

Efficiency of Nonpoint Source Pollution Instruments with Externality Among Polluters: An Experimental Study

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Abstract: In nonpoint source pollution problems, the regulator does not observe each polluter's individual emission, which prevents him from using the conventional policy instruments. Therefore new instruments have been designed to regulate this type of pollution. In an experiment, we compare the efficiency of some of these instruments: an input based tax, an ambient tax, and a group fine. We assume that the polluters themselves are affected by environmental damages. A control session without any regulation is also carried out in order to study the "status quo" situation. Our experimental data show that the input tax is almost perfectly efficient and very reliable, and the group fine is fairly efficient and reliable. Both instruments improve welfare with respect to the status quo. On the contrary, the ambient tax decreases social welfare with respect to the status quo, and its effect is very unreliable.

Résumé : En situation de pollution diffuse, le régulateur n'observe pas les émissions individuelles de chacun des pollueurs, et ne peut donc pas recourir aux instruments de régulation traditionnels. De nouveaux instruments ont alors été proposés pour traiter ce type de pollution. Nous comparons expérimentalement l'efficacité de quelques-uns d'entre eux : une taxe sur les intrants, une taxe ambiante et une amende collective. Les pollueurs sont supposés être eux-mêmes affectés par la pollution ambiante. Un traitement témoin étudie aussi le comportement des pollueurs en l'absence de régulation (le « statu quo »). La taxe sur les intrants s'avère la plus efficace et la plus fiable. L'amende collective obtient des résultats passables sur ces deux critères. Ces deux instruments augmentent le bien-être social par rapport au statu quo. A l'inverse, la taxe ambiante diminue le bien-être social et apparaît très peu fiable.

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1. Introduction

Successful regulation of nonpoint source (NPS) pollution has to satisfactorily address the associated informational problems which are mainly related to monitoring and measurement as well as natural variability.¹ In NPS pollution regulation informational asymmetries between the regulator and individual dischargers take the form of moral hazard with hidden actions, stemming from the inability of the regulator to observe individual emissions. Instead, the regulator observes the ambient concentration of the pollutant but this observation is not sufficient to allow the regulator to infer individual emissions. This type of informational asymmetries can also be observed in more general environmental and resource management problems not necessarily strictly related to pollution.

In standard NPS pollution problems the environmental externality does not affect the polluters themselves but some third party, for example consumers suffering from the environmental degradation due to ambient pollution. It is however possible to have ambient pollution affecting the polluters themselves, when the actions of each polluter contributes to ambient pollution, and the ambient pollution affects the objective function of each polluter. This endogenization of the externality which introduces strategic interaction among polluters can be found, for example, in certain situations related to irrigated agriculture.

Consider the case of farmers pumping irrigation water from an aquifer which is in close proximity to the sea. Excess pumping causes sea water intrusion and increases the salinity of the aquifer. Increased salinity has a negative impact of agricultural production. This situation can be regarded as a nonpoint source pollution problem, since typically there is no observability of individual pumping, either because farmers engage in drillings without licence, or because they violate their licences by drilling deeper than the depth that their licence prescribes, or pumping more water than their licence allows. Since in this situation there is a large number of disperse drillings, monitoring of individual pumping is very difficult. On the other hand the level of salinity in the aquifer, which corresponds to the ambient pollution level, can be measured.

Another similar problem arises if we consider again individual farmers pumping irrigation water from an aquifer with the same monitoring problem discussed above. In this case excess pumping reduces the stock of water and increases, through the stock effects, unit pumping costs. In a different set up, urban transportation contributes to the ambient

¹ See for example Braden and Segerson (1993), Xepapadeas (1999), Shortle and Horan (2001).

accumulation of pollutants, like lead, CO, CO₂, which adversely affect the drivers' welfare, while individual emissions are very difficult to monitor.

In all these problems, agents' actions contribute to the deterioration of the ambient environment, and have a negative feedback on each agent's utility. Although the "inter-polluter externality" hypothesis, as presented above, is not the typical NPS pollution situation, the moral hazard with hidden actions characteristics of all the examples given above is sufficient to establish the NPS nature of the problems. It is a NPS problem with such an inter-polluter externality that we study in this paper.

As is well known, conventional policy instruments applied to point source pollution problems cannot satisfactorily address NPS pollution problems. Hence, direct and indirect approaches have been developed to determine instruments for NPS pollution. These instruments include input-based schemes where a tax is imposed on the use of observable polluting inputs (see for example Griffin and Bromley, 1982, Shortle and Dunn, 1986, Shortle and Abler, 1994), and ambient based instruments associated with deviations between the observed ambient level of pollutant, or the value of a state variable, such as water reserve, and the desired or cut-off level of the same variable (see for example Segerson, 1988, Xepapadeas, 1991, 1992, 1995, Cabe and Herriges, 1992, Hansen, 1998, Horan, Shortle and Abler, 1998).

Since ambient pollution depends on the emissions of all polluters, ambient instruments make the polluters' payoffs interdependent. Therefore in the inter-polluter externality problem we analyse in this paper, the introduction of ambient based schemes imposes a second layer of strategic interactions, since agents' payoffs are already interrelated through the inter-polluter externality. Since ambient based instruments generate negative externality, maximizing the sum of individual payoffs would not necessarily result in the same outcome as maximizing each individual payoff individually, even if the inter-polluter externality was absent. Thus if polluters could cooperate in order to maximize group payoff, they would improve their individual payoffs with respect to the non-cooperative outcome, exactly as in a Prisoner's Dilemma. For that reason, ambient instruments may generate a social dilemma between polluters.² This is very important from an empirical point of view, since a number of experimental studies with such a social dilemma show that subjects often try to cooperate instead of following the standard non-cooperative strategy (see for example Ledyard, 1995). As ambient based instruments are designed to achieve the social optimum within a population

of polluters who behave non-cooperatively, this might significantly decrease their efficiency (see Millock and Salanié, 1997).

On the other hand, input-based instruments depend only on individual decisions and they do not imply strategic interactions like the ambient-based schemes. Whether polluters cooperate or not does not affect the efficiency of these instruments. Thus the efficiency of input based instruments should not be affected by cooperation, as opposed to ambient based instruments. In our inter-polluter externality framework this conclusion might not be true. Indeed there is a negative externality in the payoff functions, even when an input based instrument is applied. The only difference with ambient based instruments is that there is only one layer of negative externality in payoff functions, but this might be sufficient to deteriorate the efficiency of the instrument.

The purpose of this paper is to use a NPS problem with an inter-polluter externality, in order to compare in the laboratory the efficiency of different NPS pollution instruments: an input based instrument, and two ambient pollution based ones. The first ambient pollution based instrument we study is the “standard” ambient tax, which is proportional to the difference between actual ambient pollution and the socially optimal level of ambient pollution (Segerson, 1988, Xepapadeas, 1991). It can be a tax or a subsidy depending on the sign of the difference.³ We simply call this instrument “ambient tax”. The second ambient pollution based scheme, which we call “group fine”, is a lump-sum penalty which is applied if actual ambient pollution is larger than the social target. Contrary to the standard ambient tax, it can be designed so that the group optimum *is* a Nash equilibrium, so there is no social dilemma. However, as opposed to the ambient tax, it gives rise to a multiplicity of Nash equilibria, thus its efficiency may not be very high. A treatment without any regulation instrument was also carried out in order to study subjects’ behavior at the “status quo”.

The experimental data allow us to study the efficiency of each instrument, that is, the level of social welfare which is achieved when it is applied in a group of polluters. In addition, we interpret the variance of efficiency between groups of polluters and between periods within groups of polluters as “reliability” measures of instruments. Notice that given those definitions, it is also possible to evaluate the “efficiency” and “reliability” of the status quo situation. Using these two criteria, the three instruments are ranked and compared to the

² It is not always true: for example, the group fine (hereafter treatment F) we define below is without any social dilemma.

³ Hence, if actual ambient pollution is larger than the social target, then each polluter has to pay a tax; if actual ambient pollution is smaller than the social target, then each polluter receives a subsidy.

status quo.

Experimental data can be very useful for studying NPS source pollution instruments. Indeed ambient pollution based instruments have apparently never been implemented in the field. Such collective mechanisms may be rejected by the polluters and thus raise serious political problems.⁴ Experimentation provides therefore a means to test the instruments at no political cost. Of course experimentation cannot replicate the real world conditions, but some of the most significant features of reality still exist in the laboratory, such as agents' behavior and the structure of the instruments. Experimentation has another advantage compared to case studies: it allows control of most of the parameters (number of subjects, payoff functions, available information, number of periods, etc.). Finally experimentation allows us to define and assess efficiency indicators very precisely. In the real world, such measures are far more doubtful.

Our work relates to Spraggon (2002), who compares four NPS source pollution instruments in the laboratory, including an ambient tax and a group fine. However Spraggon did not consider the input tax nor the "status quo" treatment, and his analysis covered a NPS problem with *no* inter-polluter externality.⁵ So the present paper contributes to the environmental economics literature by exploring the efficiency of NPS pollution instruments when agents already interact strategically before the application of any policy instruments, while on the other hand it contributes to the experimental economics literature by providing more data on the behavior of subjects in games with negative externalities, such as oligopoly experiments, common pool resource experiments, and public good experiments in "negative framing".⁶ Our group fine treatment can also be regarded as a "negative framing" extension of Cadsby and Maynes (1999) threshold public good experiment. Finally, it should be noted that ambient pollution based instruments are group moral hazard incentive mechanisms as introduced by Holmstrom (1982). In a different setting, such group incentive schemes and others have already been experimented by Nalbantian and Schotter (1997).

Our results show that while the input tax performs very well on the efficiency and reliability criteria, and the group fine does also relatively well, the ambient tax performs

⁴ Xepapadeas (1995) develops a scheme that relies both on ambient pollution and on revealed individual emissions. That type of mixed scheme could solve the political problems raised by the ambient pollution based instruments (see also Millock, Sunding and Zilberman (in press) for a policy with endogenous monitoring).

⁵ Furthermore, the group fine we introduce is "comparatively" higher than Spraggon's. Following Cadsby and Maynes (1999), we conjectured that increasing the level of the fine would improve the instrument's efficiency.

⁶ See Ledyard (1995) for a survey on public goods experiments; concerning negative externality experiments, see Ostrom, Gardner and Walker (1994) for common pool resource experiments, Holt's survey (1995) for

poorly with respect to both criteria. We rank the instruments and the status quo situation according to efficiency and reliability. The input tax strictly dominates all other instruments and the status quo, the group fine strictly dominates the ambient tax but not the status quo, and the ambient tax is strictly dominated by all instruments and even by the status quo. This contrasts sharply with Spraggon (2002), who found in particular that the ambient tax was almost perfectly efficient.⁷ In his experiment, ambient pollution was reduced approximately to its socially optimal level, even though individual compliance was not always satisfied. While our experiment does not allow to conclude that the input tax is always the best instrument, it suggests that the effects of an ambient tax are very sensitive to the structure of the experimental environment.

Section 2 exposes the underlying theoretical model and its predictions. The experimental procedures are summarized in section 3. Section 4 presents the efficiency and reliability indicators used to assess the instruments. Section 5 is devoted to the results. Section 6 provides a discussion and section 7 concludes.

2. Theoretical predictions

2.1. The model

We present a simplified version of a more general model,⁸ which clarifies the exposition while preserving the intuitive results. One of our simplifying assumptions is to consider a perfectly symmetric situation.

Consider n firms who produce a unique good from a unique input. Let x_i be firm i 's use of input ($i \in \{1, \dots, n\}$). f is a strictly concave profit function. Firms are price takers.

Each firm emits an individual externality e_i which is a function of its input use: $e_i = e(x_i) = sx_i$, with $s > 0$. Individual externalities give rise to a global externality $a = \sum_i e(x_i)$ which corresponds to ambient pollution. Ambient pollution imposes an externality cost δa on each firm, with $\delta > 0$. Thus firm i 's net profit (hereafter "payoff") is $\pi(x_i, a) = f(x_i) - \delta a$. In

oligopoly experiments, Andreoni (1995), Willinger and Zieglmeyer (1999), Park (2000), for comparisons between positive and negative externality frameworks – the "framing effect").

⁷ This is especially true in Spraggon's deterministic treatments with inexperienced subjects. However, the results are robust in stochastic and experienced frameworks. Spraggon did not study the input tax.

general, nonpoint pollution models also assume that a affects negatively consumers' welfare. Here, we assume that there is no damage on consumers but only on firms (this is the so-called inter-polluter externality). We also assume that all functions are deterministic. An alternative and more realistic assumption would state that emission functions are stochastic.⁹

2.1.1. Non-cooperative predictions

In this subsection we consider non-cooperative predictions derived from the nonpoint source model. As our goal is to assess and compare the efficiency of nonpoint source instruments, we study four situations. The "No regulation" one (hereafter treatment N), which we shall take as a benchmark, involves n firms interacting when no instrument is implemented. Three specific instruments are implemented in three independent treatments: we shall refer to them respectively as treatment I (Input tax), treatment A (Ambient tax) and treatment F (group Fine). In the following, we show that each of those instruments achieves the first-best level of social welfare at a Nash equilibrium.

Let us first define social welfare. Let $\mathbf{x} = (x_1, \dots, x_n)$ be the vector of input decisions of all firms, and $\mathbf{x}_{-i} = (x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$ the vector of input decisions of all firms except firm i . Since we assume that there is no damage on consumers, social welfare $W(\mathbf{x})$ will be defined as the sum of the firms' payoffs (if there are taxes, they are assumed to be redistributed, and thus cancel out at the social level).¹⁰ Therefore it is a function of input use and ambient pollution:

$$W(\mathbf{x}) = \sum_i \pi(x_i, a) = \sum_i f(x_i) - n\delta s \sum_i x_i. \quad (1)$$

The regulator is assumed to determine each firm's input use x^* so as to maximize social welfare.¹¹ The first-order condition (FOC) is:

⁸ See for example Shortle and Horan (2001).

⁹ We chose to study first a situation in which there is only "strategic uncertainty" in the sense that each subject's payoff function depends on ambient pollution, which is itself dependent on the other subjects' decisions. While the introduction of exogenous uncertainty is more realistic, it considerably complicates the subjects' behavior in the experiment. Furthermore, introducing random variables in the experiment makes comparisons of different treatments difficult: outcomes of random variables may be different from one treatment to another, which either renders efficiency comparisons between instruments difficult, or requires large data sets to conclude safely. Finally, introducing random variables might have decreased the subjects' understanding of the games, and thus given rise to more errors. For all those reasons we judged more appropriate to start with a deterministic experiment.

¹⁰ If taxes are applied, they are not taken into account in the social welfare function, since it is assumed that they are redistributed to other agents than polluters. In other words, in equation (1), the payoff function π does not include taxes. This is a usual assumption in the NPSP literature.

¹¹ In this symmetric model, we have of course for all i , $x_i^* = x^*$.

$$f'(x^*) = sn\delta. \quad (2)$$

The social optimum requires that each firm equalizes its marginal profit to the marginal *social* damage.

In treatment N, the regulator does not intervene. Each firm determines x^0 so as to maximize its payoff $\pi(x_i, a)$, assuming that the other polluters' decisions x_j ($j \neq i$) are fixed. With our assumptions, the vector $\mathbf{x}^0 = (x^0, \dots, x^0)$ is the unique Nash equilibrium. Furthermore, x^0 is a dominant strategy for each firm. The FOC is:

$$f'(x^0) = s\delta. \quad (3)$$

At the Nash equilibrium, each firm chooses its input level to equalize marginal profit to the marginal *private* damage. Since f is concave, $x^* < x^0$. Hence, in the absence of regulation firms use too much input with respect to the social optimum, which advocates for regulatory intervention.

In the following, we describe each of the instruments. More details are provided in appendix 1. Since in this paper our goal is to compare first-best instruments, we assume the regulator has all the information he needs for implementing each of the three instruments.

Treatment I introduces a linear input-based tax (Griffin and Bromley, 1982, Shortle and Dunn, 1986, Shortle and Abler, 1994). The socially optimal input tax rate t^I is:

$$t^I = s(n-1)\delta. \quad (4)$$

Since the tax rate t^I is the same for all polluters, the regulator does not have to observe each polluter's input use x_i to implement this input tax. Indeed the tax can be simply included into the input price.¹²

Assuming that the input tax rate cannot be included into the input price, and that input use is unobservable, ambient-based instruments may be implemented instead of input-based instruments. Treatment A applies an ambient-based instrument. Such instruments are either continuous in a , or not. Let $T^A(a)$ be a continuous ambient-based fiscal scheme. Segerson (1988) first proposed a tax proportional to the difference between the actual level of ambient pollution a and the socially optimal level of ambient pollution $a^* = snx^*$. In our model we have:

$$T^A(a) = (n-1)\delta(a - a^*). \quad (5)$$

¹² If the model was asymmetric, each polluter i would have a specific tax rate t_i^I , and thus the regulator would have to observe input use. This is also true in the symmetric case if the input is not bought on a market but self-produced by the polluter.

As the input tax rate, the ambient tax rate is the same for all polluters in this symmetric framework. An interesting property of that scheme is that whenever polluters choose the socially optimal level of inputs, no tax is collected on them. The instrument provides therefore a perfect incentive at zero cost.¹³

Treatment F implements a group Fine under the assumption that ambient pollution is observable. It is a discontinuous ambient-based instrument: a lump-sum fine is applied on each polluter whenever ambient pollution exceeds the socially optimal level:

$$\begin{aligned}\pi^F(x_i, a) &= f(x_i) - \delta a && \text{if } a \leq a^*, \\ \pi^F(x_i, a) &= f(x_i) - \delta a - F && \text{if } a > a^*.\end{aligned}\quad (6)$$

F can be chosen so that if all firms choose the socially optimal level of inputs, no individual deviation becomes profitable. This requires the following level for the group fine:

$$i, \quad x_i, F > f(x_i) - \delta(e(x_i) + (n-1)e(x^*)) - \pi(x^*, a^*).\quad (7)$$

Under the group fine, the social optimum is a Nash equilibrium for the game. But there can be many other Nash equilibria. All vector of input choices \mathbf{x} such that $\sum_i e(x_i) = a^*$ may be an equilibrium. Since the game is symmetric, the social optimum is the only one of these equilibria which is symmetric. Furthermore, the no regulation symmetric Nash equilibrium \mathbf{x}^0 is also a Nash equilibrium here. Appendix 1 provides the proofs. In contrast, when there is no regulation (treatment N), or when there is an input tax (treatment I) or an ambient tax (treatment A), the Nash equilibrium is unique and in dominant strategies.¹⁴

2.1.2. “Cooperative” or “group optimal” outcome

The experimental literature on public goods, which deals with positive externalities, showed that standard (non-cooperative) game theoretical solution concepts often fail to predict actual behavior. Subjects frequently over-contribute to the public good, thereby increasing their payoffs compared to the Nash equilibrium payoff. In our experimental setting, the same outcome is possible. Indeed, firms can significantly increase their earnings if they tacitly coordinate in order to maximize the sum of their payoffs (group payoff). Thus in each treatment we also consider this “cooperative” solution, defined as the input choices that

¹³ The exact knowledge of a^* , which requires the knowledge of the marginal emission s , the profit function f , the marginal damage δ , and the number of firms n , is not necessary for the instrument to be efficient. Thus in general the ambient tax is less information-demanding than the input tax.

¹⁴ Expression (7) shows that the regulator has to know the marginal emission s , the profit function f , the marginal damage δ , and the number of firms n . In practice, this instrument does not necessarily require exact knowledge of all those functions. Indeed it is possible to set F sufficiently high so that condition (7) be satisfied.

maximize group payoff. Let Π be group payoff : $\Pi(\mathbf{x}) = \sum_i \pi(x_i, a)$. Π varies across treatments. Let x^{GN} be the Group payoff maximizing input choice in the No regulation case, x^{GI} in the Input tax case, x^{GA} in the Ambient tax case, and x^{GF} in the group Fine case. Appendix 1 (part B) shows that: $x^{GA} < x^{GI} < x^* = x^{GN} = x^{GF} < x^0$. One should notice that group payoff Π and social welfare W are identical in the no regulation treatment, but not in the other treatments because of taxes. Indeed taxes decrease each polluter's payoff, and thus group payoff, while they cancel out in the social welfare function (see again note ¹⁰).

2.1.3. Theoretical predictions of the repeated games

In the experiment, each of the four previous constituent games (no regulation, input tax, ambient tax, group fine) is repeated 20 times, and all subjects know it from the beginning. In treatment N, I and A, the constituent game has a unique Nash equilibrium, thus the finitely repeated game has a unique sub-game perfect equilibrium. In the constituent game corresponding to treatment F, there are already several Nash equilibria, so we do not proceed further in the analysis: those equilibria will serve as benchmarks for the repeated game analysis. Indeed, our primary goal is not to understand and formalize the subjects' behavior, but to assess the instruments' efficiency. Thus knowledge of the social optimum is more crucial than knowledge of the repeated-game Nash equilibria. Finally, the social optimum and the cooperative outcomes are not affected by the repetition of the constituent games.

2.2. Model calibration

In the experiment, subjects played the role of firms and the quantity of input use was represented by the amount of invested tokens. To make the instructions of the experiment simpler, we made the following simplifying assumptions: for the individual emission function, $s = 1$, thus $e(x_i) = x_i$, for the payoff function:

$$\pi(x_i, a) = f(x_i) - \delta \sum_i x_i = -\alpha x_i^2 + \beta x_i - \delta X_i \quad (8)$$

where $X_i = \sum_j x_j$.¹⁵ Table 1 summarizes the parameters values.¹⁶

¹⁵ Notice that $f(x_i) = -\alpha x_i^2 + (\beta + \delta)x_i$.

¹⁶ Several constraints were taken into account for the choice of the parameters: equilibria and social optimum strategies were to be integers, far from the "focal points", etc.

Table 1: Parameters values

Parameters		Values
Number of firms	n	4
Profit functions	α	3
	β	108
Marginal emission	s	1
Marginal damage parameter	δ	10
Group fine ¹⁷	F	600

Table 2 indicates each subject's payoff function in each treatment. In each period, payoffs may become negative. To prevent that subjects end the game with a negative cumulated payoff, they were given an initial endowment of 66 French Francs (10 Euros).¹⁸

Table 2: Payoff functions¹⁹

Treatment	Subject i 's payoff at period t
N	$\pi_{it} = -3x_{it}^2 + 108x_{it} - 10X_{it}$
I	$\pi_{it} = -3x_{it}^2 + 108x_{it} - 10X_{it} - 30x_{it}$
A	$\pi_{it} = -3x_{it}^2 + 108x_{it} - 10X_{it} - 30(X_t - 52)$
F	$\pi_{it} = -3x_{it}^2 + 108x_{it} - 10X_{it}$ if $X_t \leq 52$ $\pi_{it} = -3x_{it}^2 + 108x_{it} - 10X_{it} - 600$ if $X_t > 52$

Note that $X_t = \sum_i x_{it}$, $X_{it} = \sum_j x_{jt}$.

Table 3 presents the predicted input choices for each treatment. The socially optimal input use x^* is 13. Recall that the instruments are designed to induce the polluters to choose the social optimal input use, under the assumption that they act non-cooperatively.

¹⁷ The explanations given in paragraph 2.1.1. lead to $F > 75$. The end of appendix 2 justifies why the value of 600 was chosen.

¹⁸ Plott (1983) varies the initial endowments between treatments to take into account the different redistributive effects of each instrument. For example, a tax reduces each subject's earnings, while a subvention increases it. In his tax treatment, Plott redistributes the theoretical amounts of taxes into the polluters' initial endowments in compensation. The redistributive effect of instruments was not taken into account in our experiment. The money the regulator levies with taxes is supposed to be redistributed to a group of agents distinct from the group of polluters.

¹⁹ In the experiment, the payoff functions were presented to the players in two or three parts, depending on the treatment: first, a table displayed the individual part of the function " $-3x_{it}+108x_{it}$ "; second, the instructions explained literally that there was an externality among polluters " $-10X_{it}$ "; finally, in treatments I, A and F, there was a third literal part devoted to the instrument. Instructions are available upon request.

Table 3 : Predicted individual polluting input use per treatment

Treatment	Non-cooperative equilibrium input use	Cooperative outcome input use
N	18 (dom. strat.)	13
I	13 (dom. strat.)	8
A	13 (dom. strat.)	0
F	<ul style="list-style-type: none"> • x_i s.t. $\sum_j x_j = 52$ and $i, x_i \in \{4, \dots, 18\}$ (sym. equ.: 13) • 18 <p align="center">(multiplicity of equilibria)</p>	13

Note: The socially optimal input use x^* is 13.

The experiment dealt only with integer numbers so that all theoretical issues were relatively easily computable. In each period, each subject could use an input quantity between 0 and 20. Notice that all the predicted input quantities except one are far from 0 and 20, and also from other “focal points” such as 5, 10 and 15.²⁰

Notice that treatment F has a different structure compared to the other treatments. While the latter can be compared to linear (or quadratic) public goods environments, the former is closer to a threshold public goods game. Indeed the group fine is not continuous in ambient pollution, it is only triggered if ambient pollution exceeds the social target. Threshold public good games generally have several Nash equilibria, which gives rise to coordination problems between subjects. Indeed, Spraggon (2002) finds that the group fine fails to induce polluters to coordinate on the socially optimal equilibrium. Cadsby and Maynes (1999) analyze the subjects’ contributions in threshold public goods: they observe that when the threshold is higher, the public good is less likely to be provided, and that when reward in case of provision is higher, subjects are more likely to coordinate on the social optimum. This suggests that the efficiency of the group fine could depend on the socially optimal level of pollution (the threshold) and on the level of the penalty (which is a “negative reward”). In our study, the threshold is quite high (65% of the maximal input quantity) with respect to

²⁰ It is well-known that experimental subjects are more likely to choose those focal numbers than other ones whenever they are unsure of what to do (as, for example, can be the case if they do not understand the experiment). Thus it is important to locate the theoretically predicted strategies far from that points, in order to ensure that the subjects choose the predicted outcomes by rational reasoning and not simply because they did not know what to do.

Spraggon (25% of the maximal input quantity), and the fine is very high.²¹ Extrapolating Cadsby and Maynes' findings, our group fine should therefore perform better than Spraggon's.

3. Experimental procedures

The experiment was run at the University Louis Pasteur of Strasbourg in June 2001. Subjects were randomly selected from a pool of about 700 students who had agreed to participate in experiments for the entire the term. Four sessions were carried out, each session for one treatment. 16 subjects were present in each session. They were split into independent four-subject groups of "polluters", which did not change over the 20 periods (that type of framework is called "partner", as opposed to a "stranger" one, where the groups change at each period). Most subjects had already participated previously in other kinds of experiments.

We chose a "partner" design in order to obtain four independent observations for each session. That choice has a drawback: the subjects' decisions can be partly caused by strategic and/or reciprocal motivations between periods 1 and 19. Indeed, even individualistic subjects can hide their true type by cooperating (maximizing group payoff) until period 19 (Kreps, Milgrom, Roberts and Wilson, 1982). However, our primary objective is to compare the instruments' efficiency. The most important thing is to do it in identical conditions, no matter what conditions. Moreover, in the real field, the instruments would be implemented in relatively fixed groups of polluters.

The subjects were isolated from one another by partitions. Their decisions were collected through a computer network, based on an application developed by Bounmy (1998). After reading the instructions,²² they had to answer a few questions intended to check their understanding of the rules. In case of wrong answers, they were given individual explanations by monitors. After that, subjects played three trial periods. They were told that for the trial periods they would be playing "against" a computer program. Then the real game started. In each period, subjects could invest any integer number of tokens between 0 and 20. Tokens in

²¹ When all subjects stick to the social optimum, each one gets a 507 point payoff. By deviating, a subject could earn a maximum payoff of 582 points if the penalty was not applied, thus the maximum deviating net gain is 75 points. The penalty is worth 600 points, which is 8 times 75 (see appendix 2 for the choice of 600). In Spraggon (2002), the social optimum payoff is 13.75 points. The maximum deviation payoff is 25 points, so the maximum deviating net gain is worth 11.25 points. The penalty is 24 points, which is "only" 2.13 times 11.25. That intuitive explanation aims at showing that our penalty is relatively larger than Spraggon's. See also the end of appendix 2 another explanation.

the experiment were analogous to inputs in the theoretical model. After each period, subjects were informed about their individual payoff and about the sum of the invested tokens by the three other members their group. Then a new period started. At the end of the experiment, subjects earned the amount of money corresponding to their cumulated payoff.

4. Efficiency and reliability

In this section, we present the two criteria with which we assess the instruments: efficiency and reliability.

4.1. Efficiency

When an instrument is implemented in the group of polluters i at period t ($i \in \{1, \dots, 4\}$, $t \in \{1, \dots, 20\}$), the level of social welfare W_{it} , as defined in equation (1), will be taken as a measure of the instrument efficiency in this particular group at this particular period. The level of social welfare which is achieved in the no regulation treatment is the “status quo” level of efficiency. Let W^{SQ} be the *theoretical* status quo level of social welfare, i.e., the level of social welfare that is reached when emissions are not regulated (“no regulation” case) and firms follow dominant strategies ($W^{SQ} = 1728$).²³ Let W^{OPT} be the maximal attainable level of social welfare ($W^{OPT} = 2028$).²⁴ The difference $W^{OPT} - W^{SQ}$ is the potential welfare gain that can be achieved by an instrument. We define the “rate of social welfare” or “rate of efficiency” as follows:

$$E_{it} = \frac{W_{it} - W^{SQ}}{W^{OPT} - W^{SQ}}$$

A 100% rate means that the social welfare gain is maximal: the instrument is perfectly efficient. A 0% rate indicates that the social welfare gain is null, i.e., social welfare stays at the theoretical status quo level. Note that E_{it} can be negative which means that the instrument induces a welfare loss with respect to the theoretical status quo level.

4.2. Reliability

Measuring average efficiency is not sufficient in itself to analyze the performance of

²² Instructions are available upon request.

²³ $W^{SQ} = \sum [f(x_i^0) - \delta \sum x_i^0] = 4 * [-3(x_i^0)^2 + 108(x_i^0) - 10X_i^0] = 1728$ with $x_i^0 = 18$ and $X_i^0 = 3 * 18 = 54$.

instruments. Another significant feature to take into account is the variance of efficiency, which gives an insight in the reliability of instruments. The variance of efficiency can also be measured in the no regulation case, and this can be interpreted as the “unreliability” of the status quo efficiency. We are interested in three variance measures, providing three different unreliability indicators. Let V_t^{group} be the variance of efficiency between groups in period t .²⁵ Let V_t^{period} be the variance of efficiency between periods in group i .²⁶ Finally let V^{total} be the variance of efficiency for the whole experimental session.²⁷

Our aim is to compare the four different treatments (N, I, A and F) on the basis of each of these unreliability measures. Rigorous comparisons involve statistical tests. However, we can only carry out statistical tests on the V_t^{period} measures for statistical reasons.²⁸

5. Results

5.1. Efficiency and reliability: a ranking of the instruments

In this section, we focus first on each treatment’s average efficiency rate, and then on the variance of efficiency rates (reliability).

5.1.1. Average efficiency rate

Figure 1 displays the average efficiency rate per period E_t^m in each treatment, and table 4 presents the average efficiency rates per group E_i^m in each treatment.

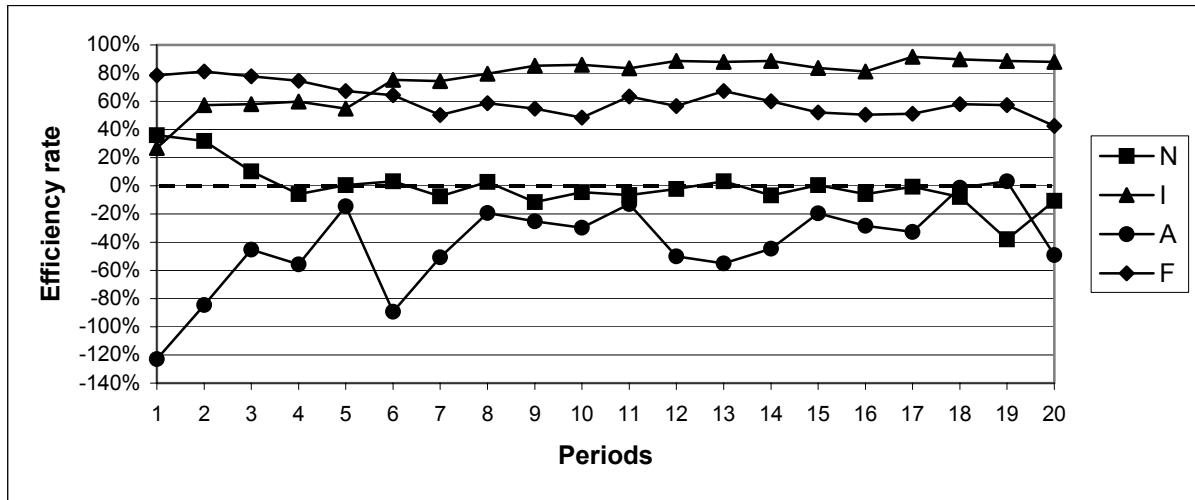
²⁴ $W^{OPT} = \Sigma[f(x_i^*) - \delta \Sigma_i x_i^*] = 4 * [-3(x_i^*)^2 + 108(x_i^*) - 10X_i^*] = 2028$ with $x_i^* = 13$ and $X_i^* = 3 * 13 = 39$.

²⁵ $V_t^{group} = (1/4) * \Sigma_i (E_{it} - E_t^m)^2$ where $E_t^m = (1/4) * \Sigma_i E_{it}$.

²⁶ $V_t^{period} = (1/20) * \Sigma_i (E_{it} - E_i^m)^2$ where $E_i^m = (1/20) * \Sigma_t E_{it}$.

²⁷ $V^{total} = (1/80) * \Sigma_i \Sigma_t (E_{it} - E^m)^2$ where $E^m = (1/80) * \Sigma_i \Sigma_t E_{it}$.

²⁸ Notice indeed that the 20 collected observations V_t^{group} are not statistically independent, to the extent that V_t^{group} is dependent on V_{t-1}^{group} , since the players’ decisions in period t depend on the players’ decisions in period $t-1$. In fact econometrics would allow the realization of such tests, but we do not have enough observations in the present case. Obviously statistical tests also cannot be carried out with observations V^{total} .



$E_t^m = 100\%$ if average social welfare gain in period t is maximal.
 $E_t^m = 0\%$ if average social welfare gain in period t is null (social welfare is at the theoretical status quo level).
 $E_t^m < 0\%$ if the instrument induces an average social welfare loss with respect to the theoretical status quo level in period t .

Fig. 1: Average efficiency rates per period and per treatment

Table 4 : Average efficiency rates per group in each treatment

Treatment	Average efficiency rates per group (%)				Mean
	G1	G2	G3	G4	
N	-2.40	27.85	-12.30	-17.20	-1.01
I	76.15	77.90	68.85	82.85	76.44
A	-90.95	-18.65	-135.85	79.95	-41.38
F	7.95	53.10	85.80	96.05	60.73

In treatment N, the average efficiency rate is -1%, which is very close to the sub-game perfect equilibrium rate (0%). It is roughly constant between period 4 and period 18. In treatment I the average rate is the highest (76%) and approaches 100% in some periods. Average efficiency increases slowly with repetition from 27% to 88%. This tendency is also true for each of the four groups of treatment I. In treatment F, average efficiency is also quite high (61%). The average rate decreases over time, but this tendency is only due to group 1. In treatment A, the average efficiency rate is negative (-41%). However it climbs up to nearly 0% (from -123% in period 1 to 3% in period 19). This increasing trend is true for groups 1, 2 and 4.

We ran statistical tests to compare efficiency rates (see hypotheses series H1 and H2, table 7, appendix 3). Since we collected few independent data (4 per treatment), we used

nonparametric tests (Wilcoxon-Mann-Whitney²⁹). The results are the following.

H_1 : *The ambient tax does not significantly increase social welfare (i.e. efficiency) with respect to status quo (Wilcoxon-Mann-Whitney, one-sided, $p=0.90$). The other instruments significantly increase social welfare ($p=0.0143$ for the input tax and $p=0.0286$ for the group fine).*

H_2 : *The two-sided Wilcoxon test does not find any significant efficiency difference between the instruments (this is probably due to a lack of data). On the contrary, a Student test results in a significant difference between treatment A efficiency and treatments I and F efficiencies (respect. $p=0.02$ and $p=0.037$)³⁰.*

5.1.2. Efficiency variance (reliability)

Figures in Appendix 4 provide insights in variances. Table 5 below displays the values of the different unreliability indicators, that we express in terms of standard deviation rather than variance for easier interpretation.

Table 5: Unreliability indicators in each treatment

Treatment	Average standard deviation (σ) between efficiency rates for each unreliability definition		
	σ_t^{group} (mean of the 20 data)	σ_t^{period} (mean of the 4 data)	σ_t^{total} (1 data)
N	0.2578	0.2107	0.2907
I	0.1743	0.2545	0.2590
A	1.0889	0.5796	1.0163
F	0.4122	0.1448	0.3918

In treatments N and I, there is a low inter-group standard deviation σ_t^{group} and a low inter-period σ_t^{period} standard deviation. In treatment F, inter-group standard deviation is quite high (in group 1 the efficiency rate is close to 0%, while in group 4 it lies close to 100%), whereas inter-period standard deviation is very low. In treatment A, inter-group and inter-

²⁹ Since this test is very conservative, our results are sometimes found to be non significant while intuition suggests that if the number of observations was larger, the results would be significant. To check this, despite the low number of data, we sometimes also provide a parametric student test.

period standard deviations are the highest.

Hypotheses series 3 and 4 (table 7, appendix 3) analyze the inter-period variance of efficiency V_t^{period} (see appendix 3 for more details).

H₃: *The inter-period variance of efficiency is significantly higher in treatment A than in treatment N (Wilcoxon-Mann-Whitney, one-sided, $p = 0.0286$). However, there is no significant differences in the inter-period variance of efficiency between treatment N and respectively treatments I ($p = 0.3429$) and F ($p = 0.8286$).*

H₄: *The inter-period variance of efficiency is not significantly different between treatments I and F ($p = 0.3429$). However, there is a significant difference between treatments A and F ($p = 0.0571$), and an almost significant difference between treatments A and I ($p = 0.1142$).*

5.1.3. Ranking of the instruments

Consider the average efficiency rate and the inverse of global standard deviation σ^{total} in each treatment to get an insight in the global performance of each instrument (Figure 2).

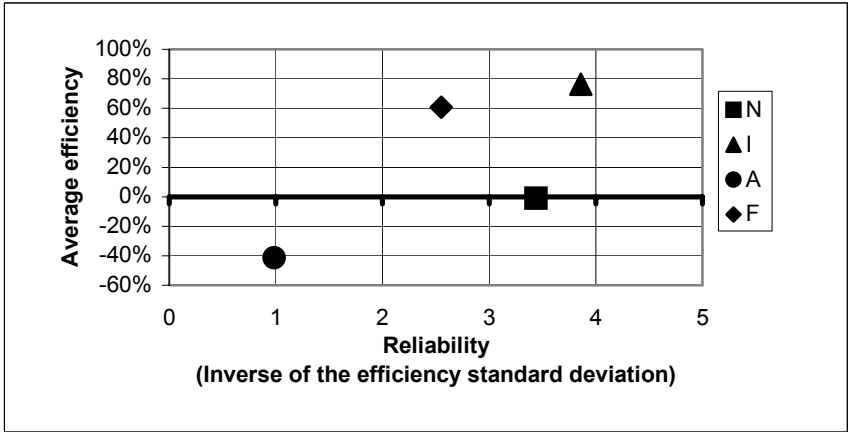


Fig. 2: Ranking of the instruments

The input tax dominates every other instrument and the status quo. The ambient tax is dominated by every other instruments and the status quo. Using the efficiency and reliability

³⁰ If an unilateral hypothesis was introduced (supporting the group payoff maximizing behavior hypothesis in treatment A), then we would conclude that the ambient tax efficiency is significantly lower than each of the two

criteria, the group fine cannot be compared to the status quo, since efficiency is higher but reliability is slightly smaller than in the status quo.

5.2. The subjects' polluting input use

In this subsection, we study the polluters' input use in order to better understand the efficiency rates presented in the previous subsection. Figure 3 displays average group input use per period in each treatment (the upper dotted line corresponds to the 72 (= 4*18) units of inputs of the no regulation Nash prediction and the lower dotted line corresponds to the socially optimal 52 (= 4*13) units of inputs). Note that the average input use is not very variable, except in treatment A.

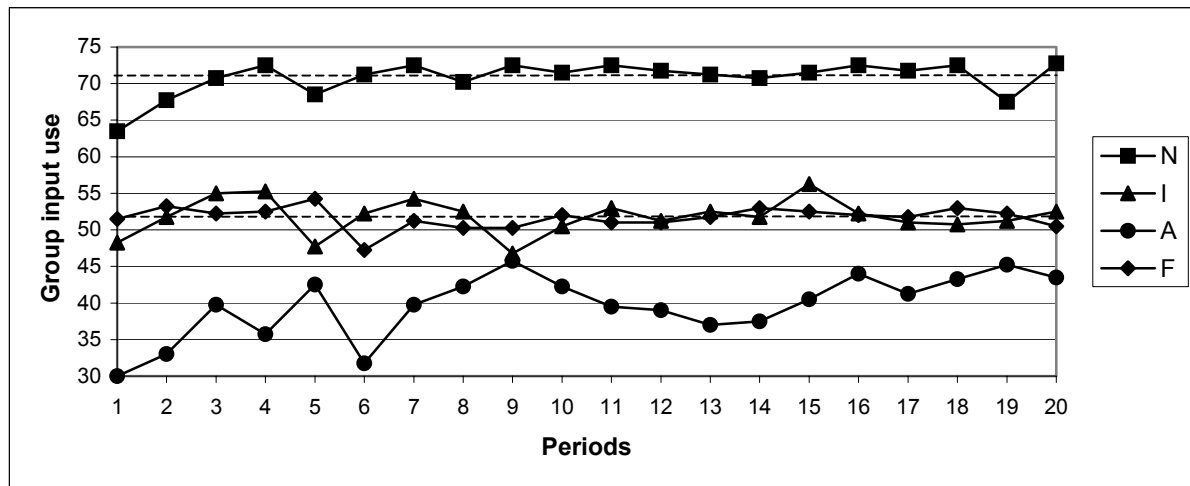


Fig. 3: Average group input use per period and per treatment

Table 6 presents the average input use per group in each treatment.

Table 6: Average group polluting input use per group in each treatment

Treatment	Average group input use ³¹				Mean
	G1	G2	G3	G4	
N	72.20	67.65	71.90	71.40	70.79
I	51.25	53.40	52.75	49.95	51.84
A	31.85	40.75	38.35	47.75	39.68
F	51.85	52.10	50.80	51.95	51.68

other instruments efficiencies (respect. $p=0.01$ and $p=0.0185$).

³¹ Each treatment was run with different subjects, so groups G_i are not the same in the different treatments.

In treatment N, the average group input use (about 71 units) is very close to the sub-game perfect equilibrium (18 units per subject or 72 units per group). Apparently, subjects did not try to maximize group payoff, and behave as predicted by non-cooperative game theory. This is confirmed by the first figure in appendix 5, which presents the frequency distribution of individual input use, and shows that 75% of all input decisions are 18 units.

In treatment I, the average group input use (about 52 units) also fits well with the sub-game perfect equilibrium (13 units per subjects). The second figure in appendix 5 again confirms this observation.

In treatment F, the average group input use (about 52 units) corresponds to one of the constituent game Nash equilibria. Therefore it is worth noticing that on average polluters were able to coordinate to avoid the fine.³² However, remember that only the symmetric equilibrium (13, 13, 13, 13) is socially optimal. Surprisingly in this fully symmetric game, polluters often coordinated on asymmetric equilibria, which explains why efficiency is not optimal. This could be due to the high level of the fine: some of the polluters were so scared of the fine that they reduced their input use below 13, and this behavior was anticipated by other polluters, who increased their input use. However, the polluters who reduced their input use also reduced their payoffs while the other polluters increased it. Therefore the group fine somehow leads to “inequitable” outcomes.

In treatment A, the average group input use equals 40 units, which is far below the sub-game perfect equilibrium (52 units). Since the maximum group payoff is achieved for a null input use, this could indicate that some of the subjects did adopt that strategy rather than the sub-game perfect equilibrium strategy (52% of the individual input use choices are smaller or equal to 10, see the third figure in appendix 5).³³ The average group input use remains below 52, but increases slightly (from 36 in the 5 first periods to 43 in the 5 last periods). Inter-group and inter-period variances are larger than in the other treatments.

We tested the average group input use differences between treatments (hypotheses series 5 and 6, table 8, appendix 3).

H₅: All instruments significantly reduce group input use with respect to the status quo

³² Apart from group 1, the group fine was seldom implemented (9 times in G1, 3 times in G2, 2 times in G3, 3 times in G4).

($p=0.0143$ for each instrument).

H₆: *The input tax and the group fine do not differ significantly with respect to their impact on group input use ($p=0.8858$). However, the ambient tax has a significantly different effect on the level of input use from the input tax and the group fine ($p=0.0286$ for both instruments).*³⁴

These results show that all instruments succeed in their goal to reduce input use. From that point of view, all instruments achieve the environmental goal of reducing pollution. However, the ambient tax reduces too much pollution with respect to the social optimum.³⁵ This observation is consistent with a cooperative behavior. In order to further explore this hypothesis, we carried out another experimental treatment, called A', very close to treatment A. In treatment A', we tested a slightly modified ambient tax: the scheme is such that if ambient pollution (a) exceeds the social target (a^*), then each polluter pays an ambient tax proportional to the difference ($\gamma (a - a^*)$, where γ is the tax rate), while if ambient pollution is below the social target, then the polluters do not get any subsidy. With this instrument, there is no social dilemma: the group optimum and the Nash equilibrium are the same ($i, x_i = 13$). Thus polluters have absolutely no incentive to cooperate, and therefore cooperation cannot reduce the efficiency of this instrument, contrary to the ambient tax A.³⁶ Indeed ambient tax A is in fact a subsidy if pollution is below the social target, and the polluters may increase their profits by reducing collectively their input use to get these subsidies, while with ambient tax A', there is no such subsidy, and thus no incentive to reduce input use. Therefore if input use is reduced below 13 in this treatment, it means that the polluters do not reduce input use *only* to cooperate.

The results of treatment A' are the following. On average, the modified ambient tax A' is almost perfectly efficient and reliable. Input use is significantly higher in treatment A' than in treatment A (Wilcoxon-Mann-Whitney, one-sided, $p = 0.0143$), but not significantly

³³ At the end of the experiments, the subjects were requested to make a few comments on their behavior during the game. Most of them pointed out that the best way to earn high payoffs was to use 0 input, provided that the other members of the group did the same!

³⁴ That test is bilateral: we did not propose any precise alternative theory to explain group input use in treatment A. Now consider the alternative theory that some subjects maximize group input use instead of individual payoffs in treatment A. The associated alternative hypothesis is that treatment A group input use is significantly lower than treatments I and F group input use. Of course that hypothesis is accepted ($p=0.0143$ in both cases).

³⁵ However it is worth noticing that if we had considered higher environmental damages (higher δ , damages on consumers,...) then the socially optimal input use would have been lower than 13, thus the ambient tax would probably have been relatively less inefficient.

³⁶ Notice however that the Nash equilibrium strategy is not dominant, which might affect the efficiency of the instrument by creating coordination problems.

different from input use in treatments I and F ($p = 0.2$ for both two-sided tests), and thus not significantly different from the Nash equilibrium strategy. These results strengthen our hypothesis that in treatment A, the subjects cooperate in order to get the subsidy and thus increase their payoffs.

6. Discussion

Let us compare our results with Spraggon's (2002). In our experiment, the average group input use in the ambient tax treatment is far below the social optimum (the difference between average group input use and the social optimum is worth 15% of the input decision range, which was 80), whereas it is very close to it for Spraggon (2002) (1% of the decision range, which was 600). As for the group fine treatment, we find that the average group input use is nearly equal to the socially optimal group input use (the difference is worth about 0% of the decision range), while Spraggon observes it to be far above the social optimum (35% of the decision range). Turning to the efficiency rates, Spraggon finds that the ambient tax is almost perfectly efficient (98%), while we got a negative rate of efficiency (-41%). The group fine treatments provide similar efficiencies (Spraggon: 54%, our experiment: 60%), but that similarity is a coincidence: the underlying behaviors are actually very different. Indeed, in Spraggon's experiment, average group input use is above the social optimum, while in ours, average group input use is equal to the social optimum, but individual input choices correspond to asymmetric equilibria of the constituent game. In conclusion our results differ from Spraggon's.

It is difficult to provide an explanation for these discrepancies since the experiments are very different.³⁷ However several hypotheses can be proposed. First, there are two layers of externality in our treatment A, while in Spraggon's, there is only one. It may have improved the subjects' awareness of the social dilemma, and thus increased their concern for group payoff. Second, we chose to locate the social optimum (the equilibrium) in a relatively high position (13 units of input over a range of 20), while Spraggon selected a relatively low position (25 units over 100). Thus in our experiment, the subjects have two good reasons for reducing input use below the social optimum in treatment A: the group maximizing payoff

³⁷ The experimental protocols are different: strategy spaces, payoff functions, number of subjects per group, instructions. Moreover, we introduce an endogenous externality between firms, while Spraggon experiments an externality which does not affect the firms themselves.

strategy is at 0, and the middle of the strategy space, which is a strong focal point, is at 10. In Spraggon's experiment, these focal points (respectively 0 and 50 units of input) have opposite effects. The same kind of argument can account for the group fines discrepancies.³⁸ Third, the fine level we chose is "relatively" higher than Spraggon's.²¹ Following Cadsby and Maynes (1999), we could expect to observe better coordination on the social optimum.

7. Conclusion

Our experiment aimed at comparing different nonpoint source pollution instruments: an input tax, an ambient tax, and a group fine were tested in independent sessions. A benchmark unregulated treatment was also run to study the "status quo". Ambient pollution was assumed to affect the polluters themselves rather than some consumers distinct from the polluters. That inter-polluter externality hypothesis gives rise to a social dilemma between the polluters even in the unregulated case or in case of a purely individual regulation as the input tax. According to non-cooperative game theory, the input and the ambient tax should be as efficient in achieving the social optimum. The group fine does not generate any social dilemma, since the group optimum *is* a Nash equilibrium outcome when this instrument is applied. However, the instrument raises a coordination problem, because there are many Nash equilibria.

In each independent session, we measured the average level of social welfare, to get the efficiency of each instrument and of the status quo. We also determined the inter-group and inter-period variances between efficiency rates, to measure what we call the reliability of each instrument and of the status quo. Our experimental data show that the input tax is almost perfectly efficient and very reliable, the group fine is fairly efficient and reliable. Both instruments improve welfare with respect to the status quo. On the contrary, the ambient tax decreases social welfare with respect to the status quo, and its effect is very unreliable.

To explain those results, we also analyzed the polluters' input choices. The three instruments all significantly reduce input use (and thus polluting emissions), but only the input tax does it optimally. Under the ambient tax, the polluters seem to cooperate to maximize their group payoff instead of choosing the dominant strategy which is designed to

³⁸ In our experiment, the social optimum is at 13, above 10. In Spraggon's experiment, the social optimum is at 25, under 50. It may be one of the reasons why our subjects were not very much attracted by high input use levels, while Spraggon's subjects were.

generate the social optimum. But by doing this they reduce too much their input use with respect to the social optimum. In the group fine treatment, average group input use is socially optimal, but not individual input choices. Polluters often coordinate on asymmetric equilibria, which are inequitable to the extent that some get high payoffs, while other get low payoffs. Indeed the latter are so scared by the fine that they prefer reducing their input use far below the “equitable” input use.

Our results would suggest the regulator to introduce input taxes if possible. If this is not feasible, the use of ambient based instruments should be considered with care. A group fine might prove satisfactory if sufficiently high and if the socially desirable level of emission does not require too much input restriction to be achieved. An ambient tax will only be implemented if the potential gains from cooperation are not too high, which depends on the payoff and damage functions.

Our results are quite different from Spraggon’s (in press), who found that the ambient tax was almost perfect and far more efficient than the group fine. We find in contrast that the implementation of the ambient tax may raise serious problems. It is worth emphasizing that those differences are likely to be due to a number of differences in frameworks, such as the shape of the profit functions and the presence of the inter-polluter externality. Thus one must not conclude from our study that the input tax is necessarily always the most efficient. Indeed, this instrument might require that the regulator observes all polluters’ input decisions, which is certainly costly in the field, and thus the efficiency we got is likely to be overestimated. Moreover, the group fine we experiment is also particular to the extent that the penalty is very high. Such a high sanction certainly increases the probability of coordination on the social optimum, but is unlikely to be accepted by taxpayers. Last but not least, our experiment does not show that all ambient taxes are inefficient. Indeed we observe that a slightly modified ambient tax, where the “subsidy part” is suppressed, is as efficient as the input tax, since there is no more incentive to cooperate.

To check the robustness of these results, the next step would be to introduce stochasticity, by assuming that ambient pollution depends on a random variable. This would incorporate more realism into the framework.

Appendix 1: Theoretical Predictions

A. Non-cooperative predictions

1. The Input Tax

Firm i 's payoff can be written as:

$$\pi^I(x_i, a) = f(x_i) - \delta a - t^I x_i. \quad (\text{A1})$$

Recalling that $a = s \sum x_i$, the FOC gives:

$$f'(x^I) = s\delta + t^I. \quad (\text{A2})$$

To achieve the social optimum (2), the tax rate must be:

$$t^I = s(n-1)\delta. \quad (\text{A3})$$

2. The Ambient Tax

Let $T^A(a)$ be the ambient tax. Firm i 's payoff can be written as:

$$\pi^A(x_i, a) = f(x_i) - \delta a - T^A(a). \quad (\text{A4})$$

The FOC gives³⁹:

$$f'(x^A) = s(\delta + T^{A'}(a^A)). \quad (\text{A5})$$

To achieve the social optimum (2), the tax rate must be:

$$T^{A'}(a^A) = (n-1)\delta. \quad (\text{A6})$$

Hence the instrument is linear⁴⁰, and its rate is:

$$t^A = (n-1)\delta. \quad (\text{A7})$$

Thus the general form of continuous fiscal ambient-based devices is:

$$T^A(a) = t_A a + k_A. \quad (\text{A8})$$

where k_A is a constant.

That general formalization (Shortle, Horan and Abler, 1998) allows to introduce a wide range of ambient-based instruments. Segerson's ambient tax (1988) is found posing $k_A = -t_A a^*$, where a^* is the socially optimal level of ambient pollution, which results in:

$$T^A(a) = t^A(a - a^*). \quad (\text{A9})$$

³⁹ Assuming that the maximum can be found by the derivative.

⁴⁰ It comes from the linearity of the damage function.

3. The Group Fine

The Group Fine F is such that:

$$\begin{aligned}\pi^F(x_i, a) &= f(x_i) - \delta a && \text{if } a \leq a^*, \\ \pi^F(x_i, a) &= f(x_i) - \delta a - F && \text{if } a > a^*.\end{aligned}\tag{A10}$$

F can be chosen so that if all firms stick to the social optimum, no individual deviation is profitable. The first step is therefore to determine the maximum deviation gain. Assume all firms other than firm i are at the social optimum: $\forall j \neq i, x_j = x^*$. Firm i 's payoff is then:

$$\begin{aligned}f(x_i) - \delta(e(x_i) + (n-1)e(x^*)) &&& \text{if } x_i \leq x^*, \\ f(x_i) - \delta(e(x_i) + (n-1)e(x^*)) - F &&& \text{if } x_i > x^*.\end{aligned}\tag{A11}$$

It is straightforward to see that firm i 's optimal deviation is for $x_i = x^0$, which is the dominant strategy when there is no regulation. Thus firm i 's payoff is:

$$f(x^0) - \delta(e(x^0) + (n-1)e(x^*)) - F.\tag{A12}$$

To keep firm i from deviating, the following condition on F must hold:

$$F > f(x_i^0) - \delta(e(x^0) + (n-1)e(x^*)) - \pi(x_i^*, a^*).\tag{A13}$$

If this is true, then the social optimum x^* becomes a Nash equilibrium for the game. But there can be many other Nash equilibria for the game. Any vector x such that $\sum_i e(x_i) = a^*$ may be an equilibrium, and the vector x^0 remains a Nash equilibrium. The following proposition shows that result.

Proposition 1: The set of Nash equilibria belongs to the set $\{(x_1, \dots, x_n) \in \mathbb{R}_+^n \mid \forall i, x_i \leq x_i^0 \text{ and } \sum e(x_i) = a^*\} \cup \{(x^0, \dots, x^0)\}$.

Proof: First, note that firm i never wants to choose $x_i > x_i^0$ since its payoff is always decreasing from x_i^0 , thus for all $i, x_i \leq x_i^0$. Second, assume that there exists an equilibrium (x_1, \dots, x_n) such that $\sum e(x_i) < a^*$. Then, as $a^* < \sum e(x_i^0)$, it follows that $\sum e(x_i) < \sum e(x_i^0)$. Since e is increasing in x_i , there exists at least one firm i such that $x_i < x_i^0$. Then it is optimal for that firm to increase x_i , since its payoff is increasing until x_i^0 : indeed, there is no risk to trigger the penalty F as soon as $\sum e(x_i) < a^*$. Therefore every firm i such that $x_i < x_i^0$ is willing to increase x_i while $\sum e(x_i) < a^*$, so that $\sum e(x_i)$ has no reason to remain under a^* at equilibrium. Thus the contradiction. Hence the Nash equilibria are necessarily such that $\sum e(x_i) \geq a^*$. Third, assume that an equilibrium x is such that $\sum e(x_i) > a^*$. In that case, the fine is applied since ambient

pollution exceeds its socially optimal level. So each firm i maximizes its payoff: $x_i = x^0$. The equilibrium is x^0 . QED.

B. “Cooperative” or “group optimal” outcome

Let Π^N be the group payoff function and x^{GN} be the Group payoff maximizing input use in the No regulation case. Of course, $x^{GN} = x^*$, since the social welfare function W and the group payoff function Π^N are the same.

In the input tax case, $\Pi^I(\mathbf{x}) = \sum_i (f(x_i) - \delta a - t^I x_i)$. The FOC is:

$$f'(x^{GI}) = sn\delta + t^I. \quad (\text{A14})$$

where x^{GI} (G for Group payoff, I for Input tax) is the solution. Recalling that $t^I = s(n-1)\delta$, we get: $x^{GI} < x^* = x^{GN}$ if $n > 1$.

In the ambient tax case, $\Pi^A(\mathbf{x}) = \sum_i (f(x_i) - \delta a - t^A(a - a^*))$. The FOC is:

$$f'(x^{GA}) = sn\delta + snt^A. \quad (\text{A15})$$

where x^{GA} (G for Group payoff, A for Ambient tax) is the solution. Recalling that $t^A = (n-1)\delta$, we get: $x^{GA} < x^{GI} < x^* = x^{GN}$ if $n > 1$.

In the group fine case, the group payoff function $\Pi^F(\mathbf{x})$ must be analyzed on two different areas: if $a \leq a^*$, no fine is applied, so that $\Pi^F(\mathbf{x}) = \Pi^N(\mathbf{x})$, which is maximized for $x^{GF} = x^{GN} = x^*$ (G for Group payoff, F for Fine); if $a > a^*$ the fine is applied, so that $\Pi^F(\mathbf{x}) = \Pi^N(\mathbf{x}) - nF$, which is also maximized for $x^{GF} = x^{GN} = x^*$, thus $a > a^*$ is impossible.

Appendix 2: The Nash Equilibria in the F Treatment with the particular parameters

Proposition 2 :

The set of Nash equilibria is: $\{(x_1, \dots, x_n) \in \mathbb{R}_+^n / \forall i, 4 \leq x_i \leq 18, \sum_i x_i = 52\} \cup \{(18, \dots, 18)\}$.

Proof: Following proposition 1, the set of Nash equilibria belongs to the set $\{(x_1, \dots, x_n) \in \mathbb{R}_+^n / \forall i, x_i \leq 18, \sum_i x_i = 52\} \cup \{(18, \dots, 18)\}$. Consider a vector x from this set distinct from $(18, \dots, 18)$. Hence $\sum_i x_i = 52$. Vector x is a Nash equilibrium if no firm has any incentive to deviate, i.e., to increase its input use. Of course a firm such that $x_i = 18$ is never willing to deviate. Consider a firm i such that $x_i < 18$. By choosing x_i , firm i 's payoff is: $\pi_i = -3x_i^2 + 108x_i - 10 \sum_{j \neq i} x_j$, since no fine is implemented. By deviating (thus choosing 18), firm i 's payoff is: $\pi_i = -3 \cdot 18^2 + 108 \cdot 18 - 10 \sum_{j \neq i} x_j - F = 372 - 10 \sum_{j \neq i} x_j$, with $F = 600$ (see below for the choice of F), since this time the fine is implemented ($\sum_i x_i > 52$). Hence deviation occurs if and only if $-3x_i^2 + 108x_i < 372$, which is equivalent to $x_i < 4$. QED.

Remarks:

- 1) The social optimum (13, 13, 13, 13) is one of the Nash equilibria. Although there are many Nash equilibria, the socially optimal one is rather likely to be observed since it is symmetric.
- 2) We chose to set $F = 600$. This value of F is relatively high with respect to the payoff function. Indeed, as previously mentioned, we wanted to test a high fine to see if it would be more efficient than Spraggon (2002)'s group fine. The high value of F can also be justified when the regulator does not have perfect information on all the parameters of the model (see again footnote ¹⁴).

Appendix 3: Statistical tests

Table 7 : Testable hypotheses on efficiency indicators

Hyp. series n°	Description of the alternative hypothesis	Null hypothesis	Alternative hypothesis
H ₁	Instruments increase significantly efficiency with respect to the status quo.	$W_N = W_X$	$W_N < W_X$
H ₂	Instruments have significantly different effects on efficiency with respect to one another.	$W_X = W_Y$	$W_X \neq W_Y$
H ₃	Instruments significantly increase the inter-period variance of efficiency with respect to the status quo.	$V_{WN} = V_{WX}$	$V_{WN} < V_{WX}$
H ₄	Impacts on the inter-period variance of efficiency are significantly different from one instrument to another.	$V_{WX} = V_{WY}$	$V_{WX} \neq V_{WY}$

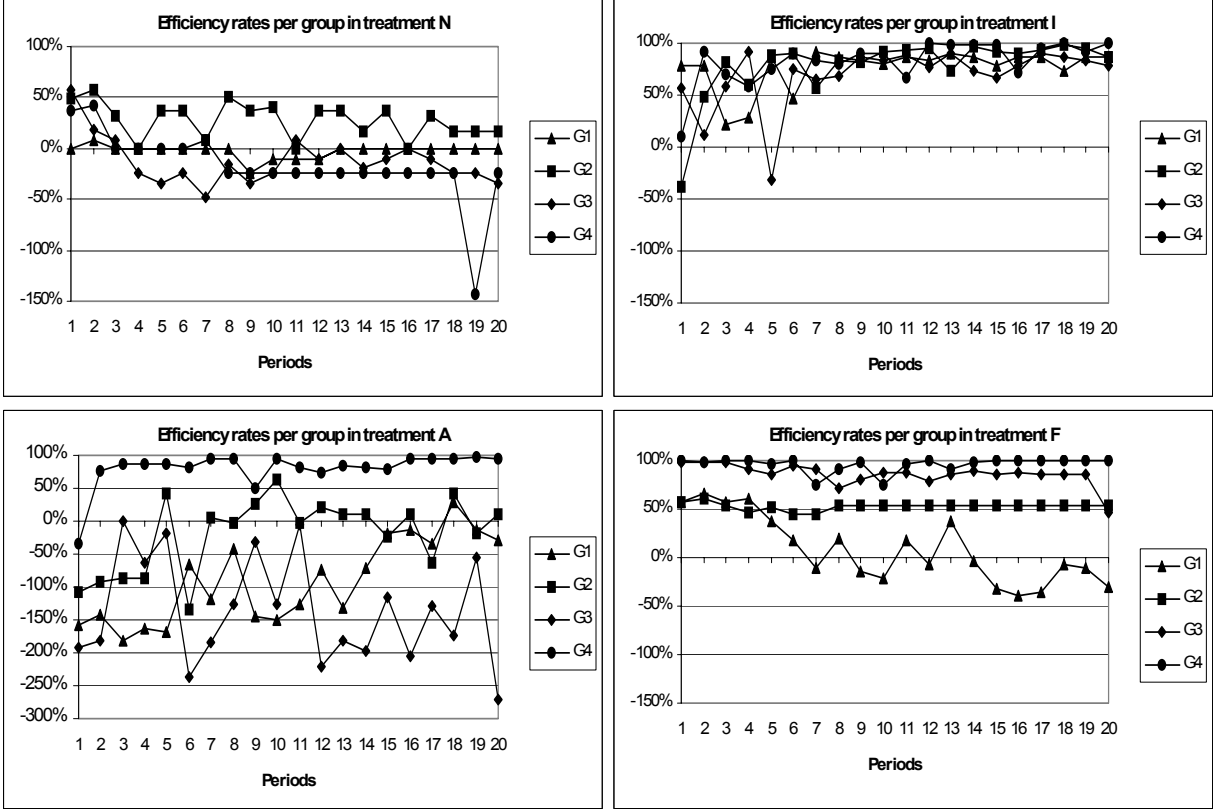
Note : W_Z is the average level of social welfare (or efficiency) achieved in treatment Z (with $Z \in \{N, X, Y\}$, $X \in \{I, A, F\}$, $Y \in \{I, A, F\}$, $X \neq Y$). V_{WZ} denotes the average inter-period variance of efficiency in treatment Z (with $Z \in \{N, X, Y\}$, $X \in \{I, A, F\}$, $Y \in \{I, A, F\}$, $X \neq Y$).

Table 8 : Testable hypotheses on group input use

Hyp. series n°	Description of the alternative hypothesis	Null hypothesis	Alternative hypothesis
H ₅	Instruments significantly decrease input use with respect to the status quo.	$I_N = I_X$	$I_N > I_X$
H ₆	Impacts on input use are significantly different from one instrument to another.	$I_X = I_Y$	$I_X \neq I_Y$

Note: I_Z designates the average group input use in treatment Z (with $Z \in \{N, X, Y\}$, $X \in \{I, A, F\}$, $Y \in \{I, A, F\}$, $X \neq Y$).

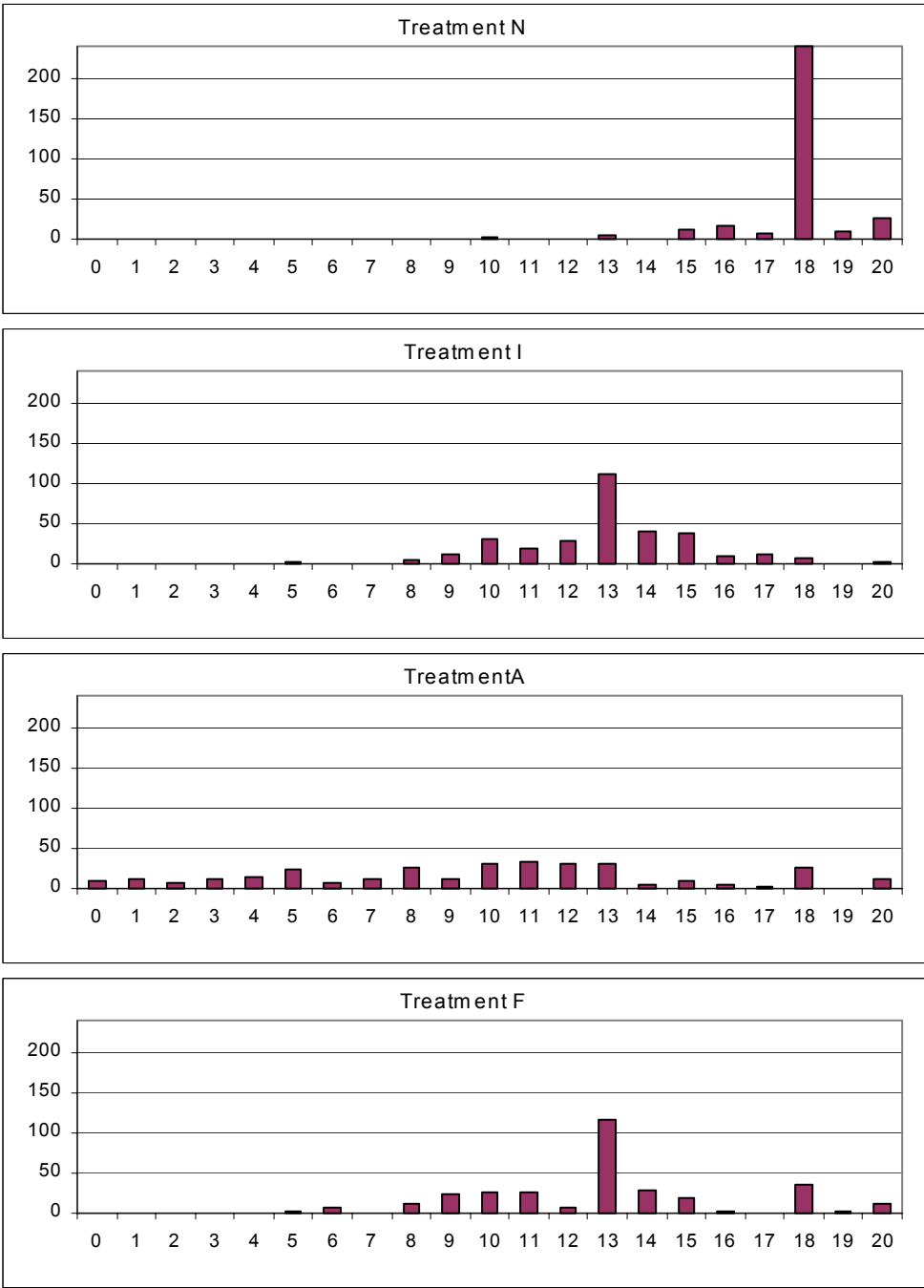
Appendix 4: Efficiency per group and per period in each treatment



Note: For treatment A the efficiency values range from -300% to 100%, while in the other treatments they range from -150% to 100%.

Appendix 5 : Individual input use

The following figure displays the frequency distribution of individual input use levels over the 20 periods, for each treatment (the horizontal axis stands for input use levels).



Note: There is a total of 320 observations per treatment (16 subjects make 20 input decisions)

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