Efficiency of Nonpoint Source Pollution Instruments:
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 endogenize pollution by assuming that the polluters are themselves affected by the environmental damages. Each instrument is experimented in an independent session. 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.*

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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 be also 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 examples 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 accumulation of pollutants, like lead,

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

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 "endogenous 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 "endogenous 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 "endogenous 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 "endogenous 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 endogenous 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,

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[2] It is not always true : for example, the collective penalty (treatment F) we define below is without any social dilemma.

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 endogenous 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 "endogenous 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) and 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 status quo.

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[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.

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 (in press), 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, furthermore the analysis covered a NPS problem with *no* endogenous externality. 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".[5] 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 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

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[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] 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 oligopoly

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 (in press), who found that the ambient tax was almost perfectly efficient.[6] 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.

Part 2 exposes the underlying theoretical model and its predictions. The experimental procedures are summarized in part 3. Part 4 presents the testable predictions. Part 5 is devoted to the results. Part 6 provides a discussion and part 7 concludes.

2. Theoretical predictions

2.1. The theoretical model

The model we have experimented is a simplified version of the general model. Thus we only present this simplified version in the paper. It clarifies the exposition while preserving the intuitive results of the general model. One of our simplifying assumptions is to consider a perfectly symmetrical situation.

Consider n firms who produce a unique good from a unique input. Let $x_i 5 \heartsuit_+$ be firm i's use of input ($i \in \{1,\ldots,n\}$). Let f the strictly concave profit function. The firms are assumed to have no collective influence on the prices of inputs or outputs.

Each firm emits an individual externality e_i which is a function of input consumption: $e_i = e(x_i) = s x_i$, with $s 5 \heartsuit_+$. Individual externalities give rise to a global externality a which corresponds to ambient pollution: $a = \varphi(e_1, \ldots, e_n) = \acute{O} e(x_i)$. Ambient pollution generates a cost

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

[6] This is especially true in Spraggon's deterministic treatments with inexperienced subjects. However, the results are robust in stochastic and experienced frameworks.

$d(a) = äa$, with $ä \, 5 \, \heartsuit_+$ on each firm.[7] Thus firm i's net profit (hereafter "payoff") is $\pi(x_i, a) = f(x_i) - d(a)$. In addition, nonpoint pollution models generally assume that a affects negatively consumers' welfare. Here, we assume that there is no damage on consumers.[8] We also assume that all functions are deterministic. An alternative and more realistic assumption would state that emission functions are stochastic.[9]

To design first-best regulation instruments, the regulator needs to know in general the damage functions d_i and D. Input taxes also require the knowledge of the individual emission functions e_i, the ambient pollution function φ, and the profit functions f_i. Ambient instruments can be less information-demanding in some cases, but they always require the knowledge of a.[10] 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 we are studying.

Each experimental session is a 20-fold repetition of a constituent game. We first give the theoretical predictions of the constituent games, and then those of the repeated games.

2.1.1. Theoretical predictions of the constituent games

2.1.1.1. Non-cooperative game theory predictions

In this subsection we consider the non-cooperative game theory 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 can

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[7] The emission function e, the ambient pollution function ö, and the damage function are assumed to be linear, but these are only simplifying assumptions.

[8] Indeed, in this model, the consumers have only a "passive" role, to the extent that they do not make any decision. Thus in the experiment, there was no use to introduce consumers.

[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] See for example Shortle, Horan and Abler, 1998.

be seen as a benchmark, involves *n* firms interacting when no instrument is implemented. Then three specific instruments are implemented in three independent treatments: the "Input tax" case (I), the "Ambient tax" case (A) and the "group Fine" case (F). According to non-cooperative game theory, each of those instruments is shown to achieve the first-best level of social welfare, or at least to be "likely" to achieve it in the group fine case.

Let us first define social welfare. Let $\vec{x} = (x_1, …, x_n)$ be the vector of input decisions of all firms, and $\vec{x}_{-i} = (x_1, …, x_{i-1}, x_{i+1}, …, x_n)$ the vector of input decisions of all firms except that of firm *i*. Since we assume that there is no damage on consumers, social welfare $W(\vec{x})$ will be defined as the sum of firms' payoffs (if there are taxes, they are assumed to be redistributed, and thus cancel out at the social level).[11] Therefore it is a function of input use and ambient pollution:

$$W(\vec{x}) = Ó_i\, ð(x_i, a), \text{ with } a = Ó_i(sx_i). \tag{1}$$

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

$$f'(x^*) = sn\text{ä}. \tag{2}$$

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 $ð(x_i, a)$, assuming that the other polluters' decisions x_j ($j \to i$) are fixed. The vector $\vec{x}^0 = (x^0, …, x^0)$ is a Nash equilibrium which exists, is unique and dominant due to the properties of the profit functions. The FOC is:

$$f'(x^0) = s\text{ä}. \tag{3}$$

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

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[11] 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 ð does not include taxes, as is usually assumed in the literature. Moreover, notice that since firms have no collective influence on the prices of input and output (perfectly competitive markets), maximizing the sum of the profits is equivalent to maximizing the consumers' surplus plus the sum of the profits. The surplus analysis is justified by assuming quasi linearity of individual utility functions with respect to a numeraire commodity.

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In treatment I, an input-based tax is assumed to be introduced (Griffin and Bromley, 1982, Shortle and Dunn, 1986, Shortle and Abler, 1994). The most simple one is linear. The socially optimal input tax rate t_I is:

$$t_I = s(n\text{-}1)\ddot{a}. \tag{4}$$

Since the tax rate t_I is the same for all polluters, the regulator does not need 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 ones. In treatment A, an ambient-based instrument is applied. 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 $a^* = \acute{O}_i e(x_i^*)$. In our model we have:

$$T_A(a) = (n\text{-}1)\ddot{a}(a - a^*). \tag{5}$$

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 a perfect incentive at zero cost.[13]

In treatment F, a group Fine is implemented, again supposing 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:

$$\pi^F(x_i, a) = f(x_i) - \ddot{a}a \qquad if\ a \leq a^*, \tag{6}$$
$$\pi^F(x_i, a) = f(x_i) - \ddot{a}a - F \ \ if\ a > a^*.$$

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:

$$-x_i,\ F > f(x_i) - \ddot{a}(e(x_i) + (n\text{-}1)e(x^*)) - \eth(x^*, a^*). \tag{7}$$

Under the group fine, the social optimum is a Nash equilibrium for the game. But there can be many

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[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.

[13] The exact knowledge of a^*, which requires the knowledge of the marginal emission s, the profit function f, the marginal damage $\ddot{a}$, and the number of firms n, is not necessary for the instrument to be socially optimal. Thus in general the ambient tax is less information-demanding than the input tax.

other Nash equilibria. All vector of input choices $\vec{x}$ such that $\acute{O}e(x_i) = a^*$ may be an equilibrium. Since the game is symmetrical, the social optimum is the only one of these equilibria which is symmetrical: $\vec{x}^* = (x^*, \ldots, x^*)$. Furthermore, the no regulation symmetric Nash equilibrium $\vec{x}^0$ 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 dominant.[14]

2.1.1.2. "Cooperative" solution: the group optimal outcome

The experimental literature on public goods, which deals with positive externalities, showed that standard (non-cooperative) game theoretical 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 maximize group payoff. Let $\ddot{I}$ be group payoff : $\ddot{I}(\vec{x}) = \acute{O}_i\, \eth(x_i, a)$. $\ddot{I}$ 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 $\ddot{I}$ 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 [11]).

2.1.2. 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

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[14] Expression (7) shows that the regulator needs to know the marginal emission *s*, the profit function *f*, the marginal damage ä, and the number of firms *n*. In practice, this instrument does not necessarily require exact

game has a unique sub-game perfect equilibrium (Selten, 1975). 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 game.

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 more simple, we made the following simplifying assumptions: for the individual emission function, $s = 1$, thus $e(x_i) = x_i$, for the payoff function:

$$\eth(x_i) = f(x_i) - \ddot{a}\acute{O}_i x_i = -\alpha x_i^2 + \hat{a} x_i - \delta X_i \tag{8}$$

where $X_i = \acute{O}_{j \circledR i} \, x_j$.[15] Table 1 summarizes the parameters values.[16]

<div align="center">Table 1: Parameters values</div>

Parameters		Values
Number of firms	n	4
Profit functions	á	3
	â	108
Marginal emission	s	1
Firm damage function d	ä	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

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knowledge of all those functions. Indeed it is possible to set F sufficiently high so that condition (7) be satisfied.

[15] Notice that $f(x_i) = -\acute{a} x_i^2 + (\hat{a} + \ddot{a}) x_i$.

[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.

[17] The explanations given in paragraph 2.1.1.1. lead to F > 75. The end of appendix 2 justifies why the value of 600 was chosen.

were given an initial endowment of 66 French Francs (10 Euros).[18]

<div align="center">Table 2: Payoff functions[19]</div>

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 $X_t = \acute{O}x_{it}$

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.

<div align="center">Table 3 : Predicted individual polluting input use per treatment</div>

Treatment	Non-cooperative equilibrium input use	Cooperative equilibrium input use
N	18 (dom. strat.)	13
I	13 (dom. strat.)	8
A	13 (dom. strat.)	0
F	• x_i s.t. $\acute{O}_j x_j = 52$ and $-i$, $x_i 5\{4,\ldots,18\}$ (sym. equ.: 13) • 18 (multiplicity of equilibria)	13

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

The experiment dealt only with integer numbers so that all theoritical issues were relatively

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[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 theoritical amounts of taxes into the polluters' initial endowments in compensation. The redistributive effect of intruments 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

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. Among the numerous equilibria, the cooperative outcome can be considered as more likely to happen. However, in Spraggon (in press), the group fine fails to achieve this. 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 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.

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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.

[20] It is well-known that experimental subjects are more likely to choose those 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.

[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 (in press), 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.

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. 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 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.

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[22] Instructions are available upon request.

4. Testable predictions on efficiency and polluting input use

4.1. Testing efficiency indicators

When an instrument is implemented in the group of polluters i at period t ($i5\{1,\dots,4\}$, $t5\{1,\dots,20\}$), 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.

Hypotheses series H_1 and H_2 in Table 4 compare the average level of social welfare (or efficiency) which is achieved in each treatment (W_X, where X designates treatment X).

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[23] $W_{SQ} = \acute{O}[f(x_i^0)\text{-}\ddot{a}\acute{O}x_i^0] = 4*[-3(x_i^0)^2 + 108(x_i^0) - 10X_i^0] = 1728$ with $x_i^0 = 18$ and $X_i^0 = 3*18 = 54$.

[24] $W_{OPT} = \acute{O}[f(x_i^*)\text{-}\ddot{a}\acute{O}x_i^*] = 4*[-3(x_i^*)^2 + 108(x_i^*) - 10X_i^*] = 2028$ with $x_i^* = 13$ and $X_i^* = 3*13 = 39$.

Table 4 : Testable hypotheses on efficiency

Hyp. series n°	Description of the alternative hypothesis	Null hypothesis	Alternative hypothesis
H_1	Instruments increase significantly efficiency with respect to the status quo.	$H^W_X: W_N = W_X$	$H^{W}_{X}{}^{A}: W_N < W_X$
H_2	Instruments have significantly different effects on efficiency with respect to one another.	$H^W_{X-Y}: W_X = W_Y$	$H^{W}_{X-Y}{}^{A}: W_X \rightarrow W_Y$
H_3	Instruments significantly increase the inter-period variance of efficiency with respect to the status quo.	$H^V_X: V_{WN} = V_{WX}$	$H^{V}_{X}{}^{A}: V_{WN} < V_{WX}$
H_4	Impacts on the inter-period variance of efficiency are significantly different from one instrument to another.	$H^V_{X-Y}: V_{WX} = V_{WY}$	$H^{V}_{X-Y}{}^{A}: V_{WX} \rightarrow V_{WY}$

Measuring average efficiency is not sufficient in itself to analyze the performance of 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_i^{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_i^{period} measures for statistical reasons.[28] Hypotheses series 3 and 4 in Table 4 are devoted to the variance of efficiency between periods in each four-person group V_i^{period}. Let V_{WX} denote the average variance of efficiency in treatment X.

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

[26] $V_i^{period} = (1/20)*Ó_t(E_{it} - E_i^m)^2$ where $E_i^m = (1/20)*Ó_t E_{it}$.

[27] $V^{total} = (1/80)*Ó_t Ó_i(E_{it} - E^m)^2$ where $E^m = (1/80)*Ó_i Ó_t E_{it}$.

[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}.

4.2. Testing polluting input use indicators

The efficiency differences can be explained by differences in the subjects' polluting input choices. Thus we are also interested in the total level of input use in each four-person group. In each treatment, we compute each four-person group average input use over the 20 periods. This provides a total of four independent observations per treatment. Let I_X designate the average group input use in treatment X. Hypotheses series 5 and 6 in Table 5 are devoted to group input use.

Table 5 : Testable hypotheses on four-person 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.	$H^I_X : I_N = I_X$	$H^I_X{}^A : I_N > I_X$
H_6	Impacts on input use are significantly different from one instrument to another.	$H^I_{X-Y} : I_X = I_Y$	$H^I_{X-Y}{}^A : I_X \rightarrow I_Y$

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.

5.1.1. Average efficiency rate

Figure 1 displays the average efficiency rate per period E_t^m in each treatment, and table 6 presents the average efficiency rates per group E_i^m in each treatment.
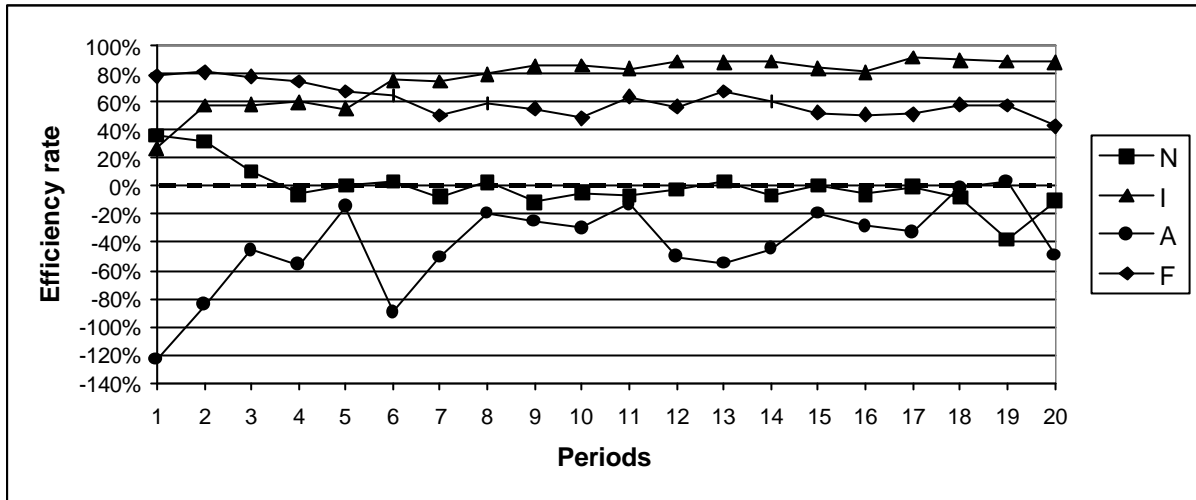
$E_t^m = 100\%$ if average social welfare gain in period t is maximal.

$E_t^m = 0\%$ 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 6 : Average efficiency rates per group in each treatment

Treatment	Average efficiency rates per group (%)				
	G1	G2	G3	G4	Mean
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.

Recall that hypotheses series 1 and 2 concern the average efficiency differences between treatments. Since we collected few independent data (4 per treatment), we used nonparametric tests

(Wilcoxon-Mann-Whitney[29], see for example Siegel and Castellan, 1988). The table in appendix 3 presents the test results for a 5% level of significance. The results are the following.

H$_1$: *The ambient tax does not significantly increase social welfare 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 the inter-group and inter-period variances (respect. V_t^{group} and V_i^{period}). Table 7 below displays the values of the different unreliability indicators, that we express in terms of standard deviation rather than variance for easier interpretation.

Table 7: Unreliability indicators in each treatment

Treatment	Average standard deviation (ó) between efficiency rates for each unreliability definition		
	$ó_t^{group}$ (mean of the 20 data)	$ó_i^{period}$ (mean of the 4 data)	$ó^{total}$ (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 $ó_t^{group}$ and a low inter-

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[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 $\acute{o}^{period}$ 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-period standard deviations are the highest.

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

H$_3$: *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).*

H$_4$: *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 $\acute{o}^{total}$ in each treatment to get an insight on the global performance of each instrument (Figure 2).

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[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 other instruments efficiencies (respect. p=0.01 and p=0.0185).
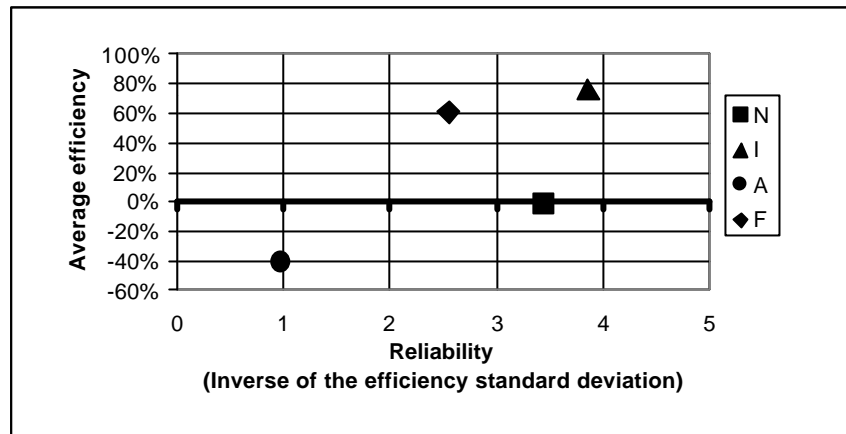
Fig. 2: Ranking of the instruments

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 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

Figure 3 displays average group input use per period in each treatment (the high dotted line corresponds to the 72 units of inputs of the no regulation Nash prediction and the low dotted line corresponds to the socially optimal 52 units of inputs). Note that the average input use is not very variable, except in treatment A.
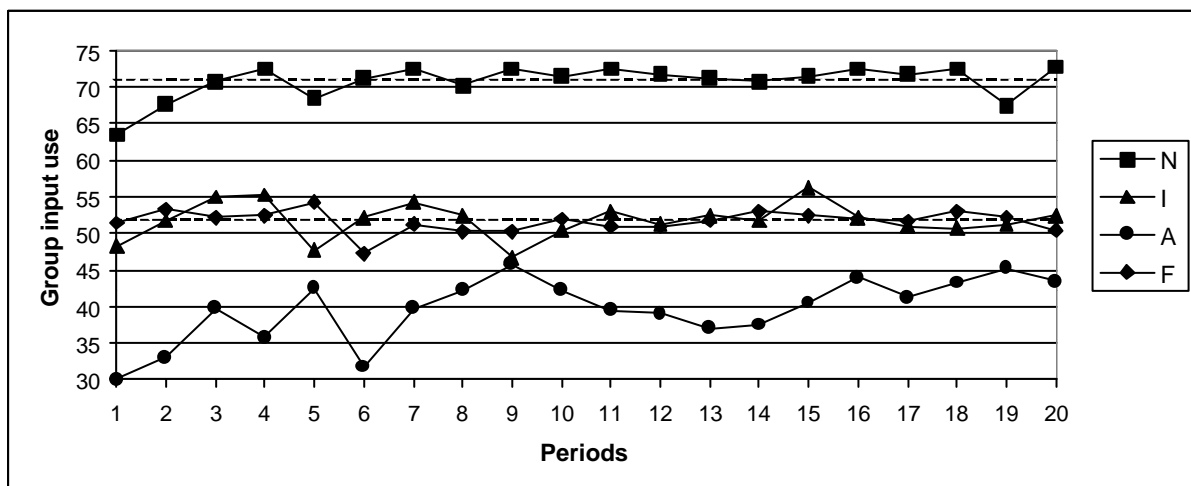
To get an insight on differences between four-person groups, table 8 presents each group input use averaged over the 20 periods.

Table 8: Average group polluting input use per treatment over the 20 periods

Treatment	Average group input use[31]				
	G1	G2	G3	G4	Mean
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

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.

In treatment I, the average group input use (about 52 units) also fits well with the sub-game perfect equilibrium (13 units per subjects).

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 that it could be implemented, that they strongly restricted their input use.

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).[33] The

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

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

[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!

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).

H_5: *All instruments significantly reduce group input use with respect to the status quo (p=0.0143 for each instrument).*
This result shows that all instruments succeed in their goal to reduce input use, even if the result is not always socially optimal.

H_6: *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]*
The different impact of the ambient tax might be due to the fact that some of the subjects chose to maximize the group payoff (cooperation) instead of maximizing their individual payoff (dominant strategy).

The figure in appendix 5 displays the frequency distribution of individual input use levels over the 20 periods, for all polluters, in each treatment. All previous comments are confirmed. In particular, polluters seem to maximize group payoff in treatment A, which explains why the efficiency of the ambient tax is so low.

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 polluters pays an ambient tax proportional to the difference ($ã (a - a^*)$, where $ã$ 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 ($-i$, $x_i = 13$).

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[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).

Thus polluters have absolutely no incentive to cooperate, and therefore cooperation cannot reduce the efficiency of this instrument, contrary to the ambient tax A.[35] 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 in this treatment, it means that the polluters do not reduce input use *only* to cooperate. Other explanations would then have to be introduced.

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 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

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 (in press) (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 (96%), while we got a negative rate of efficiency (-41%). The group fine treatments provide similar efficiencies (Spraggon: 53%, 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

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

constituent game. In conclusion our results differ from Spraggons'.

It is difficult to provide an explanation for these discrepancies since the experiments are very different.[36] However several hypotheses can be proposed. First, there are two layers of externality in our treatment A,[37] 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 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". The ambient pollution was assumed to affect the polluters themselves rather than some consumers distinct from the polluters. That "endogenous 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 payoff optimum *is* a Nash equilibrium outcome when this instrument is applied. However, the instrument raises a coordination

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[36] 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.

[37] Look again at treatment A payoff function in table 2.

[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 Spraggons' subjects were.

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 cooperate to maximize their group payoff instead of choosing the dominant strategy which is designed to 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 ready to accept very low payoffs since they fear that the group fine could be implemented.

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 to 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 endogenous 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: Theoritical Predictions

A. Non-cooperative game theory predictions

1. The Input Tax

Firm i's payoff can be written as:

$$\pi^I(x_i, a) = f(x_i) - \ddot{a}a - t_I x_i. \tag{A1}$$

Recalling that $a = \acute{O}_i(sx_i)$, the FOC gives:

$$f'(x^I) = s\ddot{a} + t_I. \tag{A2}$$

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

$$t_I = s(n\text{-}1)\ddot{a}. \tag{A3}$$

2. The Ambient Tax

Let $T_A(a)$ be the ambient tax. Firm i's payoff can be written as:

$$\pi^A(x_i, a) = f(x_i) - \ddot{a}a - T_A(a). \tag{A4}$$

Recalling that $a = \acute{O}_i(sx_i)$, the FOC gives[39]:

$$f'(x^A) = s(\ddot{a} + T_A'(\bullet)). \tag{A5}$$

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

$$T_A'(\bullet) = (n\text{-}1)\ddot{a}. \tag{A6}$$

Hence the instrument is linear[40], and its rate is:

$$t_A = (n\text{-}1)\ddot{a}. \tag{A7}$$

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

$$T_A(a) = t_A a + k_A. \tag{A8}$$

where k_A is a constant.

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[39] Assuming that the maximum can be found by the derivative.
[40] It comes from the linearity of the damage function.

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:

$$T_A(a) = t_A(a - a^*). \tag{A9}$$

3. The Group Fine

The Group Fine F is such that:

$$\pi^F(x_i, a) = f(x_i) - äa \qquad if\ a \leq a^*, \tag{A10}$$

$$\pi^F(x_i, a) = f(x_i) - äa - F \quad if\ a > a^*. \tag{A10}$$

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: $-j \to i$, $x_j = x^*$. Firm i's payoff is then:

$$f(x_i) - ä(e(x_i) + (n\text{-}1)e(x^*)) \qquad if\ x_i \leq x_i^*, \tag{A11}$$

$$f(x_i) - ä(e(x_i) + (n\text{-}1)e(x^*)) - F \quad if\ x_i > x_i^*. \tag{A11}$$

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:

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

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

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

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

<u>Proposition 1</u> :   The   set   of   Nash   equilibria   belongs   to   the   set $\{(x_1, \ldots, x_n) 5 \Re_+^n / -i, x_i \leq x_i^0 \text{ and } Óe(x_i) = a^*\} \cup \{(x^0 \ldots, x^0)\}$.

Proof: First, note that firm i never wants to choose $x_i > x^0$ since its payoff is always decreasing from x^0, thus for all i, $x_i \leq x^0$. Second, assume that there exists an equilibrium $(x_1, \ldots, x_n)$ such that

$Óe(x_i) < a^*$. Then, as $a^* < Óe(x^0)$, it follows that $Óe(x_i) < Óe(x^0)$. Since e is increasing in x_i, there exists at least one firm i such that $x_i < x^0$. Then it is optimal for that firm to increase x_i, since its payoff is increasing until x^0: indeed, there is no risk to trigger the penalty F as soon as $Óe(x_i) < a^*$. Therefore every firm i such that $x_i < x^0$ is willing to increase x_i while $Óe(x_i) < a^*$, so that $Óe(x_i)$ has no reason to remain under a^* at equilibrium. Thus the contradiction. Hence the Nash equilibria are necessarily such that $Óe(x_i) \geq a^*$. Third, assume that an equilibrium $\vec{x}$ is such that $Óe(x_i) > a^*$. 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 $(x^0, \ldots, x^0) = \vec{x}^0$. QED.

B. Cooperative game theory predictions

Let Ï be the group payoff : $Ï(\vec{x}) = Ó_i\, ð(x_i, a)$. Ï varies across treatments.

If there is no regulation, $Ï^N(\vec{x}) = Ó_i\, (f(x_i) - äa)$. The FOC is:

$$f'(x^{GN}) = snä. \tag{A14}$$

where x^{GN} (G for Group, N for No regulation) is the solution. Recalling that $f'(x^*) = snä$, we get: $x^* = x^{GN}$, which is not surprising since the social welfare function W and the group payoff function Ï are the same.

In the input tax case, $Ï^I(\vec{x}) = Ó_i\, (f(x_i) - äa - t_I x_i)$. The FOC is:

$$f'(x^{GI}) = snä + t_I. \tag{A15}$$

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

In the ambient tax case, $Ï^A(\vec{x}) = Ó_i\, (f(x_i) - äa - t_A(a - a^*))$. The FOC is:

$$f'(x^{GA}) = snä * n. \tag{A16}$$

where x_i^{GA} (G for Group payoff, A for Ambient tax) is the solution. Hence: $x^{GA} < x^{GI} < x^* = x^{GN}$.

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

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

<u>Proposition 2 :</u>

The set of Nash equilibria is: $\{(x_1, \ldots, x_n) / -i, 4 \le x_i \le 18, \sum_i x_i = 52\} \cup \{(18, \ldots, 18)\}$.

Following proposition 1, if $\sum_{j \ne i} x_j < 34 \; (= 52 - 18)$, there is no Nash equilibrium since $-x_i \, 5 \, \{0, \ldots, 18\}$, $\sum x_j < 52$, and if $\sum_{j \ne i} x_j > 52$, then the only Nash equilibrium is $(18, 18, 18, 18)$, since $-x_i \, 5 \, \{0, \ldots, 18\}$, $\sum x_j > 52$.

If $34 \le \sum_{j \ne i} x_j \le 52$, then proposition 1 states that only two cases are possible :

- either $\sum_i x_i = 52$, thus $x_i = 52 - \sum_{j \ne i} x_j$, then firm i's payoff is: $\pi_i = -3x_i^2 + 108x_i - 10 \sum_{j \ne i} x_j$, since no fine is implemented.

- or $\sum_i x_i > 52$, so $x_i > 52 - \sum_{j \ne i} x_j \Rightarrow$ the fine is applied, thus $x_i = 18$, so firm i's payoff is: $\pi_i = -3x_i^2 + 108x_i - 10 \sum_{j \ne i} x_j - F$, hence $\pi_i = 972 - 10 \sum_{j \ne i} x_j - F$, with $F = 600$ (see below for the choice of F).

Then firm i chooses $x_i = 52 - \sum_{j \ne i} x_j$ iff $-3x_i^2 + 108x_i > 972 - F$ iff $x_i \ge 4 \; (<=> \sum_{j \ne i} x_j \le 48)$.

Hence every allocation such that $\sum x_i = 52$ and $-i, 4 \le x_i \le 18$ is a Nash equilibrium. The social optimum is $(13, 13, 13, 13)$. Although there are many Nash equilibria, the socially optimal one is rather likely to be observed since it is symmetrical.

Note that " $-3x_i^2 + 108x_i > 972 - F$ " implies that the lower F, the smaller the number of equilibria. Several particular values are interesting:

- $F = 0$, there is only one equilibrium left: $(18, 18, 18, 18)$, it is of course the unregulated game equilibrium, since there is no more regulation.

- $F > 75$: the social optimum $(13,13,13,13)$ is an equilibrium.

- $F > 972$: every allocation such that $\sum x_i = 52$ and $-i, 0 \le x_i \le 18$ is an equilibrium.

We set $F = 600$. That value was chosen so that any deviation of a firm, if the other firms are at the

social optimum, leads to a loss (negative payoff). Indeed, if firm i uses 18 units of input when the other uses 13 units, then $\eth_i = 582 - F$. For the payoff to be negative, $F = 583$ is sufficient, but for simplicity, we chose $F = 600$. We wanted to study whether such a high penalty, by helping coordination on the socially optimal equilibrium, would compensate for the multiplicity of equilibria. The high value of F can also be justified by the fact that the regulator only knows the profit function f within an error range.
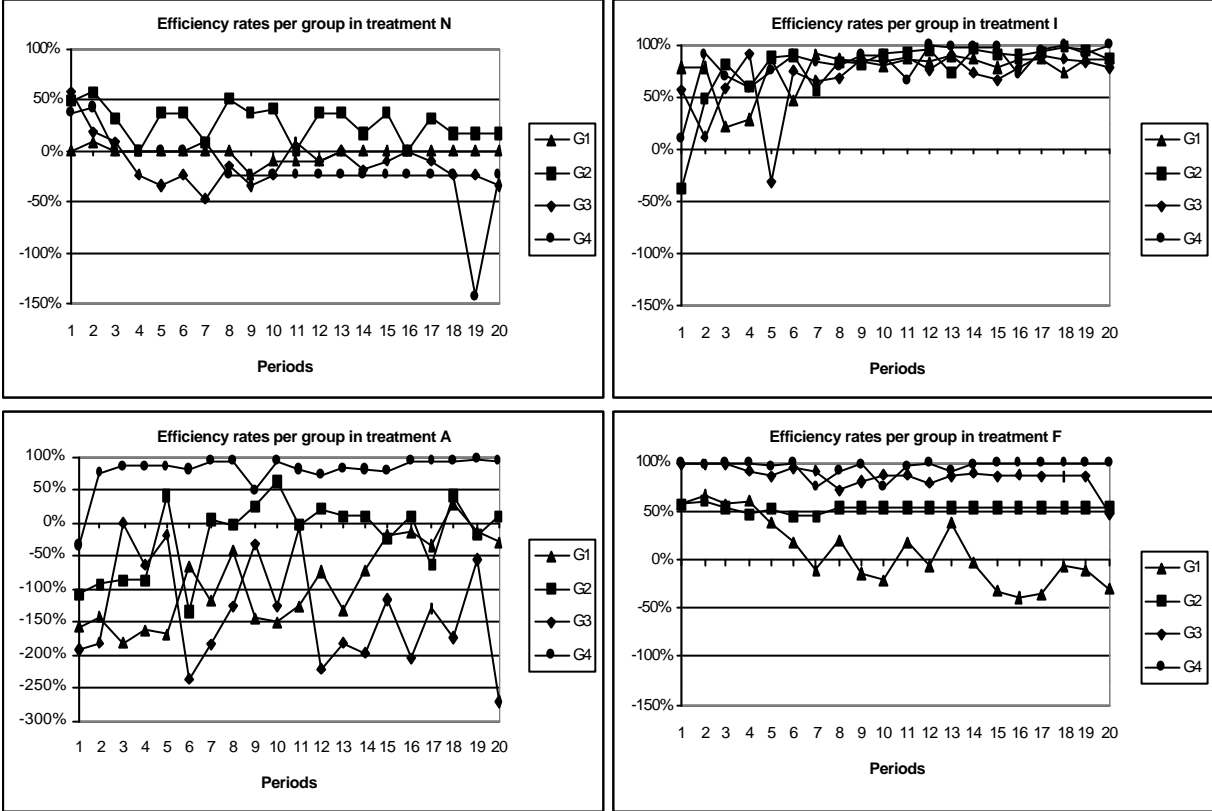
Appendix 3: Results of the statistical tests

The results are summarized in the following table.

Hyp. series n°	Test	Crit. prob.	Accepted hyp.
1	H^W_I	0.0143	$H^W_I{}^A$
	H^W_A	0.9000	H^W_A
	H^W_F	0.0286	$H^W_F{}^A$
2	$H^W_{I\text{-}A}$	0.2000*	$H^W_{I\text{-}A}$
	$H^W_{I\text{-}F}$	1.0000*	$H^W_{I\text{-}F}$
	$H^W_{A\text{-}F}$	0.1142*	$H^W_{A\text{-}F}$
3	H^V_I	0.3429	H^V_I
	H^V_A	0.0286	$H^V_A{}^A$
	H^V_F	0.8286	H^V_F
4	$H^V_{I\text{-}A}$	0.1142*	$H^V_{I\text{-}A}$
	$H^V_{I\text{-}F}$	0.3428*	$H^V_{I\text{-}F}$
	$H^V_{A\text{-}F}$	0.0572*	$H^V_{A\text{-}F}{}^A$
5	H^I_I	0.0143	$H^I_I{}^A$
	H^I_A	0.0143	$H^I_A{}^A$
	H^I_F	0.0143	$H^I_F{}^A$
6	$H^I_{I\text{-}A}$	0.0286*	$H^I_{I\text{-}A}{}^A$
	$H^I_{I\text{-}F}$	0.8858*	$H^I_{I\text{-}F}$
	$H^I_{A\text{-}F}$	0.0286*	$H^I_{A\text{-}F}{}^A$

*Bilateral test: the critical probability was doubled.

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

Efficiency rates per group in treatment N

Efficiency rates per group in treatment I

Efficiency rates per group in treatment A

Efficiency rates per group in treatment F

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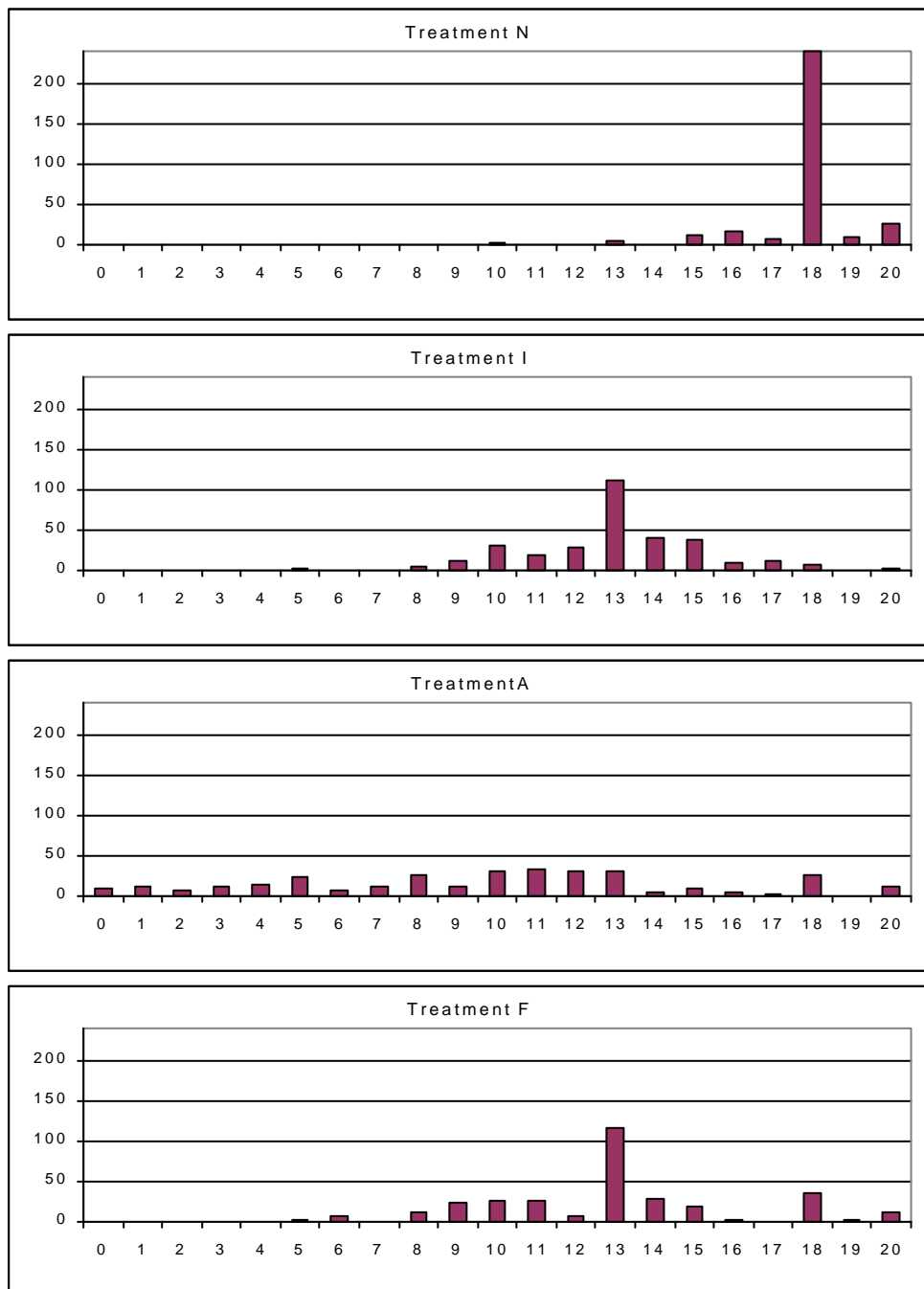
Note: There is a total of 320 observations per treatment (16 subjects make 20 input decisions)

In treatments N and I, the distributions have a single mode that corresponds to the sub-game

perfect equilibrium input use. The high mode in treatment N (18 units of input) corresponds to 75% of all input use decisions. In treatment I, the mode (13 units) is also quite high, and represents 35% of the data.[41] Note also that the distributions are roughly centered on their mode. Recalling that in treatment N, the sub-game perfect equilibrium is not socially optimal, it confirms that the subjects have a socially sub-optimal behavior when no regulation is applied. In treatment I, on the contrary, the sub-game perfect equilibrium is socially optimal. The input tax provides therefore a very strong incentive for subjects to choose the socially optimal level of input use.

The individual input use distribution of treatment F has two modes, each one corresponding to the one-shot symmetric Nash equilibrium strategies (13 and 18 units of input use). However, the socially optimal strategy (13 units) is chosen far more frequently (36% of the cases) compared to the 18-units sub-optimal symmetric Nash strategy (chosen only in 11% of the cases).

In treatment A, the individual input use distribution is almost uniform, which contrasts sharply with the other treatments. The sub-game perfect equilibrium strategy (13 units) is observed in only 9% of the cases. A majority of input choices lie between the group payoff maximizing input use (0 token) and the sub-game perfect equilibrium input use. Our hypothesis is that the subjects understood very quickly that maximizing group payoff could generate very high earnings, so that many of them tried to "cooperate" in order to reach that outcome. This could explain the low level of input use choices. We further explore this hypothesis by running treatment A'. The results are given in the main text.

The figure clearly reveals that individual input decisions are more variable in the three regulated treatments (I, A, F) than in the no regulation treatment (N). The introduction of an instrument therefore increases the variance of individual input use choices.[42] It does not imply that the variance of the efficiency rates are higher in the regulated treatments. For instance, recall that the variance of the efficiency rates is higher in treatment N than in treatment F.

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[41] In treatment N, most subjects showed both by their decisions and their comments that they had understood what the dominant strategy was. On the contrary, in treatment I, which was only a little different from treatment N, the subjects seemed a bit lost. Their comments show that they ended up finding the equilibrium strategy after trials and errors.

[42] This result is significant at the 5% level for the input and the ambient taxes, and at the 10% level for the group fine (Wilcoxon, one-sided).

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