit collusion to be successful, they need however to agree on some credible retaliation mechanism to deter profitable short-term deviations. The scope for collusion is greatest if a polluter that deviates from the collusive agreement is punished as harshly as possible. Clearly, if polluters are heterogeneous and have limited information about their strategic environment, they will have difficulties to determine the most severe punishments that can be possibly imposed on a deviator. The provision of more information about polluters' profit functions should aid polluters' emitting coordination, raise the likelihood of successful tacit collusion and therefore reduce the performance of the damage based tax mechanism.

Shortle and Horan (2001) argue that polluters' information requirements are not trivial under the damage based tax mechanism and that it is not obvious that this information burden makes good economic sense as the typical nonpoint polluter is a small business or household with limited technical information. By considering repeated interactions between polluters, we have however concluded that limited information on the part of polluters about others' environmental types might favor the performance of the mechanism. Clearly, there are welfare ambiguities associated with the amount of information available to polluters about their strategic environment and resolving these policy concerns becomes an empirical question. Our experiment is a first and consequently preliminary step in this direction.[15]

3 Experimental design, procedures and hypotheses

In our laboratory environment, subjects in groups of six take the role of polluters whose decisions correspond to the level of emissions. The larger the decision number the more emissions the polluter releases up to some maximum decision number which corresponds to the polluters uncontrolled level of emission, i.e., to the subject's endowment (in tokens).[16] In each group, one subject is endowed with 23 tokens, four subjects are endowed with 31 tokens and one subject is endowed with 45 tokens. From now on, we will refer to the subject whose endowment is the lowest as the small polluter, the subject whose endowment is the highest as the large polluter and the four remaining subjects in the group as the medium polluters. Subjects are told that their total payoff in each period is the sum of a private payoff and a group payoff. The private payoff is found by looking up their decision number on a payoff table. A different payoff table is associated to each polluter's type, small, medium or large, as the private component of the payoff function differs (see table 2 below). The group payoff depends on the group total. Subjects are informed that the group total is the sum of the decision numbers of all of the

interactions among polluters but also when interactions are repeated a finite number of times. Indeed, Neyman (1999) shows that the introduction of an exponentially small deviation from the assumption of common knowledge concerning the number of repetitions of the one-shot game can induce collusion among polluters. Consequently, the collusive outcome can be approximated by a Nash equilibrium of the finitely repeated version of the one-shot game described in subsection 2.1 provided the number of repetitions is not commonly known.

[15]It is worth mentioning that Fouraker and Siegel (1963) in their classic work on bargaining behavior report early experimental results which indicate that the (static) Nash equilibrium can provide good predictions for repeated markets in which sellers have only limited information but not necessarily in repeated markets with public payoff information. More recently, Brown Kruse, Rassenti, Reynolds, and Smith (1994) explore capacity-constrained price setting behavior in a four seller laboratory environment and investigate the effect of the amount of information provided to sellers on the sustainability of tacit collusion. They observe that prices are higher in complete information conditions, but not significantly higher than prices in limited information conditions.

[16]Emissions are restricted to integer values.

subjects and a random variable which follows a triangular distribution.[17] The group total is analogous to the ambient level of pollution in the nonpoint source pollution case. Adding a random variable to the sum of the decision numbers allows us to investigate the effects of the ambient level pollution being observed with error, or being affected by stochastic factors like weather conditions.

The number of periods and the exact time an experimental session would run were not known by any of the participants during a session.[18] Subjects were only informed that they would interact for at least 12 periods. At the end of the session, subjects are paid their accumulated payoffs, converted from laboratory points to euros. Conversion rates differ between sessions and polluters' types so that, in case of perfect individual compliance with the social optimum, payoffs are identical.

3.1 Design

Two information conditions are used. In the *limited information* condition subjects have no information about the endowments and private payoff tables of other group members. They are only informed that not all group members have been provided with the same endowment and private payoff table. In the *complete information* condition subjects know both the endowments and private payoff tables of the other people in their group. In both information conditions subjects know their own endowments and private payoff tables.

Two positions of the socially optimal level in the strategy space are considered. In the *low position of the social optimum* condition each polluter's socially optimal level of emission is between 30% and 40% of its endowment depending on its type. In the *high position of the social optimum* condition each polluter's socially optimal level of emission is between 60% and 70% of its endowment depending on its type (see table 2 and table 4 below for more details). Recent experimental literature on public good games has shown that the level of the equilibrium in the strategy space has an impact on the subjects' contributions as moving the equilibrium level of contribution closer to the collusive decision leads to a decrease in average over-contribution with respect to the equilibrium (see, among others, Isaac and Walker, 1998 and Willinger and Ziegelmeyer, 2001). By considering two different levels of the social optimum, we study whether these findings can be confirmed in a "public bad" setting (recall that in our experiment the social optimum is the Nash equilibrium of the stage game). In the high social optimum condition, the distance between the social optimum and the collusive outcome is much larger than in the low social optimum condition. Therefore, if past results can be generalized, we should observe average decisions to be closer to the social optimum in the latter case.

There are two levels of the lump-sum subsidy. Instead of assuming that the regulator can determine the level of the lump-sum subsidy which corresponds to no tax/subsidy at the social optimum, we investigate whether a miscalculation has an impact on subjects' behavior. In the *Kinf* condition the regulator under-evaluates the level of the lump-sum subsidy which implies that polluters pay taxes at the social optimum whereas in the *Ksup* condition the regulator over-evaluates the level of the lump-sum subsidy which implies that polluters are subsided at the social optimum.

The two information conditions are combined with the position of the socially optimal level factor and the level of the lump-sum subsidy factor in a complete $2 \times 2 \times 2$ factorial design. Table 1 summarizes

[17] The triangular distribution is a good approximation of the normal distribution and it is easy to explain to subjects.

[18] In order to disable beliefs that the experimenters would randomly stop the experiment we informed subjects in the instructions that the actual number of periods is fixed. We rendered this credible by sticking a poster on the wall - before the start of the session - in sight of all subjects, which had the actual number of periods written on its back. We turned the poster at the end of the session to prove that the number of periods had been fixed ex-ante.

our experimental design and table 2 provides the key parameters of the experiment.

Amount of information	Social optimum's position	Lump-sum subsidy	Treatment
Complete	Low	Kinf	*ComLowKinf*
Complete	Low	Ksup	*ComLowKsup*
Complete	High	Kinf	*ComHighKinf*
Complete	High	Ksup	*ComHighKsup*
Limited	Low	Kinf	*LimLowKinf*
Limited	Low	Ksup	*LimLowKsup*
Limited	High	Kinf	*LimHighKinf*
Limited	High	Ksup	*LimHighKsup*

Table 1: Experimental design.

Social optimum's position	Low			High		
Under-evaluated lump-sum subsidy (*Kinf*)	4200 (85% of 4922.5)			12300 (85% of 14462.5)		
Over-evaluated lump-sum subsidy (*Ksup*)	5700 (115% of 4922.5)			16700 (115% of 14462.5)		
Random variable's support	{-9,-6,-3,0,3,6,9}			{-15,-10,-5,0,5,10,15}		
Random variable's probs.	(1/16) {1,2,3,4,3,2,1}					
Polluter's type	Small	Medium	Large	Small	Medium	Large
Endowment	23	31	45	23	31	45
Value of γ	2645	3363.5	5062.5	7935	9610	15187.5
Value of α	5	3.5	2.5	15	10	7.5

Table 2: Parameters of the experiment.

3.2 Practical procedures

The experiment was run on a computer network between July and September 2003 using 192 inexperienced students at the BETA laboratory of experimental economics (LEES) at the University of Strasbourg. Sixteen sessions were organized, with 2 groups of 6 subjects per session. A total of 4 independent observations per treatment was collected. Subjects were randomly assigned to a group of 6 players on a computer terminal, which was physically isolated from other terminals. Communication, other than through the decisions made, was not allowed. The subjects were instructed about the rules of the game and the use of the computer program through written instructions, which were framed in neutral language and read aloud by a monitor (who was chosen at random from the group of subjects at the beginning of the session). A short questionnaire and three training periods followed.[19] Each

[19] We took subjects through three training periods to familiarize them with the software. During these periods, subjects played "against" the computer and not against other subjects. This was done in order to prevent strategic uncertainty from being reduced. To convince subjects that they were not interacting with each other during the training periods, simulated decisions of the other polluters and random numbers were predetermined and specified in the instructions. Subjects whose questionnaire results indicated that they had not sufficiently understood the rules of the game, were replaced and paid the minimal compensation of 3 euros for answering the questionnaire (around 15 subjects were invited for each session). The questionnaire mainly checked subjects' understanding of the payoff calculation and respectively their ability to read the payoff table.

session took between $1\frac{1}{2}$ and $2\frac{1}{4}$ hours. Table 3 summarizes the subjects' earnings in each treatment. In addition to the earnings related to their performance, subjects received a participation fee of 3 euros.[20]

	Treatment							
Amount of information	Complete				Limited			
Social optimum's position	Low		High		Low		High	
Lump-sum subsidy	Kinf	Ksup	Kinf	Ksup	Kinf	Ksup	Kinf	Ksup
Mean	15.17	5.73	8.84	7.58	6.49	4.70	8.30	6.77
Maximum	25.62	14.23	16.59	10.48	15.70	9.77	12.44	11.27
Minimum	3.82	-0.20	2.51	4.82	-1.82	1.07	4.08	2.54

Table 3: Subjects' earnings in euros.

3.3 Hypotheses

As shown in section 2, when polluters interact repeatedly, limited information about others' environmental types might favor the performance of the damage based tax mechanism as collusion is less likely to emerge.[21] In line with this conclusion, we formulate our first research hypothesis:

H1. *The damage based tax mechanism is more efficient under limited than under complete information.*

Hypothesis H1 is derived from game-theoretical considerations on repeated games with imperfect public monitoring, i.e., it assumes that polluters are able to identify and coordinate upon tacitly collusive outcomes under complete information, and that polluters' emissions are more in line with the ones predicted by the static Nash equilibrium under limited information. As the performance of the mechanism heavily depends on the distribution of the emissions, a weaker version of the research hypothesis can be formulated: *Emissions are closer to the socially optimal level under limited than under complete information.*

As already mentioned, past experimental evidence on public good games has shown that moving the equilibrium level of contribution closer to the collusive decision leads to a decrease in average over-contribution with respect to the equilibrium. Under the assumption that this behavioral finding remains valid in our setting, we expect total emissions to be further below the socially optimal level under the high social optimum than under the low social optimum condition. These behavioral considerations lead to our second research hypothesis:

H2. *Emissions are closer to the socially optimal level under the low social optimum condition than under the high social optimum condition.*

Hypothesis H2 only refers to the average level of emissions depending on the position of the social optimum in the strategy space not to their distribution. Therefore, no immediate conclusion can be

[20] We did not endow subjects with a starting cash balance at each period to cover potential losses. In case of negative payoffs at the end of a session the subject's earnings were only made of the participation fee.

[21] Theoretically, collusion is sustainable in our experimental setting as the number of interacting periods is not commonly known (see footnote 14).

drawn concerning the performance of the damage based tax mechanism depending on the position of the social optimum in the strategy space.

Clearly, the impact of a miscalculation of the lump-sum subsidy by the regulator on subjects' behavior is more difficult to assess. Still, under the assumption of compliance with the mechanism, polluters pay taxes in the *Kinf* condition and they are subsided in the *Ksup* condition. The *Kinf* condition might therefore drive the emissions further away from the socially optimal level which leads to our third research hypothesis:

H3. *Emissions are closer to the socially optimal level under the Ksup condition than under the Kinf condition.*

Again, hypothesis H3 is silent about the performance of the damage based tax mechanism.

Apart from testing the above qualitative research hypotheses, we compare our experimental data to the two following quantitative benchmarks: the social optimum and the (fully) collusive outcome. Table 4 summarizes our theoretical predictions for the two positions of the socially optimal level in the strategy space.[22]

Social optimum's position	Low			High		
Polluter's type	Small	Medium	Large	Small	Medium	Large
Socially optimal emission	9	11,11,11,11	17	15	19,19,19,19	29
Collusive emission	3	3,2,2,2	5	6	6,6,6,6	12

Table 4: Predicted emissions at the social optimum and the collusive outcome.

Total Nash equilibrium emissions released by a group of six polluters composed of one small polluter, four medium polluters and one large polluter equal 70 (respectively 120) in the low (respectively high) social optimum condition. Total collusive emissions released by the same group of polluters equal 17 (respectively 42) in the low (respectively high) social optimum condition.

4 Results

This section discusses the results from the experiment. We first compare the observed total pollution level to the socially optimal level in each treatment and discuss the impact of each treatment variable on the group totals. We then evaluate the ability of the ambient tax-subsidy mechanism to induce socially optimal outcomes by computing the efficiency of the instrument in each treatment. Finally, we analyze the individual decisions. Unless otherwise stated, acceptance or rejection of the null hypothesis is always based on a 5 percent level of significance, and only the first twelve periods have been considered for the analyses.[23]

[22]Given the parametrization of the experiment, Nash equilibrium emissions are integer values, i.e., they are given by equation (1). However, the collusive emissions reported in the table have not been computed by relying on equation (2) but they have been computed under the additional assumption that emissions are restricted to integer values.

[23]Each session had an undetermined number of periods but subjects knew that they would interact for at least 12 periods.

4.1 Analyses at the aggregate level

Our first result is in line with past experimental evidence on ambient tax/subsidy schemes according to which polluters' emissions match the specified target.

Result 1. In all treatments but *ComLowKinf*, mean group totals are close to the socially optimal level in the last six periods. There is a systematic and significant increase of the mean group total towards the socially optimal level over time.

Support. Figure 1 shows the mean group totals in each period for each treatment. In the second half of the time horizon (periods 7-12), the difference between the mean group total and the social optimum is less than 8% of the socially optimal level in all treatments but *ComLowKinf* where it approximately equals 20%. In the latter treatment, the mean group total remains systematically quite below the socially optimal level, though there is a clear increase towards the social optimum over time.

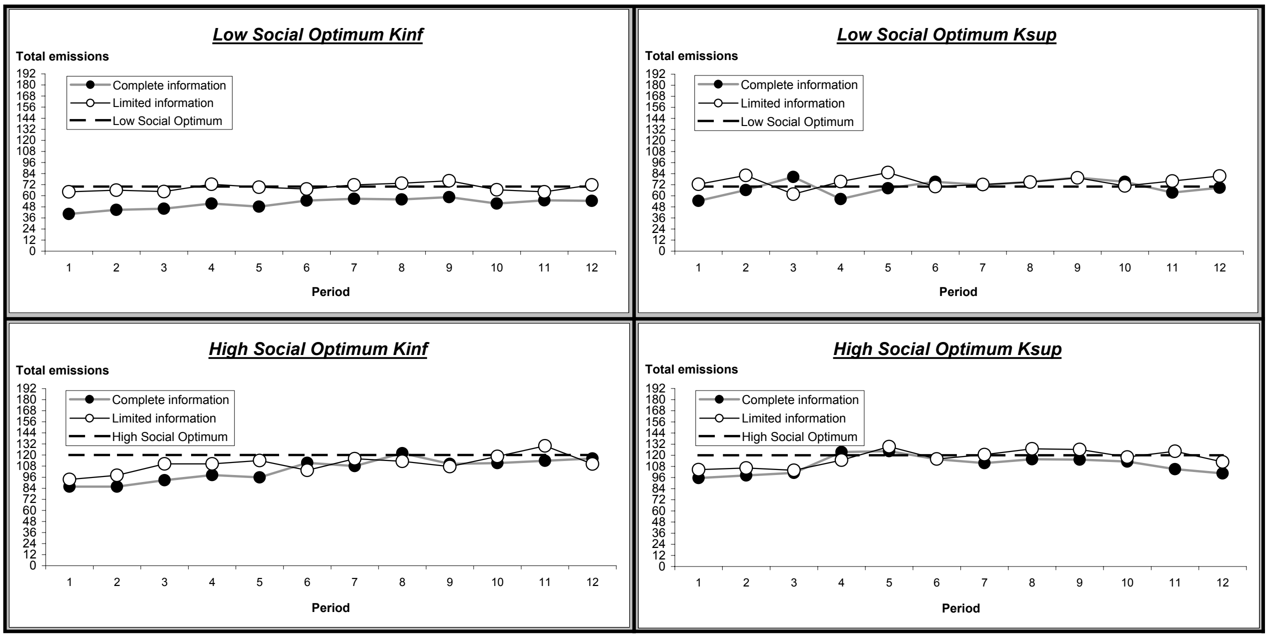

Figure 1: Mean group totals in each period.

We use an econometric analysis to evaluate the evolution of the difference between the group total pollution level and the socially optimal group total level, and to measure the impact of each treatment variable on this difference. We estimate a linear mixed effects model where the fixed effects are the treatment variables and the random effects are the groups. $Diff_{it}$ denotes the difference between group i's total observed emission level in period t and the socially optimal group total level, Com_i is a dummy variable which takes value 1 (respectively 0) if group i faces complete information (respectively limited information), $High_i$ is a dummy variable which takes value 1 (respectively 0) if group i interacts in the high (respectively low) social optimum condition, and $Ksup_i$ is a dummy variable which takes value 1 (respectively 0) when the lump-sum subsidy is over-evaluated (respectively under-evaluated). We denote by * the interaction effects between dummies. We first estimated the full model, i.e., the one including all possible interaction effects, and then sequentially dropped insignificant variables on the basis of likelihood ratio tests. The final estimated model is

$$Diff_{it} = \beta_0 + \beta_1 Com_i + \beta_2 High_i + \beta_3 Ksup_i + \beta_4 t + \beta_5 High_i * t + \beta_6 Ksup_i * t + u_i + \epsilon_{it},$$

where $i \in \{1, ..., 32\}$ since there are eight four-group treatments, $t \in \{1, ..., 12\}$ since we focus on the first 12 periods, u_i denotes the group random effect with variance σ_u^2, and ϵ_{it} is an i.i.d. residual error term with variance σ_e^2 (the hypotheses of autocorrelation and heteroscedasticity are rejected). The results of the regression analysis are displayed in table 5.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	-10.99	4.88	349	-2.25	0.0249
Com_i	-9.05	4.36	28	-2.08	0.0470
$High_i$	-12.28	5.04	28	-2.44	0.0215
$Ksup_i$	14.69	5.04	28	2.91	0.0070
t	1.12	0.34	349	3.31	0.0010
$High_i * t$	0.98	0.39	349	2.52	0.0123
$Ksup_i * t$	-0.85	0.39	349	-2.19	0.0294
Std. dev. of the random effects	$\hat{\sigma}_u = 11.61$				
Std. dev. of the residual term	$\hat{\sigma}_e = 13.09$				
Number of observations	384				

Table 5: Results of the estimation of the difference between the group total pollution level and the socially optimal group total level.

Before discussing the impact of the fixed effects, we would like to emphasize that approximately half of the total variation in the dependent variable is due to differences among groups (the estimated value of the intra-class correlation coefficient is 0.47). Groups are clearly heterogeneous and this pronounced heterogeneity puts the interpretation of the estimated fixed effects' coefficients into perspective.[24]

Except in treatment *LimLowKsup*, the estimated difference is negative in period 1, meaning that there is under-emission at the group level in the first period. The estimated differences in period 1 range from -27% of the socially optimal group total level in treatment *ComLowKinf* to 5% of the socially optimal group total level in treatment *LimLowKsup*. Moreover, there is a strong and significant positive time effect in all treatments except *ComLowKsup* and *LimLowKsup* where the time effect is still positive and significant but much weaker due to $\beta_6 < 0$. In the latter treatments, the estimated difference is rather negligible in all periods. The effect of time is stronger under the high than under the low social optimum condition as the coefficient of the interaction term $High_i * t$ is positive ($\beta_5 = 0.98$). All estimated differences in period 12 are smaller than 10% of the socially optimal group total level. To summarize, our econometric results provide clear support for result 1. □

Our second result validates most of our research hypotheses.

Result 2. The group total pollution level is further below the socially optimal group total level under complete than under limited information, in the high social optimum than in the low social optimum condition, and when the regulator under-evaluates the lump-sum subsidy than when he over-evaluates it.

[24] A closer look at the dynamics of the group total pollution levels shows that the intra-group variability is reduced over time in all treatments except *LimHighKinf*.

Support. According to table 5 on the preceding page, the difference between the group total pollution level and the socially optimal group total level is smaller (more negative) under complete information than under limited information. Since the estimated difference is negative in most periods and in most treatments, this implies that most of time the group total is further away from the socially optimal level under complete than under limited information. Similarly, the difference between the group total pollution level and the socially optimal group total level is more negative under the high position of the social optimum than under the low position of the social optimum. However, the difference in the high position condition gets closer to the one in the low position condition and both are almost identical in the last period. Finally, the group total is closer to the socially optimal level when the regulator over-evaluates the lump-sum subsidy than when he under-evaluates it even though this difference vanishes over time. Therefore, the weak version of our first research hypothesis, our second and third research hypothesis are all confirmed by our econometric results. □

Even though group totals are close to social targets, the ability of the damage based tax mechanism to induce socially optimal outcomes is not established yet. Indeed, the achieved efficiency of the instrument is strongly affected by the distribution of the emissions in the group. To precisely assess the performance of the instrument in the different experimental conditions, we rely on the efficiency rate which is the ratio of the difference between the actual efficiency level and the minimal efficiency level to the difference between the maximal efficiency level and the minimal one. The maximal efficiency level is obtained when each polluter emits at his socially optimal level. But depending on the position of the socially optimal level in the strategy space, the minimal efficiency level is either obtained if the polluters emit as much as possible (low position) or if they do not emit at all (high position). Recall that in all cases the *uncontrolled* efficiency level is achieved when all polluters emit as much as possible. This implies that the uncontrolled efficiency level is different in the low and the high social optimum conditions. In the former, it is equal to 0%, while in the latter, it is equal to 64.11%.[25]

Result 3. The efficiency of the damage tax based mechanism is higher under limited information than under complete information, and under low social optimum than under high social optimum, but under-evaluation or over-evaluation of the lump-sum subsidy is of no influence.

Support. Figure 2 on the next page shows the mean efficiency rates in each period for each treatment.[26] Clearly, mean efficiency rates are (almost) always higher under limited information than under complete information, under a low position than under a high position of the social optimum, and in the last six periods than in the first six ones. On the contrary, the level of the lump-sum subsidy has no clear impact on the efficiency rates.

[25] Alternatively one can define the efficiency rate as the ratio of the difference between the actual efficiency level and the efficiency level in the status quo state to the difference between the maximal efficiency level and the efficiency level in the status quo state. In the status quo state polluters emit at their maximal level. Our qualitative statements are not affected by the definition of the efficiency rate. Still, by relying on the alternative definition, the estimated performance of the damage based tax mechanism is largely reduced under the high position of the social optimum (it is of course unchanged under the low position).

[26] The efficiency levels should be interpreted with care. Because the regulator's objective function is rather flat around the socially optimal outcome, efficiency can be *high* though individual emissions are *not close* to the social optimal levels. Therefore, small differences between efficiency rates are economically important and, to fully appreciate the performance of the instrument, distributions of individual emissions have to be considered.

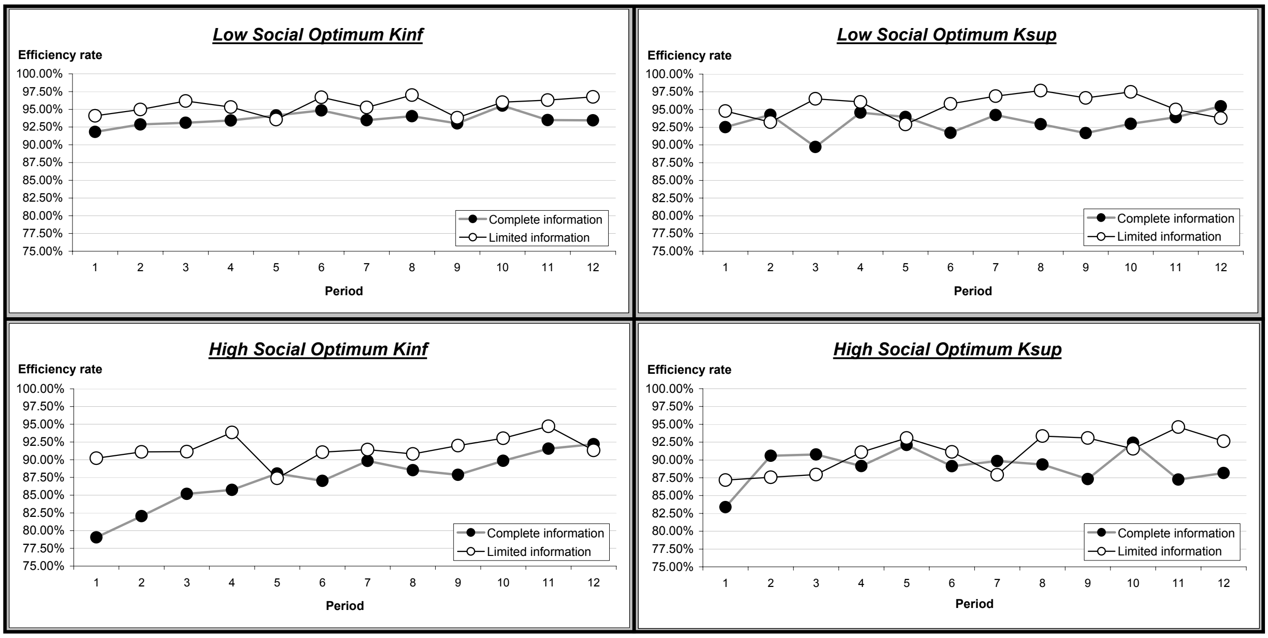

Figure 2: Mean efficiency rates in each period.

In order to capture the observed tendencies, we carry out an econometric analysis to evaluate the evolution of the efficiency rate and to measure the impact of each treatment variable. We estimate a linear mixed effects model where the treatment variables are the fixed effects and the random effects are the groups. The dependent variable is a logit transformation of the efficiency rate. If E_{it} denotes group i's efficiency rate in period t, our dependent variable is defined as $y_{it} = E_{it}/(1 - Eit)$. The final estimated model is

$$y_{it} = \beta_0 + \beta_1 Com_i + \beta_2 High_i + \beta_3 t + \beta_4 High_i * t + u_i + \epsilon_{it},$$

where $i \in \{1, ..., 32\}$, $t \in \{1, ..., 12\}$, u_i is a group random effect with variance σ_u^2, and ϵ_{it} is an error term. Assuming within-group first-order autoregressive form of the error term ($\epsilon_{it} = \phi\epsilon_{it-1} + v_{it}$, where v_{it} is an i.i.d. residual error term) provides substantially better fit of the data than the independent errors model, suggesting that within-group serial correlation is present in our data. After taking autocorrelation into account, we test the null hypothesis that the residual term v_{it} is distributed with constant variance and reject it. We correct this by considering a group-specific "constant plus power" variance function structure. The results of the regression are displayed in table 6 on the following page.

Efficiency is found to be significantly higher under limited than under complete information and significantly higher under the low social optimum level than under the high social optimum level. However, under the high social optimum condition, efficiency is found to be significantly increasing, thus the effect of the social optimum position diminishes with time, even though it remains quite large in period 12. No other significant change over time is observed. These additional econometric results support our first research hypothesis and indicate that the position of the social optimum in the strategy space has also an impact on the performance of the damage based tax mechanism. Situations in which polluters have to dramatically reduce their emissions in order to comply with the fiscal instrument might lead to higher efficiency levels than those where compliance implies less dramatic reductions. □

	Value	Std.Error	DF	t-value	p-value
(Intercept)	18.26	2.02	350	9.03	0.0000
Com_i	-3.87	1.69	29	-2.30	0.0292
$High_i$	-9.25	2.06	29	-4.49	0.0001
t	0.14	0.17	350	0.81	0.4185
$High_i * t$	0.38	0.19	350	1.97	0.0494
Std. dev. of the random effects	$\hat{\sigma}_u = 3.18$				
Std. dev. of the residual term	$\hat{\sigma}_e = 8.88e - 05$				
Number of observations	384				

Table 6: Results of the estimation of the efficiency rate.

Interestingly enough, the observation that the coefficient of the time trend is not significantly different from zero in table 6 suggests that, even though group totals systematically converge to the socially optimal group total level over time, convergence is not always guaranteed at the individual level. We further investigate the individual emissions in the next subsection.

4.2 Analyses at the individual level

Our previous analyses have shown that the damage based tax mechanism is able to induce polluters to reduce their emissions, and that, in almost all cases, groups of polluters choose the target outcome at the aggregate level in later periods of interaction. High efficiency rates are furthermore observed, in particular when the position of the social optimum is low in the strategy space and under limited information. In order to be considered as an effective solution to the nonpoint source pollution problem, the fiscal instrument should however insure compliance at the individual level.

Result 4. The damage based tax mechanism does not induce individuals to emit at the socially optimal level. The small and medium polluters' emissions increase over time to end up slightly above the social optimum, and are not significantly affected by any of the treatment variables. In contrast, the large polluters' emissions are below the social optimum, except under the low social optimum and the over-evaluated subsidy, where they are slightly higher than the social optimum.

Support. Figure 3 presents the distributions of individual emissions for each type of polluter in each treatment. In all treatments, a negligible percentage of the polluter's individual decisions, whatever their uncontrolled emission levels, coincide exactly with the socially optimal decision. By averaging over all treatments, slightly less than a quarter of the small polluter's individual decisions are within three decision numbers of the socially optimal decision (23%), slightly more than a quarter of the medium polluter's individual decisions are within three decision numbers of the socially optimal decision (26%), and 13.50% of the large polluter's individual decisions are within five decision numbers of the socially optimal decision.[27] It is worth mentioning that we do not observe an increase over time in compliance at the individual level in any of the treatments and for any of the polluter's type. Large polluters show

[27]To take into account the size of the strategy space we considered a wider interval for the large polluter than for the small and medium polluters. By considering the same interval for the medium polluter as for the large polluter we get that 33.50% of the medium polluter's individual decisions are within five decision numbers of the socially optimal decision.

a greater tendency to under-pollute than the other two types as their proportion of individual emissions averaged over all treatments which are below at least two decision numbers of the socially optimal decision is given by approximately 60% whereas the proportion of individual emissions averaged over all treatments which are below at least one decision number of the socially optimal decision is only about 40% for the other two types.

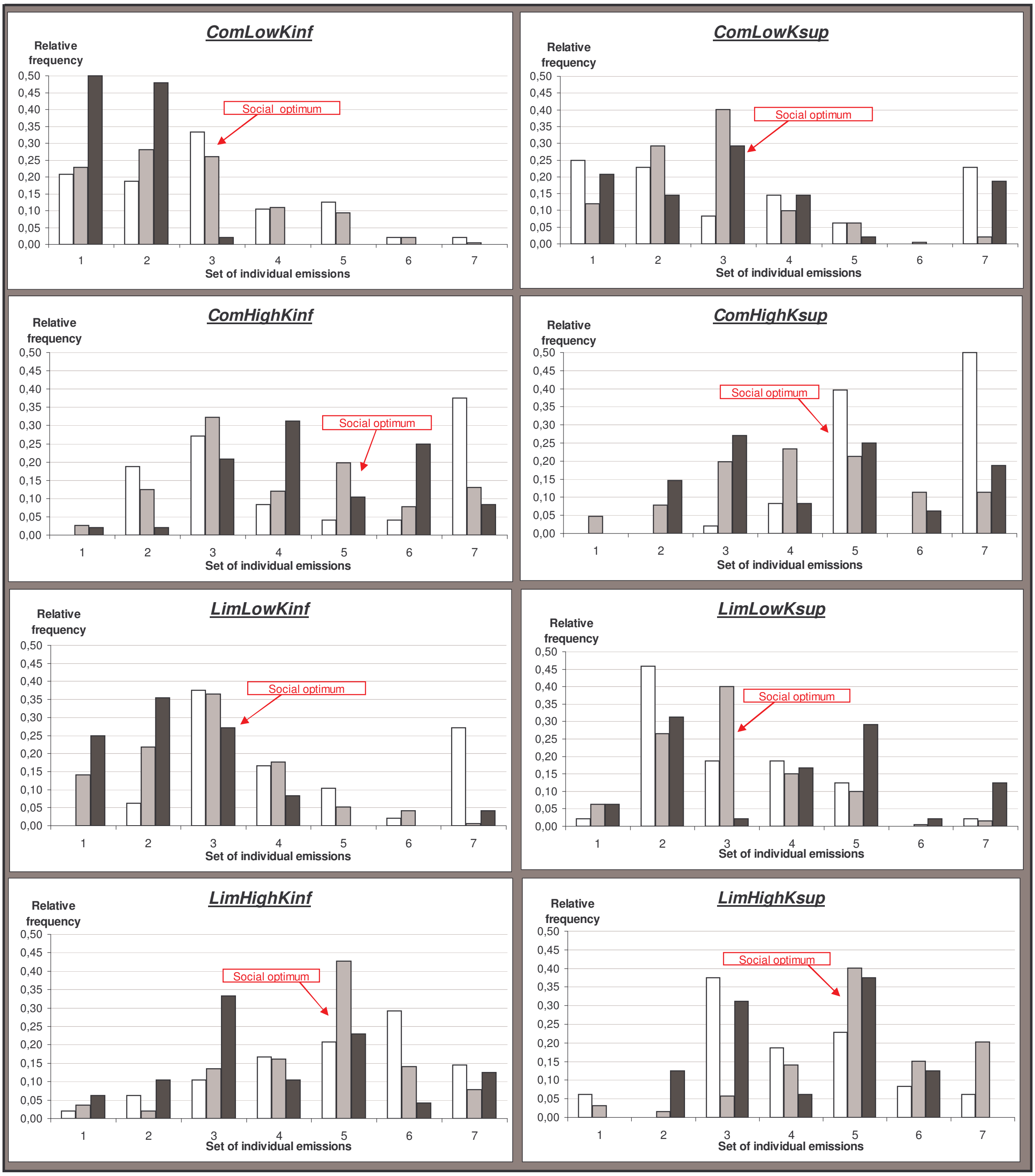

Figure 3: Distributions of individual emissions in each treatment.

Note: The blank, grey and black bars correspond respectively to the small, medium and large polluters. Individual emissions are grouped in seven sets of approximatively equal cardinality (between 9 and 17% of the total cardinality). Under the low social optimum condition, the socially optimal emission belongs to the third set; under the high social optimum condition, it belongs to the fifth set. The exact sets are the following, with a star indicating the low social optimum and a double star the high social optimum: For small polluters: {0,1,2,3}, {4,5,6,7}, {8,9*,10}, {11,12,13}, {14,15**,16}, {17,18,19}, {20,21,22,23}; For medium polluters: {0,1,2,3,4}, {5,6,7,8}, {9,10,11*,12,13}, {14,15,16}, {17,18,19**,20,21}, {22,23,24,25,26}, {27,28,29,30,31}; For large polluters: {0,1,2,3,4,5,6}, {7,8,9,10,11,12,13}, {14,15,16,17*,18,19,20}, {21,22,23,24,25}, {26,27,28,29**,30,31,32}, {33,34,35,36,37,38,39}, {40,41,42,43,44,45}.

We conduct an econometric analysis to identify the determinants of the difference between the individual pollution level and the socially optimal level. More precisely the dependent variable is the difference between subject i's individual observed emission level ($i \in \{1, ..., 192\}$ since there are eight four-group treatments with six persons per group) in period t ($t \in \{1, ..., 12\}$) and his socially optimal emission level. We resort to a linear mixed effects model, where the fixed effects are the treatment variables as in the previous econometrics analyses, along with the subjects' types dummies $Small_i$, $Medium_i$, and $Large_i$ which take value 1 if the subject is respectively of the small, medium or large type and 0 otherwise[28], and the random effects appear at two levels: effects for the groups and effects for participants within each group. We use the same iterative process as previously described to exclude the non-significant variables. However, this selection procedure relies now on a significance level of 1% for two reasons: i) in comparison with the two previous regressions, the number of observations has been multiplied by 6, and a factor of 3 levels (equivalent to two dummy variables) has been added, therefore we decided to be less conservative as the number of interaction effects has dramatically increased; ii) by relying on a significance level of 2.5% or 5% the selected model contains numerous independent variables and it is therefore difficult to interpret. We find a better fit of the data by assuming that the error term follows a within-subject serial correlation of order 1 (the estimated value of the autocorrelation parameter is 0.1150). In addition, after removing autocorrelation, the residual error term is found to be heteroscedastic, which we correct by considering type-specific constant variances. We do not display the equation of the model here because of the large number of variables. The results of the estimation are presented in table 7.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	-2.29	0.93	2111	-2.46	0.0138
$Small_i$	3.15	2.00	152	1.57	0.1174
$Large_i$	-5.61	2.13	152	-2.63	0.0094
$High_i$	-0.91	1.29	28	-0.71	0.4828
$Ksup_i$	0.55	1.29	28	0.43	0.6732
t	0.16	0.03	2111	5.53	0.0000
$Small_i * High_i$	-1.46	2.83	152	-0.52	0.6064
$Large_i * High_i$	4.02	3.02	152	1.33	0.1848
$Small_i * Ksup_i$	-1.77	2.83	152	-0.63	0.5326
$Large_i * Ksup_i$	10.65	3.02	152	3.53	0.0006
$High_i * Ksup_i$	1.03	1.82	28	0.57	0.5738
$Small_i * High_i * Ksup_i$	0.49	4.00	152	0.12	0.9028
$Large_i * High_i * Ksup_i$	-12.86	4.27	152	-3.01	0.0030
Std. dev. of the random effects	Group = 0.1883; Individual = 4.8978				
Std. dev. of the residual term	7.3984				
Std. dev. per type	Small = 0.4701; Medium = 0.6105; Large = 1.0000				
Number of observations	2304				

Table 7: Results of the estimation of the difference between the individual pollution level and the socially optimal pollution level.

We observe that the heterogeneity of the polluters within a group of polluters is much larger than the inter-group heterogeneity and that it accounts for about 40% of the total variation in the dependent variable. Moreover, the standard error for the large polluters is about twice of that for the other two

[28]Medium is the reference type as it contains most of the observations.

types. Again, this pronounced heterogeneity puts the interpretation of the estimated fixed effects' coefficients into perspective.

The amount of information available to the polluters does not influence their behavior at the individual level. This result seems to contradict results 2 and 3, which emphasized the significant influence of information on the group total and the efficiency level. However, results 2 and 3 focus on aggregate variables, and it is plausible that many insignificant individual effects give rise to significant aggregate effects.[29] According to the estimation results, no significant difference in behavior is observed between small and medium polluters. Both types under-pollute initially but the difference between the individual pollution level and the socially optimal level vanishes over time and is almost null in period 12. Neither the small polluter's difference nor the medium polluter's difference is significantly affected by the level of the lump-sum subsidy or the position of the social optimum. Except in treatments *LimLowKsup* and *ComLowKsup*, the large polluter's individual emissions are further below the social optimum than the other two types' individual emissions, and large polluters severely under-pollute even in period 12. When the social optimum is in a low position and the lump-sum subsidy is over-evaluated, large polluters slightly over-pollute. □

Even though game-theoretic reasoning is by and large capable of organizing our experimental data at the aggregate level, it cannot account for our findings at the individual level. Collusion is likely to emerge under complete information but not under limited information. Nevertheless, polluters' behavior is not affected by the amount of information available and under-pollution is observed in most cases. The most disturbing evidence for the theory is that large polluters' behavior is significantly different from small and medium polluters' behavior except when the social optimum is in a low position and the lump-sum subsidy is over-evaluated. It seems however possible to partly reconcile group behavior with individual behavior by assuming cognitive limitations on the part of polluters. Indeed, under the polluters' (wrong) belief that other polluters are of the same profit type, the one-shot emissions of the small and medium polluter are almost identical to the one-shot Nash equilibrium emissions but the one-shot emissions of the large polluter are lower.[30] Moreover, the group total pollution level is not very far from the socially optimal one whatever the position of the social optimum in the strategy space. This explanation is probably more appealing under limited information than under complete information. Still, there is by now a reasonable amount of experimental evidence pointing out subjects' tendency to impose their own reasoning on others instead of, as required by game theoretic reasoning, putting themselves in the shoes of others and think as they would.[31] Such a line of argumentation is however not fully satisfactory as Spraggon (2004) also observes that large polluters reduce their emissions by more than the optimal amount when the latter one is a dominant strategy.[32]

[29] Furthermore, we used 1% significance levels in the current analysis instead of 5% levels.

[30] Under the assumption that polluters entertain such wrong beliefs, equation (1) reduces to $\alpha_i e_i^{max}/(\alpha_i + n)$.

[31] For example, in Cournot market experiments, the Nash prediction fails to a much larger extent when firms have asymmetric costs than when firms are symmetric even though the industry cost structure is common knowledge (see, among others, Rassenti, Reynolds, Smith, and Szidarovszky, 2000). Of course, in a symmetric strategic environment, such cognitive limitations lead to similar outcomes as Nash reasoning.

[32] Our theoretical benchmarks were derived under the assumption of risk neutrality. One can show (formal details are available upon request) that risk averse polluters emit at a lower level than risk neutral polluters. We do not consider this explanation of the data as really appropriate for two reasons. First, subjects are dealing with low stakes in the laboratory which implies that the measured risk aversion should be small. Second, and more importantly, subjects interact repeatedly which should induce them to behave in a more risk neutral way.

5 Conclusion

This paper presents the results of an experiment intended to test the efficiency of an ambient tax/subsidy in a controlled environment which incorporates essential features of naturally occurring nonpoint pollution contexts. Since the damage function is strictly convex, the regulator cannot introduce a linear ambient tax if he is uninformed of polluters' types (profit functions). Instead, he can introduce a damage based mechanism, but this decentralizes the planning problem to polluters, as the social optimum is implemented as a Nash equilibrium. However, under real-world conditions, polluters are likely to have limited information on the other polluters' types. Thus, our first objective is to study the ability of the instrument to implement the social optimum both under limited and complete information regarding the polluters' types. Second, since the instrument is a fiscal scheme which is composed of a tax minus a lump-sum subsidy, we investigate the effect of varying the level of the latter. An "under-evaluated" ("over-evaluated") lump-sum subsidy leads the net tax payment to be positive (negative) at the social optimum. Third, we test the efficiency of the instrument both under a situation where the achievement of the social optimum requires a severe restriction of emissions with respect to the uncontrolled situation (the "low" social optimum position), and under a condition where the social optimum does not require very important restrictions of emissions (the "high" social optimum condition).

By establishing that the observed total pollution level matches the specified environmental target whatever the experimental condition (at least in the second half of the time horizon), our findings confirm the results of the previous experimental studies on the ambient tax/subsidy scheme. This is an important result for the literature of nonpoint source pollution control to the extent that our experimental setting captures several aspects of naturally occurring environments not taken into account previously in a single experiment. However, also in line with the early experimental evidence, we found that that the fiscal instrument does not insure compliance at the individual level indicating that only a second-best level of social welfare can be achieved.

Our experimental results further show that the efficiency performance of the ambient scheme is significantly higher when the social optimum requires larger emission restrictions, that it is always higher under limited information than under complete information, and that the level of the lump-sum subsidy has no clear impact on the efficiency rate. The latter observation is good news for the environmental regulator. Indeed, even if the regulator has limited information and cannot compute the socially optimal level of ambient pollution, he can resort to proxies to set lump-sum subsidies. The effect of the position of the social optimum in the strategy space is also of interest, since it identifies conditions that may have an impact on the efficiency of the instrument. Maybe more importantly, it reminds the experimenters that the experimental results should not be generalized before many sets of parameters have been tested since significantly different observations may be made.

The effect of information is perhaps the most striking result of this paper. Theorists have traditionally been uneasy concerning the behavioral relevance and hence the actual power of the policy instruments they suggested. The reason for this is that the suggested instruments crucially rely on Nash expectations on the part of the agents. Our experimental study shows that limited information does not decrease—and may actually increase—the efficiency of the instrument. This can be due to the fact that polluters have less incentive to play cooperatively under limited information than under complete information, which corroborates that less amount of information available to polluters about their strategic environment is beneficial from a social point of view. This observation, or at least the observation that the lack of information is not necessarily detrimental, has been already made in various experimental settings.[33] For example, Cason, Gangadharan, and Duke (2003) observe that less information is socially beneficial in their experimental test of an auction mechanism to address a nonpoint source pollution problem. In their design, each polluter submits the regulator an offer in which he commits to undertake some abating practices in exchange for some price. The regulator then ranks the price offers per unit of environmental benefit and selects the lowest cost group given the targeted ambient pollution level. The authors find that that the scheme is more efficient when polluters (sellers) are uninformed of the environmental benefits of their projects because it prevents them from strategically exploiting this information.

In order to increase social welfare beyond a second-best level, further experimental research is needed to find out the underlying determinants of individual behavior in nonpoint pollution problems.

References

Alpizar, F., T. Requate, and A. Schram (2004): "Collective versus Random Fining: An Experimental Study on Controlling Ambient Pollution," *Environmental and Resource Economics*, 29, 231–52.

Aumann, R., and A. Brandenburger (1995): "Epistemic Conditions for Nash Equilibrium," *Econometrica*, 63, 1161–1180.

Bernheim, D. (1984): "Rationalizable Strategic Behavior," *Econometrica*, 52, 1007–1028.

Brown Kruse, J., S. Rassenti, S. Reynolds, and V. Smith (1994): "Bertrand-Edgeworth Competition in Experimental Markets," *Econometrica*, 62, 343–371.

Camacho, E., and T. Requate (2004): "Collective and Random Fining versus Tax/Subsidy Schemes to Regulate Non-Point Pollution: An Experimental Study," Working Paper No 2004-10, Christian-Albrechts-University of Kiel.

Cason, T. N., and L. Gangadharan (2004): "Auction Design for Voluntary Conservation Programs," *American Journal of Agricultural Economics*, 86, 1211–17.

——— (2005): "A Laboratory Comparison of Uniform and Discriminative Price Auctions for Reducing Non-point Source Pollution," *Land Economics*, 81, 51–70.

Cason, T. N., L. Gangadharan, and C. Duke (2003): "A Laboratory Study of Auctions for Reducing Non-point Source Pollution," *Journal of Environmental Economics and Management*, 46, 446–71.

Cochard, F., M. Willinger, and A. Xepapadeas (2005): "Efficiency of Nonpoint Source Pollution Instruments: An Experimental Study," *Environmental and Resource Economics*, 30, 393–422.

Fouraker, L., and S. Siegel (1963): *Bargaining Behavior*. New York: McGraw Hill.

Fudenberg, D., D. Levine, and E. Maskin (1994): "The Folk Theorem with Imperfect Public Information," *Econometrica*, 62, 997–1039.

[33] See footnote 5.

Green, E. J., and R. H. Porter (1984): "Noncooperative Collusion under Imperfect Price Information," *Econometrica*, 52, 87–100.

Hansen, L. G. (1998): "A Damage Based Tax Mechanism for Regulation of Non-Point Emissions," *Environmental and Resource Economics*, 12, 99–112.

Horan, R. D., J. S. Shortle, and D. G. Abler (1998): "Ambient Taxes when Polluters have Multiple Choices," *Journal of Environmental Economics and Management*, 36, 186–99.

Isaac, R. M., and J. M. Walker (1998): "Nash as an Organizing Principle in the Voluntary Provision of Public Goods: Experimental Evidence," *Experimental Economics*, 1, 191–206.

Marks, M. B., and R. T. Croson (1999): "The Effect of Incomplete Information in a Threshold Public Good Experiment," *Public Choice*, 99, 103–18.

Mason, C. F., and O. R. Phillips (1997): "Information and Cost Asymmetry in Experimental Duopoly Markets," *The Review of Economics and Statistics*, 79, 290–99.

Neyman, A. (1999): "Cooperation in Repeated Games When the Number of Stages is not Commonly Known," *Econometrica*, 67, 45–64.

Poe, G. L., W. D. Schulze, K. Segerson, J. F. Suter, and C. A. Vossler (2004): "Exploring the Performance of Ambient-Based Policy Instrument When Non-Point Source Polluter Can Cooperate," *American Journal of Agricultural Economics*, 86, 1203–10.

Rassenti, S., S. Reynolds, V. Smith, and F. Szidarovszky (2000): "Adaptation and convergence of behavior in repeated experimental Cournot games," *Journal of Economic Behavior and Organization*, 41, 117–146.

Ribaudo, M. O., R. D. Horan, and M. E. Smith (1999): *Economics of Water Quality Protection from Nonpoint Sources: Theory and Practice*. Agricultural Economic Report No. (AER782).

Segerson, K. (1988): "Uncertainty and Incentives for Non-Point Source Pollution," *Journal of Environmental Economics and Management*, 15, 87–98.

Shortle, J. S., and R. D. Horan (2001): "The Economics of Nonpoint Pollution Control," *Journal of Economic Surveys*, 15, 255–89.

Spraggon, J. (2002a): "Exogenous Targeting Instruments as a Solution to Group Moral Hazards," *Journal of Public Economics*, 84, 427–56.

——— (2002b): "Exogenous Targeting Instruments under Differing Information Conditions," Lakehead University, Department of Economics, manuscript.

——— (2004): "Testing Ambient Pollution Instruments with Heterogeneous Agents," *Journal of Environmental Economics and Management*, 48, 837–56.

Taylor, M. A., B. Sohngen, A. Randall, and H. Pushkarskaya (2004): "Group Contracts for Voluntary Non-Point Source Pollution Reductions: Evidence from Experimental Auctions," *American Journal of Agricultural Economics*, 86, 1196–1202.

Tomasi, T., K. Segerson, and J. B. Braden (1994): “Issues in the Design of Incentive Schemes for Nonpoint Source Pollution Control,” in *Nonpoint Source Pollution Regulation: Issues and Analysis*, ed. by C. Dosi, and T. Tomasi, pp. 1–37. Dordrecht: Kluwer Academic Publishers.

Vossler, C. A., G. L. Poe, W. D. Schulze, and K. Segerson (2004): “Cheap Talk and Ambient-Based Nonpoint Pollution Control Mechanisms,” Working paper, Department of Economics, The University of Tennessee, Knoxville, Tennessee.

Willinger, M., and A. Ziegelmeyer (2001): “Strength of the Social Dilemma in a Public Goods Experiment: An Exploration of the Error Hypothesis,” *Experimental Economics*, 4, 131–44.

Appendix

In this appendix, we emphasize the technical computation problem which is due to the fact that the ambient pollution level $\sum_{i\in N} e_i + \epsilon$ cannot be negative. Thus the exact expression of the ambient pollution level a is:

$$a = \begin{cases} \sum_{i\in N} e_i + \epsilon & \text{if} \quad \sum_{i\in N} e_i + \epsilon \geq 0 \\ 0 & \text{if} \quad \sum_{i\in N} e_i + \epsilon < 0 \end{cases},$$

which implies that polluter i's profit function should actually be written as:

$$\pi_i(e_i) = \gamma_i - \alpha_i(e_i - e_i^{max})^2 + K - \begin{cases} \left(\sum_{i\in N} e_i + \epsilon\right)^2 + K & \text{if} \quad \sum_{i\in N} e_i + \epsilon \geq 0 \\ 0 & \text{if} \quad \sum_{i\in N} e_i + \epsilon < 0 \end{cases},$$

thus polluter i's expected profit function is:

$$E\pi_i(e_i) = \gamma_i - \alpha_i(e_i - e_i^{max})^2 + K - p(\sum_{i\in N} e_i + \epsilon \geq 0)E\left[\left(\sum_{i\in N} e_i + \epsilon\right)^2 /_{\sum_{i\in N} e_i + \epsilon \geq 0}\right],$$

where $p(\omega)$ denotes the probability of event ω, and $E[X/_{\omega}]$ denotes the expected value of the random variable X given the event ω.

If the support of ϵ is $[-v, v]$ and $v < \sum_{i\in N} e_i^{max}$ as is the case in our experimental settings, then one should consider two cases when studying this function: (i) $\sum_{i\in N} e_i \geq v$, and (ii) $\sum_{i\in N} e_i < v$. In case (i) the expected profit function simplifies to $E\pi_i(e_i) = \gamma_i - \alpha_i(e_i - e_i^{max})^2 + K - E\left[\left(\sum_{i\in N} e_i + \epsilon\right)^2\right]$, as we assume in the main text. Then $E\pi_i(e_i) = \gamma_i - \alpha_i(e_i - e_i^{max})^2 + K - \left(\sum_{i\in N} e_i\right)^2 - Var(\epsilon)$, so that this expression only depends on the variance of ϵ and not on its distribution function. But in case (ii) that simplification does not apply, and the expected profit function depends on the distribution function of ϵ. Therefore a specific analysis of the function is required in case (ii) to find the social optimum and the collusive outcome. This analysis has to be numerical since ϵ is a discrete variable (the derivative of the distribution function of ϵ cannot be computed). However, we verified that with the particular parameters used in our experiment, that the social optimum and the collusive outcome are not such that $\sum_{i\in N} e_i < v$.