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Formal and Informal Regulations: Enforcement and Compliance

Clara Villegas Palacio

UNIVERSITY OF GOTHENBURG

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A los míos

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Preface - Gracias

When you are born and raised in Colombia, the first word your parents teach you is "GRACIAS". Now that four years have passed and that the end of the "pre-yellow book era" is here, it is time for me to practice my parents' first lesson and say gracias to those who have made my PhD studies not only a possible but a pleasant experience. First of all, I will never be able to thank God enough for all He has given me through my life. He has always been next to me "with countless gifts of love". Now, it is definitely time to look up to the sky once more and say MUCHAS GRACIAS.

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To my beloved nieces Mariana, Maria Antonia, Maria Fernanda, Ana Clara and the ones to come; you are in the last sentence of this preface because you are a new beginning. You are the sweet hope of a good future. Gracias, this thesis is also for you.

Clara Inés Villegas Palacio
Gothenburg, April 2010.

Abstract

The question I address in the thesis is how cooperation in social dilemma situations and compliance with environmental regulations are determined by legal enforcement, intrinsic motivations and culture. In light of this, the thesis consists of five independent chapters.

Chapter 1 analyzes the effects of the interaction between technology adoption and incomplete enforcement on the extent of violations and the rate of abatement technology adoption. We focus on price-based and quantity-based emission regulations. First, we show that in contrast to uniform taxes, under tradable emissions permits (TEPs), the fall in permit price produced by technology adoption reduces the benefits of violating the environmental regulation at the margin and leads firms to modify their compliance behavior. Second, we show that the regulator may speed up the diffusion of new technologies by increasing the stringency of the enforcement strategy in the case of TEPs while in the case of uniform taxes, the rate of adoption does not depend on the enforcement parameters.

In ***Chapter 2***, I study the effects of targeted monitoring strategies on the adoption of a new abatement technology and, consequently, on the aggregate emissions level when firms are regulated with uniform taxes. My results suggest that a regulator aiming to stimulate technology adoption should decrease the adopters' monitoring probability and/or increase the non-adopters' monitoring probability. In contrast to previous literature, I find that, in some cases, a regulator whose objective is to minimize aggregate emissions should exert a stronger monitoring pressure on firms with higher abatement costs.

In some contexts, weak law enforcement results in only a fraction of detected transgressors actually being sanctioned. The standard theoretical models of enforcement predict that, as long as the joint probability of detection and sanction is constant, the extent of violations does not vary with different combinations of the probability of monitoring and the probability of sanction given detection. In contrast, in ***Chapter 3*** we propose an alternative theoretical model that predicts that the extent of violation is sensitive to such combinations, i.e., these two probabilities are not perfect substitutes. By using a laboratory experiment, we investigate the hypothesis of imperfect substitutability of monitoring and sanctioning probabilities. Our subjects include both environmental managers in Colombian firms and university students. Different combination of the probabilities resulting in the same joint probability of detection and sanctioning did not affect the violation behavior among managers, while students violate relatively less when facing a higher sanctioning probability for a given joint probability.

Chapter 4 investigates whether disclosure crowds out pro-social behavior using a public goods experiment. In a between-subject design, we investigate different degrees of disclosure.

We find a small positive but insignificant effect of disclosure treatments on contributions to the public good. Thus, our empirical findings are consistent crowding-out theory.

In contrast to previous studies on cross-group comparisons of conditional cooperation, in ***Chapter 5*** we keep cross- and within-country characteristics constant. The results reveal significantly different cooperation behavior between social groups in the same location.

Introduction

Given its characteristics, environmental quality can be considered a public good. With increasing recognition of the significance of environmental protection, a large number of policy instruments have been designed to regulate pollution in hopes to achieve the desired levels of this public good. Among these instruments are economic incentives such as environmental taxes and marketable emission permits. In several cases, the design of such policies gives them a social dilemma character where regulated agents have a clear incentive not to cooperate by not complying with the regulation. If nobody complies, however, then everybody is worse off than if they had cooperated by complying.[1] Sociological research has examined the role of three factors in shaping compliance with laws: the threat of sanctions, the opinions of peers, and personal morality (Tyler, 2006a). Analogously, Bénabou and Tirole (2006) and Ariely et al. (2009) discuss the role that external motivations such as rewards or punishments, intrinsic motivations such as altruism, and image motivations have on pro-social behavior of individuals.

Compliance with legal requirements and cooperation in a social dilemma situations are then determined by the coexistence and interaction between three regulatory systems (Mockus, 1994). First, is the legal system, which we refer to as *formal regulation.* This is defined by a set of laws together with enforcement mechanisms such as monitoring and legal punishment of transgressors. Enforcement mechanisms are oriented to promote compliance with the law and to avoid actions beyond what is legally allowed. The second and third among these systems are morale and culture, which we refer to as *informal regulation.* Morale consists of personal standards to which people attempt to align their behavior (Tyler 2006b). What is morally valid is delimited through judgments or arguments that an agent formulate to him or to others about the rightness of an action. Emotions like guilt or anticipated guilt are linked to the moral regulatory system and act as dissuasive factors to avoid morally wrong actions. In an environment where legal and moral systems are compatible, guilt or anticipated guilt have dissuasive power to avoid

[1] A clear example of this kind of regulation is the “National Wastewater Discharge Fee Program” implemented in Colombia since 1997 (see Blackman, 2009)

breaking the law. Culture is partly composed of social norms. What is culturally valid corresponds to what is socially accepted and it is, in some cases, independent of what the legal and moral regulatory system mandates. Emotions like shame or fear of social disapproval are linked to the cultural regulatory system and constitute dissuasive elements to avoid actions which are socially punished. Where there is harmony between legal, moral and cultural regulatory systems, social and internal norms enforce compliance with the law (Mockus, 1994, 2003). Tyler (2006b) also points at legitimacy of the law and of the regulator as a necessary condition for the law to be obeyed. Legitimacy is defined by the author as a perceived obligation to authorities or existing social arrangements and because of it people feel that they ought to ought to voluntarily obey rules. According to Tyler (2006b), although legitimacy and morality are similar in many ways they are also differentiable and sometimes do not work in concert.

The question I address in the thesis is how cooperation in social dilemma situations and compliance with environmental regulations are determined by the three regulatory systems and by the legitimacy of regulations. In light of this, the thesis consists of five independent papers. The first two papers analyze compliance with the formal environmental regulation. The third paper looks at the interaction between legal, moral and cultural regulatory systems in the context of compliance with environmental laws. The last two papers focus on the influence that the design of mechanisms such as disclosure of contributions and the background of social groups have on contributions to a public good.

The first chapter of this thesis analyzes the interaction between incomplete enforcement and technology adoption under price-based and quantity-based environmental policies. It has been recognized that different environmental policies provide different incentives for technological change which, in the long run, is considered the primary solution to environmental problems (Kneese and Schultze 1978). In this chapter we compare emission taxes and tradable emission permits in terms of: (i) how compliance changes with the use of new technologies and (ii) how technology adoption is affected by enforcement parameters such as the probability of being monitored. Our results suggest that the interactions between technology adoption and incomplete enforcement have important implications in terms of the deterrent effects of the enforcement policies and in terms of the effect of monitoring effort on the technology adoption rate. It is shown that when taxes are used, the rate of technology adoption is not affected by enforcement strategy. In contrast, when tradable emission permits are used, the rate of adoption is an increasing function of the monitoring probability.

A significant fraction of the literature on environmental regulation has been devoted to studying how environmental policies should be enforced and how they are actually enforced. Empirical studies have shown that a suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement (Gray and Deily 1996; Rousseau 2007). Using a conventional model of non-compliant firms in a setting of uniform taxes, in the second chapter of this thesis, I analyze the effects of a targeted enforcement strategy on the rate of technology adoption and aggregate emission level. The result suggest that, with a targeted enforcement strategy based on adoption status, a regulator might stimulate or slow down the adoption of the new technology through monitoring pressure on both types of firms when firms are non-compliant. The fact that the technology adoption rate is influenced by monitoring strategy is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the tax to be imposed. Such a regulator may use a differentiated monitoring strategy to induce technology adoption and therefore to reduce aggregate emissions for a given politically feasible tax level.

The third chapter of this dissertation analyzes how the interaction between legal, moral and cultural regulation systems determines compliance with tax liabilities in the context of environmental regulations with weak legal enforcement. Most standard models of enforcement and compliance with environmental regulations assume that once a violation is detected, a sanction is successfully imposed. However, in many countries, especially in developing and transitional countries, detected violators are not always sanctioned. Weak institutions for enforcing sanctions due to lack of resources, corruption and/or long, tedious and costly legal procedures are all obstacles of successful compliance (Blackman, 2009). In such a context the probability of being sanctioned does not coincide with the probability of being detected but is instead determined by the joint probability of being monitored and being sanctioned given a detected violation of the law.

Traditional models of enforcement of law assume that the probabilities of detection and sanctioning given detection are perfect substitutes. Therefore, as long as the joint probability of detection and sanctioning is constant, the extent of violations will not change with different combinations of these two probabilities. However, agents' compliance behavior is not only determined by risk preferences and expected costs and benefits from violating, but it is also influenced by aspects such as social norms, morality and legitimacy of the regulation (e.g. Andreoni et al., 1998;Torgler, 2002; Tyler, 2006a). In the third chapter of this thesis we first develop a theoretical model which, in addition to legal costs takes into account moral costs, legitimacy issues and image costs faced by the agent when making compliance decisions. In contrast to the standard model of law enforcement, our theoretical model predicts that varying the probability of detection and the probability of sanction has consequences in term of violations even when the joint probability of detection and sanctioning is kept constant. Second, by using a laboratory experiment, we empirically test the predictions from our theoretical model that different combinations of the probability of detection and the probability of sanction results in different extent of violation even when the joint probability is kept constant.

We ran our experiments with both students and environmental managers of Colombian firms. The results from the sample of managers indicate that we cannot reject the hypothesis that detection and sanctioning probabilities are substitutes. However, the level of violation chosen by environmental managers is lower than the violation predicted by the standard model, indicating that there are determinants of the extent of violations additional to economic incentives. For the sample of students, the chosen level of violation is lower than the predicted violation. When analyzing differences in deterrence effect between different combinations of probabilities, we found that students violate significantly less when facing a high sanctioning given detection probably than when facing a high monitoring probability and low probability of sanctioning.

The fourth chapter of this thesis studies the effect that the design of mechanisms like disclosure has on contributions to public goods. As pointed out by Frey and Jegen

(2001) and Nyborg and Rege (2003), external interventions may enhance intrinsic motivations (crowding in) when the external intervention is perceived by subjects as supportive, or reduce intrinsic motivations (crowding out) when the intervention is perceived by subjects as controlling. In this chapter we investigate whether disclosure, as an external intervention, crowds out contributions to a public good by using an experimental approach, and more specifically, we test the effect of different degrees of disclosure on contribution levels in our public goods experiments. We present evidence indicating that the incentives provided by the three disclosure treatments increase unconditional contributions to the public good compared to the no-disclosure treatment, although the effect is not statistically significant at conventional levels. We find that, when implementing joint in-group and out-group disclosure, the proportion of subjects contributing the whole endowment significantly increases, compared to the no disclosure treatment, while the proportion of non-contributors does not change significantly. Our results also indicate that disclosure policies with larger audiences and more detailed information may induce a higher heterogeneity in cooperation behavior and that unconditional contribution may be moved in various ways. The direction in which unconditional contribution moves with joint disclosure may depend on underlying characteristics of subjects such as the importance they assign to social approval, on the degree of internalization of the norm for cooperation, and in the interpretation they make of the disclosure policy limiting the effectiveness of the policy.

Finally, in the last chapter we investigate cooperative behavior in different social groups by keeping cross- and within-country differences constant. We worked with university students recruited from two universities in Medellin, Colombia, who differed in socio-economic conditions. Our results suggest that different social groups exhibit differences both in terms of composition of types and extent of conditional cooperation. The dominating type is conditional cooperators in both groups. Interestingly, 25 percent of the subjects in the group of high socio-economic group were classified as free riders, compared to 4 percent in the medium-low socio-economic group.

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Chapter 1

On the Interaction Between Imperfect Compliance and Technology Adoption: Taxes vs. Tradable Emissions Permits**

Clara Villegas-Palacio [a,b]
Jessica Coria[a,c]

Abstract

This paper analyzes the effects of the interaction between technology adoption and incomplete enforcement on the extent of violations and the rate of abatement technology adoption. We focus on price-based and quantity-based emission regulations. First, we show that in contrast to uniform taxes, under tradable emissions permits (TEPs), the fall in permit price produced by technology adoption reduces the benefits of violating the environmental regulation at the margin and leads firms to modify their compliance behavior. Moreover, when TEPs are used, the deterrent effect of the monitoring effort is reinforced by the effect that technology adoption has on the extent of violations. Second, we show that the regulator may speed up the diffusion of new technologies by increasing the stringency of the enforcement strategy in the case of TEPs while in the case of uniform taxes, the rate of adoption does not depend on the enforcement parameters.

Key words: technological adoption, environmental policy, imperfect compliance, enforcement.

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[a] Department of Economics. School of Business, Economics and Law. University of Gothenburg. Gothenburg, Sweden. E-mails: Clara.Villegas@economics.gu.se and Jessica.Coria@economics.gu.se
[b] Facultad de Minas. Universidad Nacional de Colombia – Sede Medellín. Medellín, Colombia. E-mail. civillegas@unal.edu.co
[c] Facultad de Economía y Empresa, Universidad Diego Portales, Santiago, Chile.

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1. Introduction

In the long run, technological change is considered the primary solution to environmental problems (Kneese and Schultze 1978), and it has long been recognized that environmental policy creates incentives that affect the process of technological development (Jaffe et al. 2002; Requate 2005). Many scholars have therefore analyzed how alternative policy instruments affect the rate and direction of technological change. Among market-based policies, the analyses tend to support the use of emission taxes (price-based regulation) over tradable emission permits (TEPs) (quantity-based regulation), when the regulator is myopic and does not adjust the level of the policy in response to the advent of new technology.[1] The fact that the emission price is fixed under the tax while it decreases under permits creates a wedge between the two instruments and between the rates of adoption they induce.

Previous analyses of technology adoption under different policies share a common and implicit assumption: *Firms perfectly comply with environmental regulations.* However, reality generally differs from this assumption. In some cases, a fraction of firms do not comply with an environmental regulation and furthermore, the expected enforcement costs can be substantial. The intuition of the interaction between incomplete enforcement and technology adoption can be thought of in two ways: (1) incomplete enforcement, and therefore the possibility that firms do not comply with a regulation, may influence the profits of firms from technology adoption and thus the adoption decision, and (2) the existence of a new technology that reduces the abatement costs may influence a firm's compliance decisions since the marginal benefit of violations is reduced.

The purpose of the present paper is to analyze the interaction between incomplete enforcement and technology adoption under price-based and quantity-based policies. We compare emission taxes and TEPs in terms of: (i) how compliance changes with the use

[1] See Milliman and Prince 1989; Jung, Krutilla, and Boyd 1996; Kennedy and Laplante 1999; Requate and Unold 2001; and Requate and Unold 2003 for comparison of incentives provided by environmental policies.

of new technologies and (ii) how technology adoption is affected by enforcement parameters such as the probability of being monitored.

To our knowledge, the interaction between technology adoption and imperfect compliance and its effects on the comparison between uniform taxes and tradable permits has not yet been directly addressed. Some literature has been devoted to comparing policy instruments when incomplete enforcement is an issue (Montero 2002; Rousseau and Proost 2005; Macho-Stadler 2008), but no previous study considers the interaction between an enforcement policy and technology adoption, which is the objective of the present paper. [2]

To analyze the links between technology adoption and imperfect compliance, we model a competitive industry consisting of a continuum of firms that are subject to environmental regulation that could take the form of either emissions taxes or auctioned tradable permits. Before the arrival of new abatement technology, the firms' abatement costs are homogeneous. When the new technology becomes available, each firm can independently decide to invest or not invest in a new technology that shifts the firm's abatement cost function downwards at the expense of a fixed cost. The adoption decision is made based on the comparison of the expected costs of abatement and compliance under the current and the new technology. For simplicity, we focus on the analysis of interior solutions, i.e., firms provide positive reports of their emissions under taxes and hold a number of permits higher than zero under a scheme of TEPs.

Our results suggest that the interactions between technology adoption and incomplete enforcement have important implications in terms of the deterrence effect of the enforcement policies and in terms of the effect of monitoring effort on the technology adoption rate.

[2] The ranking of priced-based versus quantity-based environmental regulation was first studied by Weitzman (1974), who analyzed the choice between these two types of instruments when there is uncertainty. After Weitzman (1974), the comparison between price- and quantity-based policies has been further developed (Roberts and Spence 1976; Yohe 1978; Finkelshtain and Kislev 1997; Hoel and Karp 2002; Montero 2002; Moledina et al. 2003; Baldursson and von der Fehr 2004; Quirion 2004; Stranlund and Ben-Haim, 2008).

It is shown that when taxes are used, the rate of technology adoption is not affected by enforcement strategy. In contrast, when TEPs are used, the rate of adoption is an increasing function of the monitoring probability. Additionally, under TEPs, for a given monitoring probability, the fall in permit price produced by technology adoption reduces the benefits of violating the environmental regulation at the margin and ultimately leads both adopters and non-adopters to modify their compliance behavior. This is not the case under emissions taxes where the tax rate remains unchanged after technology adoption. Thus, in contrast to taxes, the extent of violations under TEPs decreases with the rate of adoption. Moreover, when TEPs are used, the deterrent effect of the monitoring effort is reinforced by the effect that technology adoption has on the extent of violations. These results constitute good news for a regulator who, by choosing TEPs, may be able to obtain a higher reduction in the extent of violation due to the availability of new technologies. Also, the regulator may be able to use monitoring effort as a tool influence the diffusion of new abatement technologies.

The paper is organized as follows. Section II presents the model of adoption, and Section III introduces the compliance analysis under emission taxes and TEPs. Section IV explores the way in which the rate of technology adoption is affected by the enforcement strategy under both policy instruments, and how the influence of monitoring probability on technology adoption reinforces the effect of the former on the extent of violations under TEPs. Finally, Section V offers a discussion of the policy implications of our results and concludes the paper.

2. The model

We consider a competitive industry consisting of a continuum of firms $\Lambda \subset [0,1]$ that are risk-neutral. In the absence of environmental regulation, each firm emits a quantity e_0 of a homogeneous pollutant. We assume there is an environmental authority that sets an environmental target – a maximum level of emissions – and then chooses a policy instrument to reach this target. Since the regulator cannot observe firms' emissions, costly monitoring is undertaken. In our model, the regulator has a fixed monitoring budget given by *B*, and the cost of an audit to a firm is given by *w*. The ratio between the number of possible audits given the regulator's budget ($\frac{B}{w}$) and the size of the continuum of firms defines the probability of being monitored, π, which is known by firms. Once the regulator monitors a firm, it is able to perfectly determine the firm's compliance status. If the monitoring reveals that the firm is non-compliant, it faces the penalty $F(v)$, where v represents the extent of the violation. This is a strictly convex function of the extent of violation: $F'(v) > 0; F''(0)$.[3] For zero violation, the penalty is zero *F(0)=0*, but the marginal penalty is greater than zero: *F'(0)>0*.

Firms can reduce emissions through the current abatement technology. As Requate and Unold (2003), we assume that initially all firms are alike in abatement costs, $c(e)$. We assume that $c(e)$ is strictly convex and decreasing in emissions: $c'(e) < 0; c''(e) > 0$. A new and more efficient technology arrives and firms must decide whether or not to invest in it. The new technology allows firms to abate emissions at a lower cost, given by $\theta c(e)$, where $\theta \in (0,1)$ is a parameter that represents the drop in abatement cost due to adoption of the new technology. As in Requate and Unold (2003), technology adoption implies a lower marginal abatement cost curve $-c'(e) > -\theta c'(e) \text{ for all } e < e_0$.[4]

[3] Stranlund et al. 2009 mention some authors who assume that the penalty function is strictly convex: Harford 1978, 1987; Sandmo 2002; and Macho-Stadler and Perez Castrillo 2006. Stanlund et al. 2009 assume a linear penalty function in their model, an assumption that is not common in the literature. If the probability of being monitored is exogenous and the marginal penalty is constant, the decision on reporting emissions will be of the type reporting everything or reporting nothing (see Sandmo 2002 and Heyes 2000).

[4] To keep the analysis mathematically tractable and simple, we assume that firms are homogeneous in terms of current abatement costs. Nevertheless, our results still hold in the case of heterogeneous abatement. For example, following Coria 2009, we could have assumed that firms' current abatement costs are heterogeneous and that firms can be ordered according to their adoption savings from the firm with the highest to the firm with the lowest current abatement cost. Therefore, the arbitrage condition that states that the adoption savings for the marginal adopter offset the adoption costs still holds. In such a setting, and as is shown later, adopters will increase their abatement effort due to the availability of the new technology and will reduce their demands for emissions.

We assume that buying and installing the new technology implies a fixed cost that differs among firms.[5] Let k_i denote the fixed cost of adoption for firm i, where k_i is uniformly distributed on the interval $(\underline{k}, \bar{k})$. Let μ_{NAi} and μ_{Ai} be firm i's total expected costs of abatement and compliance when using the current abatement technology (non-adoption) and new technology (adoption), respectively, such that the expected cost saving from adopting is $\mu_{NAi} - \mu_{Ai}$. Any firm whose expected cost saving offsets its adoption cost will adopt the new technology[6]. In the continuum of firms $\Lambda \subset [0,1]$, the marginal adopter is then identified by the arbitrage condition $\tilde{k}_i = \mu_{NAi} - \mu_{Ai}$. Hence, following Coria (2009b), the rate of firms $\lambda \in [0,1]$ adopting the new technology is defined by the integral

(1) $$\lambda = \int_{\underline{k}}^{\tilde{k}_i} f(k_i)dk = F(\tilde{k}_i) = F(\mu_{NAi} - \mu_{Ai}) = \frac{\mu_{NAi} - \mu_{Ai} - \underline{k}}{\bar{k} - \underline{k}} = \psi(\mu_{NAi} - \mu_{Ai}) - \zeta \in (0,1)$$

where the right-hand side follows from the definition of the uniform cumulative distribution of $k_i \sim U(\underline{k}, \bar{k})$, $\psi = \frac{1}{\bar{k} - \underline{k}}$ and $\zeta = \psi \underline{k}$.

From equation (1), it is straightforward that the adoption rate depends on the total expected savings in the costs of abatement and compliance, which are endogenous to the choice of policy instrument, the stringency of the environmental policy, and the enforcement policy.

[5] The assumption that adoption costs differ among firms is not new in the literature analyzing the effects of the choice of policy instruments on the rate of adoption of new technologies. See, e.g., Requate and Unold (2001). On the other hand, Stoneman and Ireland (1983) point out that although the majority of the theoretical and empirical literature on technological adoption concentrates on the demand side alone, supply-side forces might be very important for explaining patterns of adoption in practice. Thus, for example, costs of acquiring new technology might vary among firms according to firm characteristics, e.g., location or output, or because of competition among suppliers of capital goods.

[6] We assume that firms minimize their costs for any level of output, but do not treat the output decision explicitly.

In the next section, we analyze the firms' compliance behavior when environmental regulation takes the form of a uniform emission tax or TEPs. It is sufficient to keep track of the marginal adopter's optimal choices of emissions and report in order to derive the rate of adoption; therefore the subscript i is hereinafter omitted.

3. Compliance behavior and technological adoption

In a uniform emission tax system, firms are required to self-report their emissions. A firm is non-compliant if it attempts to evade some part of its tax responsibilities by reporting an emission level that is lower than the true level. In the case of a regulation using permits, a firm should hold one permit for each unit of emissions. A firm that in equilibrium holds fewer permits than its emissions is a non-compliant firm.

The interaction between the regulator and firms is described by the following two-stage mechanism:

Stage 1. The regulator sets the environmental target before the arrival of the new technology and chooses a policy instrument to reach it. We assume that the regulator does not modify the level of the environmental policy in response to the availability of the new technology. The enforcement strategy is exogenously determined and consists of a probability of being monitored and a sanctioning scheme. The enforcement strategy is set regardless of the regulatory scheme selected by the environmental authority; i.e., firms face the same enforcement policy regardless of policy instrument. This assumption does not contradict reality since, in many cases, the institutional arrangements separate the design of the regulatory instrument from the design of enforcement strategies.

Stage 2. Firms make compliance and adoption decisions. The adoption decision is made based on the comparison of the expected costs of abatement and compliance under the current and the new technology.

Let us now analyze the extent of violation of both adopter and non-adopter firms when regulated by either uniform emission taxes or TEPs.

Uniform Emission Tax

Let us assume that firms must pay a uniform tax t per unit of pollutant emitted and that they self-report their emissions. If a firm reports truthfully, the total amount of taxes to be paid is te. Since there is incomplete enforcement, the firm could try to evade a fraction of its tax payment by reporting a lower level of emissions. If the firm reports emissions equal to r, where $r < e$, then the total tax payment is given by tr. In this case, the firm's violation equals the difference between the actual emissions and reported emissions, $v_i = e_i - r_i$. If the firm is caught in violation, a penalty is imposed according to the penalty function explained above.

Adopters select the emissions and report levels that minimize their expected costs of abatement and compliance:[7]

(2) $$Min_{e,r}\,\theta c(e) + tr + \pi F(e-r), \quad \text{s.}t.\ e - r \geq 0.$$

Note that the constraint in the optimization problem reflects the fact that there are no economic incentives to over-report emission levels.[8] Solving this minimization problem, *if the solution is interior*, a firm's choice of emission is given by $\theta c'(e) + t = 0$. Each firm chooses its emission levels such that the marginal abatement cost equals the tax rate. The emission levels for adopters and non-adopters are, respectively,

(3) $$e_A(t) = \left\{ e \middle| \theta c'(e) + t = 0 \right\}; \quad e_{NA}(t) = \left\{ e \middle| c'(e) + t = 0 \right\}.$$

Since there is a uniform tax rate, in equilibrium firms' marginal abatement costs are equal irrespective of their adoption status: $c'(e_{NA}) = \theta c'(e_A)$. Since $\theta \in (0,1)$, it is necessary that $c'(e_{NA}) < c'(e_A)$, which is only possible, given the properties of the abatement cost function, if $e_{NA} > e_A$. Therefore, adopters' actual levels of emissions are reduced due to the availability of the new technology and - in this setting- are lower than

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[7] The problem of the firms that do not adopt the new abatement technology is analogous to problem (2); the main difference is that the abatement costs for these kinds of firms are given by $c(e)$ instead of $\theta c(e)$.

[8] We have omitted the calculations of the optimization problem (available upon request).

those of non-adopters.[9] In addition, in line with previous literature analyzing the compliance behavior of firms under imperfectly enforceable taxes, we find that since the tax is exogenous and not influenced by the enforcement strategy, firms' actual emissions do not depend on the parameters of the enforcement problem (e.g., Harford 1978). However, this result only holds when the monitoring probability is high enough to guarantee more than zero reported emissions. When firms report zero emissions, the level of emissions is decreasing in monitoring probability (see Macho-Stadler and Pérez-Castrillo 2006 for detailed analyses of corner solutions).

Let us now look at a firm's emission report and extent of violation. When the firm is noncompliant, then $e-r>0$, which from the Kuhn Tucker conditions for (2) implies that $t-\pi F'(e-r)=0$. The report levels of adopter and non-adopter firms are, respectively,

(4) $$r_A(t,\pi,F)=\left\{r\middle|t-\pi F'(e_A-r_A)=0\right\};\ r_{NA}(t,\pi,F)=\left\{r\middle|t-\pi F'(e_{NA}-r_{NA})=0\right\}.$$

The equations in (4) state that firms choose to report a level of emissions such that the marginal expected fine equals the marginal benefit of non-compliance, i.e., the tax. Combining both equations, we obtain $e_A-r_A=e_{NA}-r_{NA}$. Note that $r_{NA}>r_A$ since $e_{NA}>e_A$. Hence, the emissions reported by adopters are lower than those reported by non-adopters. Working on comparative statics, it is possible to show that the report levels of adopter and non-adopter firms are decreasing in the tax rate and increasing in the monitoring probability (see proof in Appendix A). This result is in line with previous findings in the literature on TEPs (see Stranlund and Dhanda 1999).

Proposition 1: *With uniform taxes, the extent of violation of firms is independent of the adoption status and is therefore the same for adopters and non-adopters of the new technology.*

[9] The fact that adopters' emissions are lower than non-adopters emissions is mainly due to the new technology being the most efficient alternative available. Indeed, adoption shifts every firm's abatement cost function downwards at the expense of a fixed cost. The introduction of some heterogeneity in the current abatement costs might imply that some firms do not obtain significant savings from adopting. However, it might still imply a lower level of emissions by non-adopters if no current technology is more efficient than the new one.

Proof 1: The extent of a violation is given by $v(t,\pi,F) = e(t) - r(t,\pi,F)$. From equation (4), we obtain that $\pi F'(e_A - r_A) = \pi F'(e_{NA} - r_{NA})$, and since the enforcement strategy is exogenously set and independent of the adoption status, it is straightforward to observe that $e_A - r_A = e_{NA} - r_{NA}$. Q.E.D.

The intuition behind this result is as follows. On one hand, since the enforcement strategy does not depend on adoption status, the expected marginal cost of evasion does not change with adoption. On the other hand, the marginal benefit of violation does not depend on adoption status either, since it is given by the unit tax rate. Therefore, given that the marginal benefits and expected marginal costs of disobeying the law are the same for all firms, the extent of the violation is the same regardless of adoption status.

Tradable Emissions Permits

A firm regulated by TEPs can abate a fraction of its emissions and buy permits to compensate for the remaining fraction. The equilibrium price of each permit is represented by p, and a firm that emits e should spend pe on buying permits. Assume that the authority issues L emission permits each period and that the possession of a permit gives the legal right to emit one unit of pollutant. In the presence of imperfect compliance, polluters have an incentive to hold in equilibrium a quantity of permits lower than e to reduce their expenditure on permits. Let l denote the quantity of permits held by a firm in equilibrium and l^0 be the number of emissions permits initially allocated to it. A firm is non-compliant if after trade it holds a number of permits that is lower than its corresponding units of emissions. The extent of violation is then given by $v = e - l$. We assume that the enforcement authority keeps perfect track of each firm's permit holding.[10] Adopters select the emission level and demand for permits that minimize total expected costs:

[10] Assume, for instance, that all transactions performed in the market have to be registered with the authority. Since the authority has information about initial allocation, it is able to have perfect information about each firm's permit holding at any point in time.

(5) $\quad Min_{e,l}\, \theta c(e) + p\left[l - l^0\right] + \pi F(e-l)$, $\quad$ s.t. $\; e - l \geq 0$.

From the solution to the optimization problem, if the solution is interior, the emissions levels for adopters and non-adopters are, respectively,

(6) $\quad e_A(p) = \left\{ e \middle| \theta c'(e) + p = 0 \right\}$; $\; e_{NA}(p) = \left\{ e \middle| c'(e) + p = 0 \right\}$.

The equations in (6) state that in equilibrium each firm chooses its emissions such that the marginal abatement cost equals the equilibrium permit price, which is the same for all firms regardless of adoption status. Since the adopters' marginal abatement cost is lower than that of the non-adopters, $e_{NA}(p) > e_A(p)$. The number of permits held by adopters and non-adopters is, respectively,

(7) $\quad l_A(p,\pi,F) = \left\{ l \middle| p - \pi F'(e_A - l_A) = 0 \right\}$, $\; l_{NA}(p,\pi,F) = \left\{ l \middle| p - \pi F'(e_{NA} - l_{NA}) = 0 \right\}$.

The equations in (7) show that in equilibrium, firms hold a quantity of permits such that the marginal expected fine equals the marginal benefit of non-compliance, i.e., the equilibrium permit price. Since the permit price and the enforcement strategies faced by adopters and non-adopters are the same, we obtain that $e_A - l_A = e_{NA} - l_{NA}$. Given that $e_{NA} > e_A$, it follows that $l_{NA} > l_A$ for the equality to hold. Therefore, with TEPs, the actual emissions and the quantity of permits that firms hold in equilibrium are reduced following adoption and are lower than the actual emissions and the quantity of permits held by non-adopters in equilibrium.[11]

Proposition 2*: With TEPs, a firm's extent of violation is independent of its adoption status and is therefore the same for adopters and non-adopters of the new technology. However, for a given monitoring probability, the extent of violation is decreasing in the rate of adoption.*

[11] Analogous to the tax case, the introduction of some heterogeneity in current abatement costs might imply that adopters hold more permits than non-adopters if the new technology is not more efficient than all the current technologies available. However, the main results in this section remain the same since both adopters and non-adopters improve their compliance behavior due to the drop in equilibrium permit price given the availability of a new technology.

Proof 2: The extent of violation of a firm is determined by the arbitrage condition $\pi F'(v) = p$. Since the equilibrium permit price and the enforcement strategies faced by adopters and non-adopters are the same, we obtain that the extent of violation is the same regardless of adoption status, $e_A - l_A = e_{NA} - l_{NA}$. The fact that changes in abatement cost parameters do not affect the extent of violation as long as the enforcement strategy and the permit price remain the same is well known in the literature (see, e.g., Stranlund and Dhanda 1999 and Chávez et al. 2009). However, the adoption rate affects the extent of violation of adopters and non-adopters via the equilibrium permit price and hence the extent of the violation of adopters and non-adopters: $\frac{\partial v}{\partial \lambda} = \frac{\partial v}{\partial P}\frac{\partial P}{\partial \lambda}$.

Violations are an increasing function of permit price, $\frac{\partial v}{\partial P} > 0$ [12]. The sign of $\frac{\partial v}{\partial \lambda}$ therefore depends on the sign of $\frac{\partial P}{\partial \lambda}$. To determine the influence of the adoption rate on the equilibrium permit price $\frac{\partial P}{\partial \lambda}$, consider the market equilibrium equation. The permit price that clears the market is given by the equilibrium between supply and total demand for permits:

(8) $$L = \lambda l_A(p(\lambda,\pi)) + [1-\lambda] l_{NA}(p(\lambda,\pi)).$$

Taking the total derivative of equation (8) with respect to the technology adoption rate – and given that the supply of permits is fixed – we observe in equation (9) that an increase in λ reduces the equilibrium permit price due to the fact that adoption decreases adopters' demand for permits and consequently the aggregate demand in $-[l_A - l_{NA}]$. This reduction in aggregate demand pushes the permit price down.

[12] Taking the total derivative of $P = \pi F'(v)$ with respect to price, it is easy to derive $\frac{\partial v}{\partial P} = \frac{1}{\pi F''(v)}$, which, given the properties of the penalty function, is positive (see Stranlund and Dhanda 1999).

$$(9) \qquad \frac{\partial P}{\partial \lambda} = \frac{-\left[l_A - l_{NA}\right]}{\left[\lambda \frac{\partial l_A}{\partial P} + (1-\lambda)\frac{\partial l_{NA}}{\partial P}\right]} < 0.$$

Given that the permit price decreases with the rate of technology adoption ($\frac{\partial P}{\partial \lambda} < 0$) and that a drop in permit price implies a reduction in the extent of violations, it follows that *for a given monitoring probability*, violations are decreasing in the rate of adoption. Q.E.D

Therefore, technology adoption does provide incentives to improve compliance when firms are regulated by TEPs. This is an important difference between uniform taxes and TEPs, which relates to the assumption that the regulator does not respond to the advent of a new technology by changing the level of the environmental policies or the enforcement strategy. If the regulator instead adjusts the level of the tax and the cap on emissions before adoption takes place, the adoption incentives provided by the policies will coincide (Requate and Unold 2003; Coria 2009), as will the compliance incentives.

Note from equation (8) that the equilibrium permit price is linked not only to the adoption rate but also to the monitoring probability, π. Changes in the monitoring effort might therefore affect the rate of technology adoption and hence the extent of violation.

4. Monitoring probability and effects on technology adoption

As stated in the beginning of the present paper, the rate of adoption is determined by the difference between the expected costs of abatement and compliance under the current and the new technology. For the case of uniform taxes, these costs are expressed as:

$$(10) \qquad \mu_A(t,\pi,F) = \theta c(e_A(t)) + tr_A(t,\pi,F) + \pi F(e_A(t) - r_A(t,\pi,F)),$$

$$(11) \qquad \mu_{NA}(t,\pi,F) = c(e_{NA}(t)) + tr_{NA}(t,\pi,F) + \pi F(e_{NA}(t) - r_{NA}(t,\pi,F)).$$

***Proposition 3**: When uniform emission taxes are used, the adoption rate does not depend on the enforcement strategy but is determined only by the tax rate.*

Proof 3: Subtracting (10) from (11) and considering that $r_{NA} - r_A = e_{NA} - e_A$, the adoption rate can be characterized as follows:

(12) $$\lambda^{TAX} = \psi\{c(e_{NA}(t)) - \theta c(e_A(t)) + t[e_{NA}(t) - e_A(t)]\} - \zeta.$$

The term $c(e_{NA}(t)) - \theta c(e_A(t))$ in (12) gives account of the decrease in abatement costs when the firm adopts the new technology, and $t[e_{NA}(t) - e_A(t)]$ gives account of the difference in tax payment on reported emissions without and with adoption. From equation (12), it is straightforward that adoption savings are increasing in the tax rate but are not affected by monitoring probability or sanction structure. The enforcement strategy therefore does not affect the rate of adoption, since neither the emissions level nor the tax rate is a function of monitoring probability or of the sanction structure. Q.E.D

Analogously to the case of taxes, the rate of adoption in the case of TEPs is determined by the difference between the expected costs of abatement and compliance under the current and the new technology.

(13) $$\begin{gathered}\mu_A(p(\pi,\lambda),\pi) = \theta c(e_A(p(\pi,\lambda))) + p(\pi,\lambda) l_A(p(\pi,\lambda),\pi) + \\ \pi F(e_A(p(\pi,\lambda)) - l_A(p(\pi,\lambda),\pi))\end{gathered},$$

(14) $$\begin{gathered}\mu_{NA}(p(\pi,\lambda),\pi) = c(e_{NA}(p(\pi,\lambda))) + p(\pi,\lambda) l_{NA}(p(\pi,\lambda),\pi) + \\ \pi F(e_{NA}(p(\pi,\lambda)) - l_{NA}(p(\pi,\lambda),\pi))\end{gathered}.$$

Proposition 4*: When tradable emissions permits are used, the adoption rate is an increasing function of the monitoring probability.*

Proof 4: Subtracting (13) from (14), the adoption rate can be characterized as follows:

$$(15)\qquad \lambda^{TEP} = \psi \left\{ \begin{array}{l} c(e_{NA}(p(\pi,\lambda^{TEP}))) - \theta c(e_A(p(\pi,\lambda^{TEP}))) + \\ p(\pi,\lambda^{TEP})\left[l_{NA}(p(\pi,\lambda^{TEP}),\pi) - l_A(p(\pi,\lambda^{TEP}),\pi) \right] \end{array} \right\} - \zeta .$$

The terms in equation (15) give account of the decrease in abatement costs and the difference in expenditure on permits when the firm adopts the new technology.

Since the permit price and the demand for permits by firms with and without the new technology are increasing functions of the monitoring probability, the rate of technology adoption depends on this parameter as well. However, given that the equilibrium permit price is, at the same time, a function of the rate of technology adoption, $P(\pi,\lambda^{TEP})$ and $\lambda^{TEP}(\pi,P)$ are therefore endogenous variables simultaneously determined in our model by equations (8) and (15).

Formally, by taking the total derivative of equation (15) with respect to monitoring probability, we observe that the monitoring probability affects the adoption savings and hence the rate of adoption through two channels. First, it increases the demand for permits with and without the new technology. We call this the “direct effect.” Second, it changes the equilibrium permit price and therefore affects the components of the adoption savings function (i.e., abatement costs and expenditures on permits). We call this the “price effect.” These two effects are shown in equation (16).

(16)

$$\frac{1}{\psi}\frac{d\lambda^{TEP}}{d\pi} = \underbrace{P\left[\frac{\partial l_{NA}}{\partial \pi} - \frac{\partial l_A}{\partial \pi}\right]}_{\text{Direct Effect}} + \underbrace{\begin{array}{l} \frac{dP}{d\pi}\left\{c'_{NA}\frac{\partial e_{NA}}{\partial P} - \theta c'_A\frac{\partial e_A}{\partial P} + \left[l_{NA} - l_A\right] + P\left[\frac{\partial l_{NA}}{\partial P} - \frac{\partial l_A}{\partial P}\right]\right\} + \\ \frac{dP}{d\lambda}\frac{d\lambda^{TEP}}{d\pi}\left\{c'_{NA}\frac{\partial e_{NA}}{\partial P} - \theta c'_A\frac{\partial e_A}{\partial P} + P\frac{\partial l_{NA}}{\partial P} - P\frac{\partial l_A}{\partial P} + \left[l_{NA} - l_A\right]\right\} \end{array}}_{\text{Price Effect}}$$

Since in equilibrium, an increase in the monitoring probability affects the demand for permits with and without the new technology to the same extent, i.e., $\frac{\partial l_{NA}}{\partial \pi} = \frac{\partial l_A}{\partial \pi}$, the direct effect is equal to zero. Additionally, the price effect in equation (16) can be simplified considering that $c'_{NA} = \theta c'_A = -P$ and that the change in the extent of violation as a response to changes in the permit price is the same with and without the new technology, i.e., $\frac{\partial e_A}{\partial P} - \frac{\partial l_A}{\partial P} = \frac{\partial e_{NA}}{\partial P} - \frac{\partial l_{NA}}{\partial P}$ (see Appendix B). Therefore, equation (16) can be re-written as:

(17) $$\frac{d\lambda^{TEP}}{d\pi}\left[\frac{1}{\psi} - \left[l_{NA} - l_A\right]\frac{dP}{d\lambda}\right] = \frac{dP}{d\pi}\left[l_{NA} - l_A\right].$$

Since the equilibrium permit price is an increasing function of the monitoring probability (see Appendix C) and a decreasing function of the rate of technology adoption, and given that a firm that adopts the new technology reduces the number of permits it holds in equilibrium, it follows that the rate of technology adoption is an increasing function of the monitoring probability. Q.E.D

If the regulator increases the stringency of the monitoring strategy, and by doing so increases the equilibrium permit price, firms that adopt the new technology enjoy larger savings due to the reduction in the use of permits.[13]

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[13] It is worth mentioning that although we have assumed that firms are homogeneous in terms of current abatement costs, such an assumption could be removed without affecting the validity of our

Propositions 3 and 4 demonstrate another important difference between taxes and TEPs. In contrast to uniform taxes, the rate of technology adoption is an increasing function of monitoring probability when the regulation takes the form of TEPs. This result has interesting implications for the comparison of the adoption incentives provided by these two policy instruments. Indeed, it is well known in the literature that adoption of advanced abatement technologies depreciates the permit prices while the tax is fixed by the regulator. Since firms with higher costs of adoption can free ride on the decreased permit price caused by other firms' adoption, the private gains from adopting the technology under permits are reduced and so is the rate of adoption. However, the results in this section show that by increasing the monitoring probability, the regulator can offset the permit price depreciation while encouraging firms to reduce the extent of violation. Therefore, under permits, a more stringent enforcement strategy may increase the rate of adoption of new technology while still providing firms with larger incentives to increase compliance than taxes. This is good news for the regulators since by choosing TEPs, the continuous adoption of cleaner technologies may imply a larger rate of compliance with environmental regulations.

Monitoring probability and the extent of violation under TEPs

Clearly, the extent of violation also changes in response to increased monitoring probability. However, since in this setting the equilibrium permit price and the rate of

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results. Indeed, let us assume for a moment that there are two groups of firms (group 1 and group 2) that differ in terms of current abatement costs ($c_1(e)$ and $c_2(e)$) and that adoption is profitable only for firms in group 1 ($c_1(e) > \theta c_1(e) > c_2(e)$; $\mu_{NA1} - \mu_{A1} \geq k_1$, $\mu_{NA2} - \mu_{A2} < k_2$). In such a setting, firms in group 1 (adopters) will hold more permits than firms in group 2 (non-adopters) in equilibrium, i.e., $l_{A1} > l_{NA2}$ However, Proposition 4 remains valid since the second term on the right-hand side in equation (17) is giving account of the reduced demand of permits by firms adopting the new technology. Since the new technology allows firms in group 1 to abate emissions to a lower cost, the use of permits by firms in group 1 decreases after adopting the new technology, i.e., $l_{NA1} > l_{A1}$.

adoption are endogenous, the monitoring probability affects the extent of the violation through several channels, as is clear in equation (18). Taking the total derivative of $v(\pi, P(\pi, \lambda^{TEP}))$ with respect to π yields:

$$(18) \qquad \frac{dv}{d\pi} = \frac{\partial v}{\partial \pi} + \frac{\partial v}{\partial P}\frac{\partial P}{\partial \pi} + \frac{\partial v}{\partial P}\frac{\partial P}{\partial \lambda^{TEP}}\frac{\partial \lambda^{TEP}}{\partial \pi}$$

Firstly, there is a direct effect that pushes the extent of violation down given that the expected cost of infringing the regulation increases $\frac{\partial v}{\partial \pi} < 0$. Secondly, there is an indirect effect through the permit price that increases the extent of violation: when the monitoring probability increases, so does the price of permits, increasing the marginal benefit of violation, $\frac{\partial v}{\partial P}\frac{\partial P}{\partial \pi} > 0$. Thirdly, there is an indirect effect through the adoption rate and the permit price. Increasing the monitoring probability leads to a higher adoption rate, which at the same time lowers the permit price, causing a decrease in the extent of violation, $\frac{\partial v}{\partial P}\frac{\partial P}{\partial \lambda^{TEP}}\frac{\partial \lambda^{TEP}}{\partial \pi} < 0$.

All the effects are negative except the indirect effect through the permit price. However, its size is lower than the absolute value of the direct effect $\left|\frac{\partial v}{\partial \pi}\right| > \left|\frac{\partial v}{\partial P}\frac{\partial P}{\partial \pi}\right|$ (see Appendix D for a demonstration). Murphy and Stranlund (2006) refer to the first two effects as the direct and the market effects. They conducted laboratory experiments to examine the two effects on pollution and compliance decisions, and their experimental data is consistent with the theoretical prediction that the direct effect is always larger, hence increased enforcement results in a lower extent of violations.

Therefore, the violation extent is decreasing in monitoring probability. Although this is a standard result in the literature, our analysis uncovers the fact that the deterrent effect of the monitoring effort is reinforced by the effect of the technology adoption rate on the extent of violations.

5. Conclusions

In this paper, we analyze the effects of the interaction between incomplete enforcement and technology adoption under each of two alternative policy instruments: uniform taxes and tradable emissions permits (TEPs). Our model is simple in many ways. We assume that firms are homogeneous in terms of current abatement costs and focus on the analysis of interior solutions, i.e., firms provide positive reports of their emissions under taxes and hold a number of permits that is higher than zeroIn particular, we show three main results:

First, compliance incentives are affected by the technology adoption rate under TEPs but not under taxes. As is already well known from the technology adoption literature, in our model the adoption of advanced abatement technologies depreciates the price of emission under TEPs while it is fixed by the regulator under uniform taxes. Given that the equilibrium price of emissions represents the marginal benefits from adoption, such benefits are affected by the rate of technology adoption only under TEPs. The greater the rate of technology adoption, the lower the equilibrium permit price, and therefore the lower the marginal benefits of violation. This of course alters the compliance incentives under TEPs in the presence of technology adoption, leading to a reduction in individual violations under TEPs. In contrast, under uniform taxes, the incentive to comply remains the same as in the absence of technology adoption since the emissions price is set by the regulator and is not depreciated by the technology adoption. Therefore, the expected enforcement costs necessary to achieve compliance under TEPs are lower under TEPs than under taxes.

Second, the adoption rate under taxes is not influenced by the enforcement strategy while the adoption rate under TEPs is an increasing function of monitoring probability. This is, again, related to the fact that the pollution price does not change under an emissions tax while under TPEs an increased monitoring pressure results in a higher permit price. When the permit price increases, the savings from adoption are higher and therefore the rate of technology adoption increases. This means that if under TEPs the regulator wants to stimulate use of a new abatement technology, he/she may use the monitoring probability as a tool. This decision of course depends on the benefits of increasing adoption versus the costs of increasing monitoring pressure.

Third, our paper shows that the extent of violation is decreasing in monitoring pressure. Although this is a standard result in the literature, our analysis reveals that the interaction between monitoring probability and rate of technology adoption is reinforced by the effect that the technology adoption rate has on the extent of violations. Previous literature has not explored this reinforcement effect. This is good news for an enforcement regulator who can achieve a higher reduction in the extent of violation with an increase in enforcement monitoring in the presence of technology adoption than in the absence of technology adoption. This lowers the enforcement costs of achieving a certain compliance level.

Although our paper shows several differences between uniform taxes and TEPs when technological adoption and imperfect compliance are present, the social welfare obtained with each policy instrument is not unambiguous. The ranking of the two instruments will depend on the relative weight given to emission damages compared to elements such as abatement costs, investment costs and expected enforcement costs. Furthermore, there are some other aspects that in practice do affect the welfare comparison but that are outside the present analysis, e.g., differences in distributional consequences and differences in political acceptance of the instruments. For example, the stringency of the tax and the TEP system is subject to a complicated political economy process. The regulator may know that permit prices will fall during the course of a TEPs program. He/she may therefore make the TEP scheme tougher than he/she would with a tax scheme, as a counteracting measure.

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APPENDIX A.

Comparative statics for emission level and report level under uniform taxes:

- **Emission level:**

We know that the emission level of adopters of the new abatement technology is determined by the condition $\theta c'(e)+t=0$. Take the total derivative with respect to the tax rate to obtain $\frac{dt}{dt}=-\theta c''(e)\frac{de}{dt}$. Solving for $\frac{de}{dt}$ we get $\frac{de}{dt}=\frac{-1}{\theta c''(e)}$, which, given the properties of the marginal abatement function, is negative; emissions are therefore decreasing in the tax rate. The analysis for non-adopters of the new technology is analogous.

- **Report level:**

We know that the report level of adopters of the new abatement technology is determined by the condition $t=\pi F'(e_A-r_A)$. Take the total derivative with respect to the monitoring probability to obtain $\frac{dt}{d\pi}=F'(e_A-r_A)-\frac{dr_A}{d\pi}\pi F''(e_A-r_A)$. Solving for $\frac{dr_A}{d\pi}$ we get $\frac{dr_A}{d\pi}=\frac{F'(e_A-r_A)}{\pi F''(e_A-r_A)}$, which, given the properties of the penalty function, is positive. The report level of adopters is therefore increasing in monitoring probability. The analysis for non-adopters of the new technology is analogous.

APPENDIX B

Effect of monitoring probability on rate of technology adoption under TEPs

Equation (16) can be written as:

$$\frac{1}{\psi}\frac{d\lambda^{TEP}}{d\pi} = P\left[\frac{\partial l_{NA}}{\partial \pi} - \frac{\partial l_A}{\partial \pi}\right] + \frac{dP}{d\pi}\left\{ - P\left[\frac{\partial e_{NA}}{\partial P} - \frac{\partial e_A}{\partial P} - \frac{\partial l_{NA}}{\partial P} + \frac{\partial l_A}{\partial P}\right]\right\} +$$
$$\frac{dP}{d\lambda}\frac{d\lambda^{TEP}}{d\pi}\left\{ P\left[\frac{\partial e_{NA}}{\partial P} - \frac{\partial e_A}{\partial P} - \frac{\partial l_{NA}}{\partial P} + \frac{\partial l_A}{\partial P}\right]\right\} + \left[l_{NA} - l_A\right]\left[\frac{\partial P}{\partial \pi} + \frac{\partial P}{\partial \lambda}\frac{\partial \lambda}{\partial \pi}\right].$$

Equation (16) can be simplified in the following way: Taking the partial derivative of the equilibrium condition $\pi F'(e_A - l_A) = \pi F'(e_{NA} - l_{NA})$ with respect to monitoring probability and rearranging terms, it is possible to show that the change in permit demand as a response to a changed monitoring probability is the same for adopters and non-adopters: $\frac{\partial l_A}{\partial \pi} = \frac{\partial l_{NA}}{\partial \pi}$. Therefore, the direct effect on permit demand cancels out.

Taking the partial derivative of $\pi F'(e_A - l_A) = \pi F'(e_{NA} - l_{NA})$ with respect to permit price, considering that $\frac{\partial c(e_{NA})}{\partial e_{NA}} = \theta \frac{\partial c(e_{NA})}{\partial e_{NA}} = P$, and rearranging terms, it is possible to show that the change in the extent of violation in response to a change in the equilibrium permit price is the same for adopters and non-adopters: $\frac{\partial v_{NA}}{\partial P} = \frac{\partial v_A}{\partial P}$. This can be expressed as $\frac{\partial e_A}{\partial P} - \frac{\partial e_{NA}}{\partial P} = \frac{\partial l_A}{\partial P} - \frac{\partial l_{NA}}{\partial P}$.

Replacing and rearranging, equation (16) becomes:

$$\frac{d\lambda^{TEP}}{d\pi}\left[\frac{1}{\psi} - \left[l_{NA} - l_A\right]\frac{dP}{d\lambda}\right] = \frac{dP}{d\pi}\left[l_{NA} - l_A\right].$$

APPENDIX C

Total effect of monitoring probability on equilibrium permit price

The permit price that clears the market is given by the equilibrium between supply and total permit demand:

$$L = \lambda(p(\pi))l_A(p(\pi),\pi) + [1-\lambda(p(\pi))]l_{NA}(p(\pi),\pi).$$

Taking the total derivative of the market equilibrium equation with respect to monitoring probability and rearranging terms yields:

$$0 = \underbrace{\left[\lambda\frac{\partial l_A}{\partial \pi} + [1-\lambda]\frac{\partial l_{NA}}{\partial \pi}\right]}_{\text{Direct Effect}} + \underbrace{\left[\lambda\frac{\partial l_A}{\partial P} + [1-\lambda]\frac{\partial l_{NA}}{\partial P}\right]\frac{dP}{d\pi}}_{\text{Indirect Demand Effect}} + \underbrace{\left[l_A - l_{NA}\right]\left[\frac{\partial \lambda}{\partial P}\frac{dP}{d\pi}\right]}_{\text{Indirect Adoption Effect}}.$$

Monitoring probability influences total permit demand via three channels.

(i) **The direct effect (DE)**, which shows how the permit demand of both adopters and non-adopters is directly affected by changes in the monitoring probability,

(ii) **The indirect demand effect (IDE)**, which reflects the influence of monitoring probability on the permit demand of adopters and non-adopters via permit price, and

(iii) **The indirect adoption effect (IAE)**, which indicates how the permit demand changes due to the influence of monitoring probability on the permit price and consequently on the adoption rate. Rewriting:

$$0 = \underbrace{\left[\lambda\frac{\partial l_A}{\partial \pi} + [1-\lambda]\frac{\partial l_{NA}}{\partial \pi}\right]}_{\text{Direct Effect} >0} + \frac{dP}{d\pi}\left[\underbrace{\lambda\frac{\partial l_A}{\partial P} + (1-\lambda)\frac{\partial l_{NA}}{\partial P}}_{<0} + \underbrace{(l_A - l_{NA})\frac{\partial \lambda}{\partial P}}_{<0}\right].$$

For the right-hand side of this equation to be zero, the permit price must increase with monitoring probability.

APPENDIX D

Effects of monitoring probability on extent of violation.

From equation (18) we know that two of the effects of monitoring probability on extent of violation are called the direct effect (DE) $\frac{\partial v}{\partial \pi} < 0$ and the indirect effect through the permit price (IEP) which increases the extent of violation, $\frac{\partial v}{\partial P}\frac{\partial P}{\partial \pi} > 0$.

From $P = \pi F'(v)$ we get that $\frac{\partial v}{\partial P} = \frac{1}{\pi F''(v)}$ and $\frac{\partial v}{\partial \pi} = \frac{-F'(v)}{\pi F''(v)}$ and therefore

$$\frac{\partial v}{\partial \pi} = -\frac{\partial v}{\partial P} F'(v).$$

Summing up DE and IEP, $DE + IEP = \frac{\partial v}{\partial P}\left[\frac{\partial P}{\partial \pi} - F'(v)\right]$.

To explore the sign of this equation, let us first derive an expression for $\frac{\partial P}{\partial \pi}$.

For a given technology adoption rate, the change in equilibrium permit price when the monitoring probability changes is given by:

$$\frac{\partial P}{\partial \pi} = F'(v) + \pi F''(v)\left[\frac{\partial v}{\partial \pi}\right].$$

This implies that $DE + IEP = \underbrace{\frac{\partial v}{\partial P}}_{(+)}\left[\underbrace{\pi F''(v)\frac{\partial v}{\partial \pi}}_{(-)}\right]$. Therefore, $DE + IEP < 0$

Chapter 2

Targeted Enforcement and Aggregate Emissions With Uniform Emission Taxes

Clara Villegas-Palacio* [a,b]

Abstract

In practice, targeted monitoring seems to be a strategy frequently used by regulators. In this paper, I study the effects of targeted monitoring strategies on the adoption of a new abatement technology and, consequently, on the aggregate emissions level when firms are regulated with uniform taxes. My results suggest that a regulator aiming to stimulate technology adoption should decrease the adopters' monitoring probability and/or increase the non-adopters' monitoring probability. In contrast to previous literature, I find that, in some cases, a regulator whose objective is to minimize aggregate emissions should exert a stronger monitoring pressure on firms with higher abatement costs.

Key words: technology adoption, environmental policy, imperfect compliance, targeted enforcement.

JEL classification: L51, Q55, K31, K42.

[a] Department of Economics. School of Business, Economics and Law. University of Gothenburg. P O Box 640 SE 405 30. Gothenburg, Sweden Phone +46-(0)31- 7862642. Fax +46-(0)31-786 1043.
E-mails: Clara.Villegas@economics.gu.se
Department of Economics. School of Business, Economics and Law.
[b] Facultad de Minas. Universidad Nacional de Colombia – Sede Medellín. Medellín, Colombia. E-mail. civillegas@unal.edu.co
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1. Introduction

Previous theoretical literature on enforcement of environmental regulations has shown that a firm will comply with a regulation when its compliance costs are lower than the expected penalty associated with the violation (Hardford, 1978; Hardford, 1987; Stranlund and Dhanda, 1999; Stranlund and Chávez, 2000; Sandmo, 2002; Friesen, 2003). However, in many circumstances, the frequent monitoring and relatively high fines necessary to deter firms from violating regulations are not available, leading to imperfect enforcement. Imperfect enforcement may be driven by the lack of accurate monitoring technology (Segerson 1988 and Heyes, 1994), reticence to use high penalties (Harrington, 1988) and/or budget constraints (Rousseau, 2007). In fact, one common argument against the use of market-based approaches in developing countries is that these countries lack resources to properly monitor and enforce policies (Coria and Sterner, 2010; Bell, 2002, Blackman and Harrington, 2000). A suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement and define a monitoring schedule to firms according to their past compliance records or to their potential emissions (Rousseau, 2007).

In practice, targeted enforcement is a strategy used by regulators. Gray and Deily (1996) use data on individual U.S. steel plants to test whether differences in firm characteristics and behavior affect enforcement decisions at the plant level. They find that regulators exert more enforcement pressure on plants expected not to be in compliance and firms producing large amounts of pollution irrespective of compliance status. Similarly, Rousseau (2007) empirically tests the targeting policy used by the Flemish Environmental Inspection Agency in Belgium and shows that the agency uses targeting to select the textile firms it will routinely inspect. The agency decides on routine inspections for water based on discharged waste load, the receiving medium of the discharge, the presence of hazardous pollutants, and the available budget and personnel. Given that targeted monitoring seems to be a practice used by regulators, the objective of the present paper is to analyze its effects on adoption of new abatement technology and, consequently, on the aggregate emission level when firms are regulated with uniform taxes.

Little attention has been paid to the relationship between diffusion of new technologies and the compliance behavior of risk-neutral firms. An exception is Villegas and Coria (2009), who focus on market-based regulations enforced through a uniform monitoring probability across firms. They find that in the case of uniform taxes the rate of adoption does not depend on the enforcement parameters. While this result relies on a uniform enforcement strategy, the monitoring probability can depend on firm characteristics as well (Macho-Stadler and Pérez-Castrillo, 2006), implying a targeted enforcement strategy. Previous theoretical literature has studied whether targeted enforcement based on specific firm characteristics, e.g., abatement cost parameters, is a plausible strategy to minimize violations. When firms are regulated by standards on emissions, a greater monitoring effort should be directed at firms with higher abatement costs (Garvie and Keeler, 1994). In contrast, when firms operate under tradable emission permits (TEPs), the distribution of optimal monitoring effort should be independent of differences in firms' abatement costs (Stranlund and Dhanda 1999)[1]. Murphy and Stranlund (2007) confirm these findings in an experimental setting. Consistent with theoretical predictions, they find that pursuing targeted enforcement strategies when firms face fixed emission standards is justified, but not in the case of TEPs.

Macho-Stadler and Pérez Castrillo (2006) show that when firms are regulated by uniform emission taxes, for a regulator who has as its objective to minimize aggregate emissions it is optimal to bias her monitoring strategy against firms that value pollution less, i.e., firms with low abatement costs. Nevertheless, they do not consider the fact that firms can change their type, i.e., that firms can adopt a new and more efficient abatement technology as a response to the monitoring strategy announced by the regulator. In this paper, I allow for such a response from firms, i.e., firms can make adoption decisions as a response to the enforcement strategy. In this setting, I analyze the influence of targeted enforcement policies on aggregate emissions.

[1]With respect to the theoretical approach to study targeted enforcement strategies, Harrington (1988) develops a dynamic repeated-game model of state-dependent enforcement of pollution standards. He shows how a regulatory agency using such an enforcement strategy can create stronger incentives to comply than when using a simple random monitoring strategy with fewer monitoring resources. Subsequent papers evaluate Harrington's results for social optimality (Harford 1991; Harford and Harrington 1991), evaluate the validity of Harrington's results under asymmetric information (Raymond 1999) and derive the optimal targeting scheme in Harrington's framework (Friesen 2003)

Particularly, I analyze how a regulator can use enforcement strategy to influence industry composition in terms of high and low abatement cost firms and the effect of this strategy on aggregate emissions.

The paper models the following interaction between a regulator and a set of firms. A regulator who has as its objective to minimize aggregate emissions sets and announces a uniform tax level per unit of pollutant released that firms should pay. The regulator establishes a self-report requirement that asks the regulated firms to report their emission levels. However, since the regulator cannot determine whether firms try to evade taxes by underreporting emissions, it is necessary to implement costly monitoring. The regulator therefore chooses the probability of monitoring firms based on firms' adoption status of a new available and more efficient abatement technology. The regulator sets and announces adopters' and non-adopters' monitoring probabilities. Based on the tax level and their monitoring probabilities, firms make their adoption decisions. After the adoption decisions have been made, firms decide on their actual and reported emission levels. Finally, the regulator monitors adopters and non-adopters based on the announced monitoring probabilities and imposes sanctions if non-compliance is detected.

The results of the model suggest that under uniform emission taxes, the rate of technology adoption is influenced by adopters' and non-adopters' monitoring probabilities. In contrast to previous literature, I find that, in some cases, a regulator whose objective is to minimize aggregate emissions should exert a stronger monitoring pressure on firms with higher abatement costs. A regulator aiming to stimulate technology adoption under a differentiated monitoring scheme should decrease the monitoring probability of adopters and/or increase that of non-adopters. This is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the tax to be imposed. Such a regulator may use a differentiated monitoring strategy that exerts a higher monitoring pressure on firms with high abatement costs in order to induce technology adoption and therefore reduces aggregate emissions for a given tax level.

The paper is organized in the logic of backwards induction. In our model, Section 2 presents the firm's optimal decisions on the actual and reported emission levels. Section 3 presents the model of adoption of the new abatement technology and analyzes the impact of monitoring strategy on rate of technology adoption. Section 4 studies the effects of a targeted monitoring strategy on aggregate emissions. Section 5 presents the problem of a regulator who chooses her monitoring strategy to minimize aggregate emissions. Finally, Section 6 concludes the paper.

2. The problem of the firm

Consider the following interaction between a regulator and a set of firms regulated by a uniform tax on emissions.

Stage 1. Consider a competitive industry consisting of a continuum of firms $\Lambda \subset [0,1]$ that are risk-neutral and initially homogeneous in abatement costs.[2] In the absence of environmental regulation, each firm emits a quantity e^0 of a homogeneous pollutant. The environmental authority sets the aggregate emissions target $\overline{E}$ before the arrival of the new technology and chooses a tax level t that firms are supposed to pay per unit of pollutant emitted. Since regulators very often face political constraints with respect to tax level, in this model the tax level chosen by the regulator does not necessarily coincide with the tax level that would be required to achieve the aggregate emissions target. Firms decide on their emission level e and are required to self-report their emissions. The quantity that is self-reported by the firm is denoted *r*. A firm could try to evade a fraction of its tax responsibilities by reporting a lower level of emissions, incurring in a violation given by $v = e - r$.

The regulator is unable to observe firms' emissions without implementing costly monitoring. In this model, the regulator has a fixed monitoring budget given by B, which is beyond its control, and the cost of an audit is given by ϖ. Let π_A denote the probability that the regulator audits an adopter and π_{NA} the probability of monitoring a non-adopter firm. I assume that these probabilities are common knowledge among firms before they make their adoption decisions. Once the regulator monitors a firm, it is able to perfectly determine the firm's compliance status.

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[2] This setting is close to that in Villegas and Coria (2009)

If the monitoring reveals that the firm is non-compliant, it faces a penalty given by $\phi(v)$, where v is the level of the violation. This is a strictly convex function in the level of violation with $\phi'(v) > 0; \phi''(v) > 0$. For zero violation, the penalty is zero $\phi(0) = 0$, but the marginal penalty is greater than zero $\phi'(0) = 0$. I assume that the regulator commits to its policy announcement and does not modify the level of the environmental policy in response to the availability of the new technology.

Stage 2. Firms respond to policy parameters by making two kinds of decisions: They decide on extent of underreporting, which constitutes a continuous choice, and they make a dichotomous choice on whether to adopt the new abatement technology. I assume that adoption decisions made by firms are observable by the regulator. Let the abatement cost function of an individual firm be denoted $c(e)$, which is strictly convex and decreasing in emissions. A new and more efficient technology arrives and firms must decide, *after being informed about the vector of monitoring probabilities* (π_A, π_{NA}), whether or not to invest in the technology, and on actual and reported emission levels. The new technology allows firms to abate emissions at a lower cost $\theta c(e)$, where $\theta \in (0,1)$ is a parameter that represents the drop in abatement cost by adopting the new technology. After making the adoption decision, firms decide on actual and reported emission levels.

Firms decide on their emission and report levels in order to minimize their total expected costs subject to the fact that there are no economic incentives to over-report emissions since it implies a higher tax payment. I assume that each firm chooses non-negative emissions and report levels. Equation (1) displays the problem of the firms. For non-adopters, $\theta = 1$

$$(1) \qquad \begin{aligned} &Min_{e,r} \theta c(e) + tr + \pi\phi(e - r) \\ &s.t.\ e - r \geq 0 \end{aligned}$$

.

The Lagrange equation for (1) is $\varphi = \theta c(e) + tr + \pi\phi(e-r) + \eta[e-r]$ and the Kuhn-Tucker conditions are[3]:

(2) $$\frac{\partial\varphi}{\partial e} = \theta c'(e) + \pi\phi'(e-r) - \eta = 0,$$

(3) $$\frac{\partial\varphi}{\partial r} = t - \pi\phi'(e-r) + \eta = 0,$$

(4) $$\frac{\partial\varphi}{\partial\eta} = r - e \geq 0; \eta \geq 0; \eta[r-e] = 0$$
.

If the report is interior, i.e., $0 < r < e$, from equations (2) and (3) the firm selects an emission level that satisfies the following condition: $\theta c'(e) + t = 0$. This level coincides with the one the firm would select under perfect monitoring $e^{\min *}$, which corresponds to the minimum emission level that the regulator can achieve with its enforcement policy. From equation (4), if $r - e > 0$, it follows that $\eta = 0$; and from equation (3), the report level selected by the firm is given by $t = \pi\phi'(e^{\min *} - r)$. From the properties of the penalty function, we know that $\pi\phi'(0) < \pi\phi'(e-r) < \pi\phi'(e)$. This can be written as $\pi\phi'(0) < t < \pi\phi'(e)$.

If $\pi\phi'(e) \leq t$, the firm does not report any of its emissions $r = 0$ and selects an emission level such that $\theta c'(e^*) + \pi\phi'(e^*) = 0$. This implies $-\theta c'(e^*) \leq t$ and therefore $e^* > e^{\min *}$. If $\pi \geq \frac{t}{\phi'(0)}$, the firm will make a truthful report of its emissions. Therefore, the solution is interior if and only if $\pi\phi'(0) < t < \pi\phi'(e^{\min *})$. If $\pi = 0$, the firm reports zero emissions which from

[3] The first-order conditions are both necessary and sufficient since the second-order conditions are fulfilled: $\frac{\partial^2\varphi}{\partial e^2} = \theta c''(e) + \pi\phi''(e-r) > 0; \frac{\partial^2\varphi}{\partial r^2} = \pi\phi''(e-r) > 0$; $\frac{\partial^2\varphi}{\partial e^2}\frac{\partial^2\varphi}{\partial r^2} - \frac{\partial^2\varphi}{\partial e\partial r} = \theta c''(e)\pi\phi''(e-r) > 0$.

equation (4) implies $\eta = 0$. From equation (2), the firm will select an emission level such that $\theta c'(e) = 0$, which coincides with the initial emission level e^0.

Following Macho-Stadler and Pérez-Castrillo (2006), previous results about the optimal behavior of adopters and non-adopters of the new technology, summarized in Result 1, can be represented as in Figure 1:

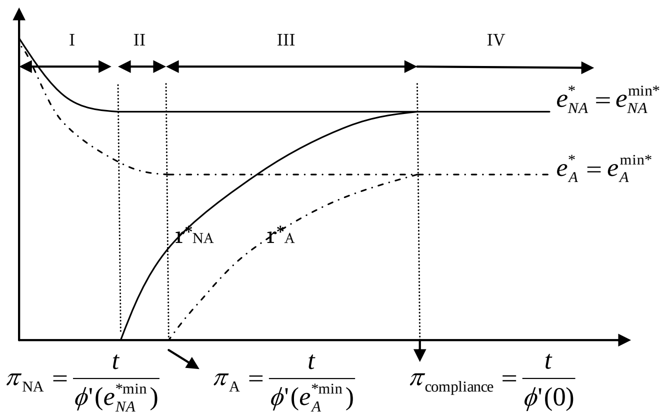

Figure 1. Optimal behavior of adopters and non-adopters under uniform taxes.

We can divide Figure 1 into four regions as follows: In Region I, defined by the interval $\left(0, \frac{t}{\phi'(e^{\min *}_{NA})}\right)$, both adopters and non-adopters report zero emissions, and their actual emission levels are decreasing in monitoring probabilities. In Region II, corresponding to the interval $\left[\frac{t}{\phi'(e^{\min *}_{NA})}, \frac{t}{\phi'(e^{\min *}_{A})}\right)$, non-adopters make a positive report of their emissions while adopters continue reporting zero emissions. In Region III, defined by interval $\left[\frac{t}{\phi'(e^{\min *}_{A})}, \frac{t}{\phi'(0)}\right)$, both adopters and non-adopters make a positive report of their emissions but still under-report a fraction of them. Finally, in Region IV, i.e., $\left[\frac{t}{\phi'(0)},1\right]$, firms make a truthful report of their emissions. In order to allow for perfect compliance to be a positive outcome, we assume that $\frac{t}{\phi'(0)} \leq 1$.

Result 1. *For a given tax rate, monitoring probabilities* π_A *and* π_{NA}*, and penalty function* $\phi(v)$*, the optimal actual and reported emission levels* (e^*, r^*) *of adopters and non-adopters of the new technology are:*

(a) If $\pi_A = \pi_{NA} = 0$*, then* $e_A^* = e_{NA}^* = e^0$ *and* $r_A^* = r_{NA}^* = 0$*, where sub-indexes A and NA represent adopters and non-adopters of the new abatement technology respectively.*

(b) If π_{NA} *is in Region I, then* $e_{NA}^* \in (e_{NA}^{\min *}, e^0)$ *with* e_{NA}^* *defined by* $C'(e_{NA}^*) + \pi_{NA}\phi'(e_{NA}^*) = 0$ *and* $r_{NA}^* = 0$.

If π_A *is in either Region I or II, then* $e_A^* \in (e_A^{\min *}, e^0)$ *with* e_A^* *defined by* $\theta C'(e_A^*) + \pi_A \phi'(e_A^*) = 0$ *and* $r_A^* = 0$.

(c) If π_{NA} *is in either Region II or III, then* $e_{NA}^* = e_{NA}^{\min *}$ *with* e_{NA}^* *defined by* $C'(e_{NA}^*) + t = 0$ *and*

r_{NA}^* *defined by* $\pi_{NA}\phi'(e_{NA}^* - r_{NA}^*) = t$.

If π_A *is in Region III, then* $e_A^* = e_A^{\min *}$ *with* e_A^* *defined by* $\theta C'(e_A^*) + t = 0$.

(d) If π_{NA} *is in Region IV, then* $e_{NA}^* = r_{NA}^*$ *is defined by* $C'(e_{NA}^*) + \pi_{NA}\phi'(0) = 0$.

If π_A *is in Region IV, then* $e_A^* = r_A^*$ *is defined by* $\theta C'(e_A^*) + \pi_A \phi'(0) = 0$.

Let us first analyze the results for the interval where both adopters and non-adopters make a positive report of their emissions, i.e., $\pi_A \wedge \pi_{NA} \in \left[\frac{t}{\phi'(e_A^{\min*})}, \frac{t}{\phi'(0)}\right)$, which corresponds to Region III in Figure 1. In this interval, each firm chooses its emissions such that the marginal abatement cost equals the tax rate $c'(e_{NA}) = \theta c'(e_A) = t$, implying that the firms' marginal abatement costs are equal irrespective of adoption status. Given that $\theta \in (0,1)$, $c'(e_{NA}) = \theta c'(e_A)$ implies that $e_A^{\min*} < e_{NA}^{\min*}$. The fact that $e_A^{\min*} < e_{NA}^{\min*}$ together with the properties of the penalty function implies that the monitoring probability required for the firms to start making a positive report of their emissions is higher for adopters than for non-adopters, i.e., $\frac{t}{\phi'(e_{NA}^{\min*})} < \frac{t}{\phi'(e_A^{\min*})}$. This means that adopters of the new technology can afford a higher monitoring probability before they start making a positive report of their emissions.

Note that, as Harford (1978) first stated, if the monitoring probability is high enough to guarantee positive reported emission levels, the actual emissions levels do not depend on the parameters of the enforcement problem. Additionally, in Region III, the expected marginal cost of violation is equalized among firms, i.e., $\pi_A \phi'(e_A - r_A) = \pi_{NA} \phi'(e_{NA} - r_{NA})$. In this context, if the regulator sets a targeted enforcement strategy such that firms that potentially pollute more are audited with a higher probability, i.e., $\pi_A < \pi_{NA}$, it follows that $v_A > v_{NA}$.[4] Hence, if the monitoring probabilities are high enough to guarantee positive reports of emissions of both adopters and non-adopters, but not sufficient to guarantee perfect compliance, the violation size of an adopter firm is higher than that of a non-adopter. The intuition is as follows. The marginal benefit from violations is represented by the tax rate and is the same for adopters and non-

[4] This is consistent with the empirical evidence that when targeted monitoring is used, regulators bias monitoring efforts against firms with higher potential emissions. In a set of firms that differ only in abatement costs, firms with high abatement costs have a higher level of potential emissions. Therefore, a regulator can define its targeting monitoring strategy based on technology adoption status. Section 5 presents a formal analysis of the convenience of this kind of targeted monitoring strategy from the regulator point of view.

adopters. The marginal cost of violating the regulation is given by the marginal expected sanction. Given that the tax rate is independent of adoption status, the marginal expected benefit is equal for adopters and non-adopters and so is the marginal expected cost of violation. Since the monitoring probability of adopters is lower than that of non-adopters, adopters can afford a higher fine for violation. A higher fine implies that the violation of adopters' is higher than the violation of non-adopters'. In contrast, when $\pi_A \wedge \pi_{NA} \geq \dfrac{t}{\phi'(0)}$, i.e., Region IV in Figure 1, the extent of violation of adopters and non-adopters equals zero since both types of firms truthfully report their emissions.

If the monitoring probabilities of both adopters and non-adopters are in Region I in Figure 1, i.e., $\pi_A \wedge \pi_{NA} \in \left(0, \dfrac{t}{\phi'(e_{NA}^{\min *})}\right)$, both types of firms report zero emissions and therefore their extent of violation coincides with their level of emissions. In this interval, the level of emissions is determined such that the marginal cost of abatement, which also represents the marginal benefit from violation, equals the marginal expected marginal fine. In contrast to the other intervals, in this interval the marginal benefit from violation is not necessarily equal between adopters and non-adopters, and the extent of violation before adoption can therefore be higher than, lower than, or equal to the extent of violation after adoption. It depends on the difference between the monitoring probabilities π_A and π_{NA} as well as on the size of the parameter θ. Result 2 follows from the previous analysis:

Result 2. *For a given tax rate, a pair of adopters' and non-adopters' monitoring probabilities and a penalty function $\phi(v)$, the extent of violation v^* of adopters and non-adopters of the new technology is:*

(a) If $\pi_A = \pi_{NA} = 0$, then $v_A^* = v_{NA}^* = e^0$ where sub-indexes A and NA represent adopters and non-adopters of the new abatement technology respectively.

(b) If π_A is in Region I, then $v_A^* = e_A^*$.

If π_{NA} *is in Region I, then* $v_{NA}^{*} = e_{NA}^{*}$.

(c) If π_{A} *is in Region II, then* $v_{A}^{*} = e_{A}^{*}$ *and is defined by* $\theta c'(e_{A}^{*}) + \pi_{A}\phi'(e_{A}^{*}) = 0$.

If π_{NA} *is in Region II, then* v_{NA}^{*} *is defined by* $\pi_{NA}\phi'(e_{NA}^{\min*} - r_{NA}^{*}) = t$.

(d) If π_{A} *is in Region III, then* v_{A}^{*} *is defined by* $\pi_{A}\phi'(e_{A}^{\min*} - r_{A}^{*}) = t$.

If π_{NA} *is in Region III, then* v_{NA}^{*} *is defined by* $\pi_{NA}\phi'(e_{NA}^{\min*} - r_{NA}^{*}) = t$.

(e) If π_{A} *is in Region IV, then* $v_{A}^{*} = 0$.

If π_{NA} *is in Region IV, then* $v_{NA}^{*} = 0$.

3. The model of adoption

I assume that buying and installing the new technology implies a fixed cost that differs among firms.[5] Let k_i denote the fixed cost of adoption for firm i, and assume that it is uniformly distributed on the interval $(\underline{k}, \overline{k})$.

Let μ_{NAi} and μ_{Ai} be firm i's total expected costs of abatement and compliance when using the current abatement technology (non-adoption) and new technology (adoption). Total abatement costs of abatement and compliance are composed of the abatement costs, the tax liabilities given the self-reported level of emissions, and the expected fines in case the firm is caught under-reporting emissions. The savings in total expected cost of abatement and compliance generated with adoption is given by $\mu_{NAi} - \mu_{Ai}$. Any firm whose savings in total expected costs offsets its adoption cost will adopt the new technology[6]. In the continuum of firms

[5] The assumption that adoption costs differ among firms is not new in the literature analyzing the effects of choice of policy instruments on rate of adoption of new technologies. See for example Requate and Unold (2001). On the other hand, Stoneman and Ireland (1983) point out that although most theoretical and empirical literature on technological adoption focuses on the demand side alone, supply-side forces might be very important explaining patterns of adoption in practice. Thus, for example, costs of acquiring new technology might vary among firms due to firm characteristics, e.g., location and output, or because of competition among suppliers of capital goods.

[6] I assume that firms minimize their costs for any level of output, but do not treat the output decision explicitly.

$\Lambda \subset [0,1]$, the marginal adopter is then identified by the arbitrage condition $\tilde{k}_i = \mu_{NAi} - \mu_{Ai}$. Hence, the rate of firms $\lambda \in [0,1]$ adopting the new technology is defined by the integral $\lambda = \int_{\underline{k}}^{\tilde{k}} f(k_i)dk = F(\tilde{k}_i)$. From the definition of the uniform cumulative distribution of $k_i \sim U(\underline{k}, \bar{k})$ it follows that $F(\tilde{k}_i) = \frac{\mu_{NAi}^x - \mu_{Ai}^x - \underline{k}}{\bar{k} - \underline{k}}$, and the rate of technology adoption can be defined as shown in equation (5) : [7]

(5) $\lambda = \psi(\mu_{NAi} - \mu_{Ai}) - \zeta \in [0,1]$, where $\psi = \frac{1}{\bar{k} - \underline{k}}$ and $\zeta = \psi \underline{k}$.

The technology adoption rate is therefore a function of the shift in abatement costs θ, the tax level t, the enforcement policy reflected in the sanctions structure ϕ, and the monitoring probabilities π_A and π_{NA}: $\lambda(\theta, t, \pi_A, \pi_{NA}, \phi)$. It is sufficient to keep track of the marginal adopter's optimal choices of emissions and reporting in order to derive the rate of adoption; therefore, the subscript *i* is omitted hereafter. [8]

To account for effects of targeted enforcement on the rate of technology adoption, I calculate the expected costs of abatement and compliance for the marginal adopter before adoption μ_{NA} and after adoption μ_A and replace them in equation (6) to get:

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[7] This follows Coria's (2009) approach when analyzing the impacts of the interaction of multiple policy instruments on technology adoption rate.

[8] I assume that firms are initially homogeneous in terms of abatement costs. Nevertheless, the results still hold in the case of heterogeneous abatement costs. For example, following Coria 2009b, I could have assumed that firms' current abatement costs are heterogeneous and that firms can be ordered according to their adoption savings from the firm with the highest to the firm with the lowest current abatement cost. Therefore, the arbitrage condition that states that for the marginal adopter the adoption savings offsets the adoption costs still holds. In such a setting, and as is shown later, adopters will increase their abatement effort due to the availability of the new technology and will reduce their demands for emissions.

(6) $$\lambda = \psi\{[c(e_{NA}) - \theta c(e_A)] + t[r_{NA} - r_A] + [\pi_{NA}\phi(e_{NA} - r_{NA}) - \pi_A\phi(e_A - r_A)]\} - \zeta \quad .$$

The first term in brackets in (6) gives account of the savings on the abatement costs from adopting the new technology. The second term in brackets accounts for the difference in payment on reported emissions. The last term in brackets represents the difference in expected fines between non-adoption and adoption status. Note that in the presence of targeted monitoring policy, the rate of technology adoption under uniform taxes is a function of the monitoring probabilities of adopters and non-adopters. This is in contrast to the case of uniform monitoring probability where under uniform taxes the rate of technology adoption is not affected by enforcement policy (Villegas and Coria, 2009).

Take partial derivatives of equation (6) with respect to π_A and π_{NA} to get (see appendix A for derivation):

(7) $$\begin{aligned} \frac{\partial \lambda}{\partial \pi_{NA}} &= \psi\phi(e_{NA} - r_{NA}) \geq 0 \\ \frac{\partial \lambda}{\partial \pi_A} &= -\psi\phi(e_A - r_A) \leq 0 \end{aligned} \quad .$$

When firms perfectly comply with the regulation, i.e., monitoring probabilities are in Region IV in Figure 1, the size of the fine $\phi(0)$ equals zero and, therefore, the rate of technology adoption is not affected by changes in monitoring probabilities. The rate of technology adoption increases in non-adopters' monitoring probability when this probability is in Regions I, II, or III. Analogously, the rate of technology adoption decreases in adopters' monitoring probability when this probability is in Regions I, II, or III.[9]

---

[9] Note that the conditions in (7) only hold for rate of technology adoptions such that $\lambda \in (0,1)$. When monitoring probabilities are such that all the firms already adopted the new technology, an increase in non-

Result 3. Under uniform taxes and targeted enforcement, the adoption rate is increasing in non-adopters' monitoring if and only if $\pi_{NA} \in \left[0, \frac{t}{\phi'(0)}\right)$. Analogously, the adoption rate is decreasing in adopters' monitoring probability if and only if $\pi_A \in \left[0, \frac{t}{\phi'(0)}\right)$.

4. Targeted enforcement and aggregate emissions

Let us now study the influence of monitoring probabilities on aggregate emissions. The aggregate emissions level E is the weighted average between emissions of adopters and non-adopters, i.e., $E = \lambda(\pi_A, \pi_{NA}, t, \phi)e_A + [1 - \lambda(\pi_A, \pi_{NA}, t, \phi)]e_{NA}$. Taking the partial derivative of aggregated emissions with respect to π_A, i.e., $\frac{\partial E}{\partial \pi_A}$, yields :

(8) $$\frac{\partial E}{\partial \pi_A} = \underbrace{\lambda \frac{\partial e_A}{\partial \pi_A}}_{\text{Direct effect}} + \underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect thr ough} \\ \text{technology adoptrion rate}}}$$

The change in aggregate emissions from a change in adopters' monitoring probability is given by two effects, a direct effect and an indirect effect through technology adoption rate. When adopters' monitoring probability is in Region IV in Figure 1, both the direct and the indirect effect are equal to zero and, thus, aggregate emissions do not change with adopters' monitoring probability. When adopters' monitoring probability is in Region III in Figure 1, the direct effect $\lambda \frac{\partial e_A}{\partial \pi_A}$ equals zero and the indirect effect through technology adoption is increasing in π_A. Therefore, if the monitoring pressure is high enough for adopters to make a positive report of their emissions, exerting a higher monitoring pressure on adopters will decrease the rate of technology adoption, leading to a higher level of aggregate emissions. When adopters'

---

adopters' monitoring probability does not change the rate of technology adoption. Analogously, if the rate of technology adoption is zero, even if adopters' monitoring probability is increased, it is not possible that the rate of technology adoption goes down.

monitoring probability is in Region II, their emissions decrease with monitoring probability and, therefore, the direct effect is decreasing in π_A. In Region II, a higher monitoring pressure on adopters reduces the rate of technology adoption, which increases aggregate emissions; therefore, the indirect effect through adoption rate is increasing in π_A. In this region, aggregate emissions are decreasing in adopters' monitoring probability if and only if the direct effect offsets the indirect effect. If adopters' monitoring probability is in Region I, adopters' emissions decrease with monitoring probability. The indirect effect through the adoption rate $\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]$ is decreasing in π_A if and only if $\left[e_A^* - e_{NA}^*\right]$>0. If we zoom in on Region I, as in Figure 2 and use result 1 (b), we can derive the necessary conditions for $\left[e_A^* - e_{NA}^*\right]$ to be positive. The two necessary conditions are $\pi_A < \frac{-\theta c'(e_{NA}^{\min *})}{\phi'(e_{NA}^{\min *})}$ and, for a given π_A^* that satisfies such a condition, the probability of non-adopters should satisfy $\pi_{NA}^* > \frac{-\theta c'(e_A^*)}{\phi'(e_A^*)}$.

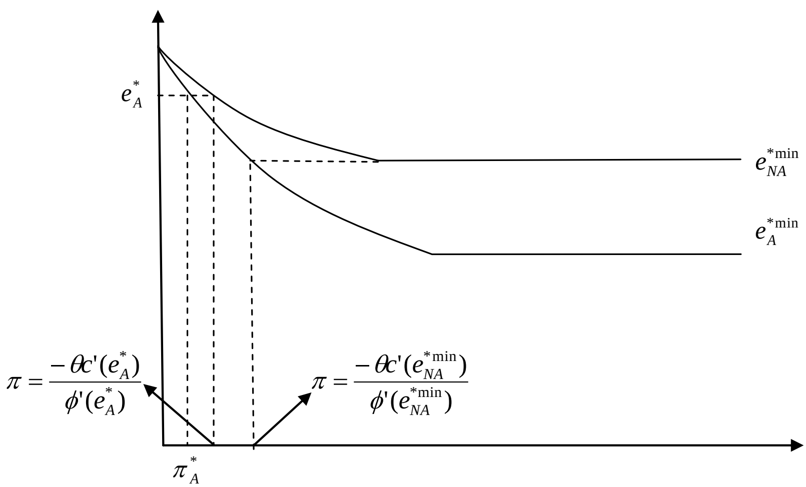

Figure 2. Necessary conditions for adopters' emissions to be higher than non-adopters' emissions in Region I.

Analogously, the effect of non-adopters' monitoring probability on aggregated emissions is given by two effects as shown in equation (9).

(9) $$\frac{\partial E}{\partial \pi_{NA}} = \underbrace{[1-\lambda]\frac{\partial e_A}{\partial \pi_{NA}}}_{\text{Direct effect}} + \underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect thr ough} \\ \text{technology adoptrion rate}}}$$

If non-adopters' monitoring probability is in Region IV in Figure 1, aggregate emissions do not change in non-adopters' monitoring probability, since in this region both the direct effect and the indirect effect equal zero. If non-adopters' monitoring probability is in Region II or III, the direct effect equals zero. In these regions, increasing non-adopters' monitoring probability leads to a higher adoption rate and, hence, lower aggregate emissions, i.e., the indirect effect through the adoption rate $\frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right]$ is decreasing in π_{NA}. When non-adopters' monitoring probability is in Region I, the direct effect is decreasing in π_{NA} and the indirect effect is decreasing as long as $\left[e_A^* - e_{NA}^*\right]$ is negative. Analogous to the previous case, if we zoom in on Region I, as in Figure 3, and use result 1(b), we can derive the necessary condition for $\left[e_A^* - e_{NA}^*\right]$ to be negative. For a given non-adopters' monitoring probability, $\left[e_A^* - e_{NA}^*\right] < 0$ if $\pi_A^* > \frac{-\theta c'(e_{NA}^*)}{\phi'(e_{NA}^*)}$.

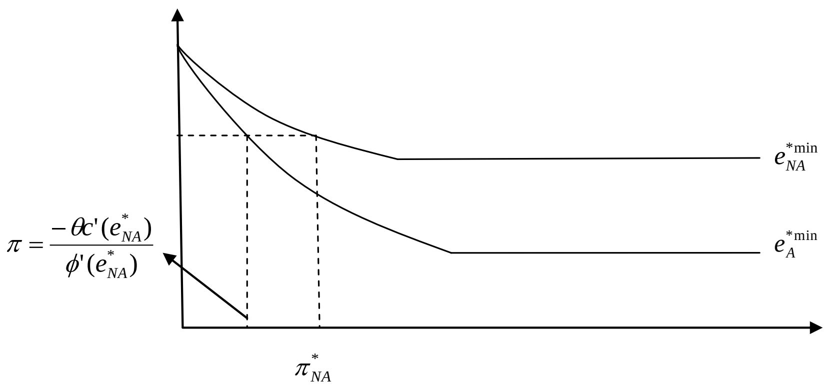

Figure 3. Necessary conditions for adopters' emissions to be lower than non-adopters' emissions in Region I.

The analysis is summarized in Result 4 as follows:

Result 4. *Under uniform taxes, aggregate emission level changes with adopters' and non-adopters' monitoring probability as follows:*

(a) If π_A is in Region I:

$\frac{\partial E}{\partial \pi_A} < 0$ *if either of following two conditions holds:*

(a1) $\left[e_A^* - e_{NA}^*\right] > 0$,

(a2) $\left[e_A^* - e_{NA}^*\right] < 0$ *and* $\underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect through}\\ \text{technology adoption rate}}} < -\underbrace{\lambda \frac{\partial e_A^*}{\partial \pi_A}}_{\text{Direct effect}}$.

(b) If π_A is in Region II:

$\frac{\partial E}{\partial \pi_A} < 0$ *if and only if* $\underbrace{\frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect through}\\ \text{technology adoption rate}}} < -\underbrace{\lambda \frac{\partial e_A^*}{\partial \pi_A}}_{\text{Direct effect}}$.

(c) If π_A is in Region III:

$$\frac{\partial E}{\partial \pi_A} = \frac{\partial \lambda}{\partial \pi_A}\left[e_A^* - e_{NA}^*\right] > 0.$$

(d) If π_A is in Region IV:

$$\frac{\partial E}{\partial \pi_A} = 0.$$

(e) If π_{NA} is in Region I:

$\frac{\partial E}{\partial \pi_{NA}} < 0$ *if either of following two conditions holds:*

(e1) $\left[e_A^* - e_{NA}^*\right] < 0$,

(e2) *If* $\left[e_A^* - e_{NA}^*\right] > 0$ *and* $\underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right]}_{\substack{\text{Indirect effect thr ough} \\ \text{technology adoption rate}}} < \underbrace{-[1-\lambda]\frac{\partial e_{NA}^*}{\partial \pi_{NA}}}_{\text{Direct effect}}$.

(f) If π_{NA} is either in Region II or in Region III:

$$\frac{\partial E}{\partial \pi_{NA}} = \frac{\partial \lambda}{\partial \pi_{NA}}\left[e_A^* - e_{NA}^*\right] < 0 .$$

(g) If π_{NA} is in Region IV:

$$\frac{\partial E}{\partial \pi_{NA}} = 0 .$$

The results of the influence of monitoring probabilities on aggregate emissions bring a new element to the analysis. It considers the fact that under targeted monitoring, firms can change their type by adopting a new abatement technology as a response to the monitoring pressure. By this means, a regulator may influence the aggregated emissions using enforcement pressure.

5. The problem of the regulator

In this section, I consider the optimal monitoring policy of a regulator whose only objective is to minimize total emissions.[10] The regulator decides on a pair of non-negative monitoring probabilities π_A and π_{NA} that minimize aggregated emissions *E*. The regulator is subject to a monitoring budget constraint B and a rate of technology adoption that cannot be higher than one. The problem of the regulator is:

[10] This assumption is not new in the literature. See Macho-Stadler and Pérez-Castrillo (2006) and Garvie and Keeler (1994).

$$
(10)\quad \begin{aligned}
&\underset{\pi_A,\pi_{NA}}{Min}\ \lambda(\pi_{\mathrm{A}},\pi_{NA})e_A + [1-\lambda(\pi_{\mathrm{A}},\pi_{NA})]e_{NA} \\
&s.t.\ \ \varpi\pi_{\mathrm{A}}\lambda + \varpi\pi_{\mathrm{NA}}[1-\lambda] \le B \\
&\lambda \le 1
\end{aligned}
$$
.

The Lagrange equation for this minimization problem is given by $L = \lambda e_A + [1-\lambda]e_{NA} + \gamma[B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda]] + \eta[1-\lambda]$ with the following Kuhn-Tucker conditions:

$$
(11)\quad \frac{\partial L}{\partial \pi_A} = \frac{\partial E}{\partial \pi_A} + \gamma\left[-\varpi\lambda - \pi_A\varpi\frac{\partial\lambda}{\partial\pi_A} + \pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_A}\right] - \eta\frac{\partial\lambda}{\partial\pi_A} \le 0;\ \pi_A \ge 0;\ \pi_A\frac{\partial L}{\partial\pi_A} = 0
$$

(12)

$$
\frac{\partial L}{\partial \pi_{NA}} = \frac{\partial E}{\partial \pi_{NA}} + \gamma\left[-\varpi[1-\lambda] - \pi_A\varpi\frac{\partial\lambda}{\partial\pi_{NA}} + \pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_{NA}}\right] - \eta\frac{\partial\lambda}{\partial\pi_{NA}} \le 0;\quad \pi_{NA} \ge 0;\quad \pi_{NA}\frac{\partial L}{\partial\pi_{NA}} = 0
$$

$$
(13)\quad \frac{\partial L}{\partial\gamma} = B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda] \ge 0;\qquad \gamma \ge 0;\qquad \gamma\,[B - \varpi\pi_{\mathrm{A}}\lambda - \varpi\pi_{\mathrm{NA}}[1-\lambda]] = 0
$$

$$
(14)\quad \frac{\partial L}{\partial\eta} = [1-\lambda] \ge 0;\qquad \eta \ge 0;\qquad \eta\,[1-\lambda] = 0\,.
$$

In order to solve the minimization problem, first it is necessary to establish which of the possible combinations of π_A and π_{NA} constitutes the feasible set, i.e., which of the combinations satisfies all the constraints (see appendix B for derivation). Once the feasible set is established, it is necessary to study which of the solutions in the feasible set are dominated solutions, i.e., in which of them aggregate emissions are definitely not minimized. Such an analysis is presented in Table 1.

From Table 1, combinations A, B, and D constitute the feasible set to solve the minimization problem. However, by comparing aggregate emissions under combinations A, B, and D, it is straightforward to see that combinations B and D are dominated by combination A.[11] Therefore, the pair of adopters' and non-adopters' monitoring probabilities that minimize aggregate emissions should satisfy the conditions in (15a) or in (15b):

(15a) $\pi_A^* = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA}^* \geq \dfrac{t}{\phi'(e_{NA}^{\min *})}$ with non-binding restriction: $\varpi\pi_A^*\lambda + \varpi\pi_{NA}^*[1-\lambda] < B$,

(15b) $\pi_A^* = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA}^* > 0$ such that $\lambda = 1$ with non-binding restriction: $\varpi\pi_A^*\lambda + \varpi\pi_{NA}^*[1-\lambda] < B$.

Table 1. Solution to the problem of the regulator

Combination	π_A	π_{NA}	Does this combination satisfy the restriction?	Aggregate emissions $E = \lambda e_A^* + [1-\lambda]e_{NA}^*$
A	Positive	Positive	This combination satisfies the restrictions if : (a) $\pi_A = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} \geq \dfrac{t}{\phi'(e_{NA}^{\min *})}$ with non-binding budget restriction, or (b) $\pi_A = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} > 0$ such that $\lambda = 1$ with non-binding budget restriction.	$E_{\text{Combination A}} = \lambda e_A^{\min *} + [1-\lambda]e_{NA}^{\min *}$ $E_{\text{Combination A}} \in [e_A^{\min *}, e_{NA}^{\min *}]$

[11] There is one special case in which $E_{\text{Combination B}} = E_{\text{Combination A}} = e_{NA}^{\min *}$. It requires zero technology adoption in combination A together with a π_{NA} in either Region II, III, or IV.

B	Zero	Positive	This combination always satisfies the restrictions	$E_{\text{Combination B}} \in \left[e_{NA}^{\min *}, e^{0}\right]$
C	Positive	Zero	This combination never satisfies the restrictions	
D	Zero	Zero	This combination always satisfies the restrictions	$E_{\text{Combination D}} = e^{0}$

The fact that I in this model do consider that the rate of technology adoption is a function of the monitoring probabilities of adopters and non-adopters explains why the optimal monitoring policy in the present paper is not guaranteed by the strict equality in conditions (15a) and (15b). The intuition is as follows. Let us for a moment assume that the parameters of the rate of technology adoption function are such that $\lambda < 1$ for all possible combinations (π_A, π_{NA}). In such a scenario, condition (16b) is not feasible. Therefore, following condition (15a), a regulator who sets $\pi_A^* = \dfrac{t}{\phi'(e_A^{\min *})}$ can increase non-adopters' monitoring probability to a level higher than $\dfrac{t}{\phi'(e_{NA}^{\min *})}$ to increase the rate of technology adoption and, by this means, decrease aggregate emissions[12]. In a similar setting, Macho-Stadler and Pérez-Castrillo (2006) derive the optimal monitoring policy of a regulator whose objective is to minimize aggregated emissions. They find that adopters and non-adopters of the new abatement technology should be monitored with probabilities $\pi_A = \dfrac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} = \dfrac{t}{\phi'(e_{NA}^{\min *})}$. The fact that they do not consider that firms can react to the monitoring probabilities by adopting a new abatement technology explains why, in their model, monitoring non-adopters with a probability higher than $\pi_{NA} = \dfrac{t}{\phi'(e_{NA}^{\min *})}$ does not lead to a reduction in aggregate emissions. In my model, for certain sets of parameters it might

[12] Remember that $\dfrac{\partial \lambda}{\partial \pi_{NA}} > 0$ as long as $\pi_{NA} < \dfrac{t}{\phi'(0)}$.

be optimal for a regulator to exert a pressure on non-adopters that is higher than that suggested by their model, and, eventually, bias its strategy against firms that value pollution more, i.e., $\pi^*_{NA} > \pi^*_A$.

6. Conclusion

A significant fraction of the literature on environmental regulation has been devoted to studying how environmental policies should be and are enforced. Empirical studies have shown that a suitable strategy for the regulator to deal with the budget constraints in the enforcement activity is to target enforcement. Regulators can define a monitoring schedule for firms according to their past compliance records or to their potential emissions. If firms face a targeted enforcement strategy in which those with higher potential emissions are monitored more closely, a plausible response may be to adopt a new and more efficient abatement technology that allows them to reduce potential emissions and thus to avoid a more stringent monitoring pressure. Using a conventional model of non-compliant firms in a setting of uniform taxes, I have analyzed the effects of a targeted enforcement strategy on rate of technology adoption and aggregate emission level.

The results suggest that, with a targeted enforcement strategy based on adoption status, a regulator might stimulate or slow down the adoption of the new technology through monitoring pressure on both types of firms when firms are non-compliant. An increase in non-adopters' monitoring probability induces a higher rate of technology adoption while increasing adopters' monitoring probability induces a lower rate of technology adoption.

In addition, I analyze the optimal strategy for a regulator whose objective is to minimize aggregate emissions. In contrast to previous literature, I find that, for certain sets of parameters, it might be optimal for a regulator to bias its monitoring strategy against those firms that value pollution more.

The interaction between technology adoption rate and targeted enforcement also has consequences on aggregate emissions, and brings some issues to the policy arena. The model in this paper considers that firms can adopt a new abatement technology as a response to the monitoring probabilities set by the regulator. Therefore, the actions of the regulator in terms of monitoring probabilities have consequences on the aggregate emission level through the rate of technology adoption. If the regulator increases the monitoring probability of non-adopters, the rate of technology adoption increases, causing an additional deterrent effect on aggregate emissions. In this setting, a regulator who instead focuses its monitoring efforts on adopters of the new technology slows down the spread of the new abatement technology and faces a higher level of aggregate emissions than achieved with the opposite enforcement policy. The fact that the technology adoption rate is influenced by monitoring strategy is good news for a regulator who wants to achieve a given level of aggregate emissions but has political constraints on the level of the tax to be imposed. Such a regulator may use a differentiated monitoring strategy to induce technology adoption and therefore to reduce aggregate emissions for a given politically feasible tax level. Consequently, targeted monitoring strategies should not be ruled out as a plausible enforcement policy if the interaction between monitoring probabilities and technology adoption is taken into consideration.

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Appendix A

The rate of technology adoption under uniform taxes is given by:

(A1)

$$\lambda^{TAX} = \psi\left[c(e_{NA}(t)) - \theta c(e_A(t))\right] + \psi\left[tr_{NA}(t,\pi_{NA},F) - tr_A(t,\pi_A,F)\right] + \psi\left[\pi_{NA}F(v_{NA}) - \pi_A F(v_A)\right] - \zeta$$

Taking the partial derivative of λ^{TAX} with respect to adopters' monitoring probability yields:

(A2) $$\frac{\partial\lambda^{TAX}}{\partial\pi_A} = \psi\left[-t\frac{\partial r_A}{\partial\pi_A} - \pi_A F'(v_A)\frac{\partial v_A}{\partial\pi_A} - F(v_A)\right].$$

Taking into consideration that $\pi_A F'(v_A) = t$ and $\frac{\partial v_A}{\partial\pi_A} = -\frac{\partial r_A}{\partial\pi_A}$ and rewriting:

(A3) $$\frac{\partial\lambda^{TAX}}{\partial\pi_A} = -\psi F(v_A).$$

Analogously, taking the partial derivative of λ^{TAX} with respect to non-adopters' monitoring probability yields:

(A4) $$\frac{\partial\lambda^{TAX}}{\partial\pi_{NA}} = \psi\left[t\frac{\partial r_{NA}}{\partial\pi_{NA}} + \pi_{NA}F'(v_{NA})\frac{\partial v_{NA}}{\partial\pi_{NA}} + F(v_{NA})\right].$$

Taking into consideration that $\pi_{NA}F'(v_{NA}) = t$ and $\frac{\partial v_{NA}}{\partial\pi_{NA}} = -\frac{\partial r_{NA}}{\partial\pi_{NA}}$ and rewriting:

(A5) $$\frac{\partial\lambda^{TAX}}{\partial\pi_{NA}} = \psi F(v_{NA}).$$

Appendix B

The problem of the regulator is to minimize aggregate emissions subject to a budget constraint. Aggregate emissions are given by the weighted average between adopters' and non-adopters' emissions where the weights are given by the fraction of firms that adopt the new technology and the fraction that do not.

$$\underset{\pi_A,\pi_{NA}}{Min}\ \lambda(\pi_{\mathrm{A}},\pi_{NA})e_A+\left[1-\lambda(\pi_{\mathrm{A}},\pi_{NA})\right]e_{NA}$$
$$s.t.$$
$$\varpi\pi_{\mathrm{A}}\lambda+\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\le B$$
$$\lambda\le 1$$

The Lagrange equation for this minimization problem is given by:

$$L=\lambda e_A+\left[1-\lambda\right]e_{NA}+\gamma\left[B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\right]+\eta\left[1-\lambda\right].$$

The Kuhn-Tucker conditions are as follows:

(B1)

$$\frac{\partial L}{\partial\pi_A}=\frac{\partial E}{\partial\pi_A}+\gamma\left[-\varpi\lambda-\pi_A\varpi\frac{\partial\lambda}{\partial\pi_A}+\pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_A}\right]-\eta\frac{\partial\lambda}{\partial\pi_A}\le 0;\qquad \pi_A\ge 0;\qquad \pi_A\frac{\partial L}{\partial\pi_A}=0$$

(B2)

$$\frac{\partial L}{\partial\pi_{NA}}=\frac{\partial E}{\partial\pi_{NA}}+\gamma\left[-\varpi\left[1-\lambda\right]-\pi_A\varpi\frac{\partial\lambda}{\partial\pi_{NA}}+\pi_{NA}\varpi\frac{\partial\lambda}{\partial\pi_{NA}}\right]-\eta\frac{\partial\lambda}{\partial\pi_{NA}}\le 0;\quad \pi_{NA}\ge 0;\qquad \pi_{NA}\frac{\partial L}{\partial\pi_{NA}}=0$$

(B3)

$$\frac{\partial L}{\partial\gamma}=B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\ge 0;\qquad \gamma\ge 0;\qquad \gamma\left[B-\varpi\pi_{\mathrm{A}}\lambda-\varpi\pi_{\mathrm{NA}}\left[1-\lambda\right]\right]=0$$

(B4)

$$\frac{\partial L}{\partial\eta}=\left[1-\lambda\right]\ge 0;\qquad \eta\ge 0;\qquad \gamma\left[1-\lambda\right]=0.$$

In order to obtain the feasible set of solutions, let us now explore the different possible combinations of π_{A} and π_{NA} that are candidate solutions to the minimization problem.

CASE A. Let us assume $\pi_{\mathrm{A}} > 0$ ***and*** $\pi_{\mathrm{NA}} > 0$.

From (B1):

(B5) $$\lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0.$$

From (B2):

(B6)
$$[1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + e_A \frac{\partial \lambda}{\partial \pi_{NA}} - e_{NA} \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \left[-\varpi[1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} = 0.$$

Multiplying (B5) by $\frac{\partial \lambda}{\partial \pi_{NA}}$ yields:

(B7)
$$\left[\lambda \frac{\partial e_A}{\partial \pi_A} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_A} \right] \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \frac{\partial \lambda}{\partial \pi_{NA}} \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} = 0$$

Multiplying (B6) by $\frac{\partial \lambda}{\partial \pi_A}$ yields:

(B8)
$$\left[[1-\lambda] \frac{\partial e_A}{\partial \pi_{NA}} + [e_A - e_{NA}] \frac{\partial \lambda}{\partial \pi_{NA}} \right] \frac{\partial \lambda}{\partial \pi_A} + \gamma \frac{\partial \lambda}{\partial \pi_A} \left[-\varpi[1-\lambda] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} + \pi_{NA} \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} = 0$$

Substracting (B8) from (B7) yields:

(B9)

$$\lambda \frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}} - [1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A} - \gamma \frac{\partial \lambda}{\partial \pi_{NA}}\left[\varpi\lambda + \varpi \frac{\partial \lambda}{\partial \pi_A}[\pi_A - \pi_{NA}]\right] + \gamma \frac{\partial \lambda}{\partial \pi_A}\left[\varpi[1-\lambda] + \varpi \frac{\partial \lambda}{\partial \pi_{NA}}[\pi_A - \pi_{NA}]\right] = 0$$

CASE A1. Assuming $\gamma = 0$, i.e., the budget is not binding, from (B9) implies:

(B9a) $\lambda \frac{\partial e_A}{\partial \pi_A}\underbrace{\frac{\partial \lambda}{\partial \pi_{NA}}}_{\geq 0} - [1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\underbrace{\frac{\partial \lambda}{\partial \pi_A}}_{\leq 0} = 0 \cdot$

Condition (B9a) only holds when $\lambda \frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}} = 0$ and $-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A} = 0$. Table A1 presents the conditions under which each of these two equalities hold:

Table A1.

$\lambda \frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}} = 0$ if one of the following two conditions holds:	$-[1-\lambda]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A} = 0$ if one of the following three conditions holds:
(a) $\frac{\partial e_A}{\partial \pi_A} = 0$. It requires: $\pi_A \geq \frac{t}{\phi'(e_A^{\min *})}$ (b) $\frac{\partial \lambda}{\partial \pi_{NA}} = 0$. It requires: $\pi_{NA} \geq \frac{t}{\phi'(0)}$	(c) $\lambda = 1$ (d) $\frac{\partial e_{NA}}{\partial \pi_{NA}} = 0$. It requires: $\pi_{NA} \geq \frac{t}{\phi'(e_{NA}^{\min *})}$ (e) $\frac{\partial \lambda}{\partial \pi_A} = 0$. It requires: $\pi_A \geq \frac{t}{\phi'(0)}$

The following combinations of conditions in Table A1 satisfy condition (B9a): (a)-(c); (a)-(d); (a)-(e); (b)-(c); (b)-(d); (b)-(e). However, the following sets of combinations yield to the same conditions:

- Combination (b)-(c) and combination (a)-(e)
- Combination (b)-(c), combination (b)-(a), and combination (b)-(d).

Therefore, the following are the required combinations to fulfill condition (B9a):

(i) $\pi_A \geq \frac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} > 0$ such that $\lambda = 1$. We know that $\frac{\partial \lambda}{\pi_A} \leq 0$ and it therefore is enough to monitor with $\pi_A = \frac{t}{\phi'(e_A^{\min *})}$. Under this combination, aggregate emissions are $E = e_A^{\min *}$.

(ii) $\pi_A \geq \frac{t}{\phi'(e_A^{\min *})}$ and $\pi_{NA} \geq \frac{t}{\phi'(e_{NA}^{\min *})}$. We know that $\frac{\partial \lambda}{\pi_A} \leq 0$, and it is therefore enough to monitor with $\pi_A = \frac{t}{\phi'(e_A^{\min *})}$. Under this combination, aggregate emissions are $E = \lambda e_A^{\min *} + [1-\lambda] e_{NA}^{\min *}$.

(iii) $\pi_A \geq \frac{t}{\phi'(0)}$ and $\pi_{NA} > 0$. Under this condition, aggregate emissions are $E = \lambda e_A^{\min *} + [1-\lambda] e_{NA}^{*}$.

(iv) $\pi_{NA} \geq \frac{t}{\phi'(0)}$ and $\pi_A > 0$. Under this condition, aggregate emissions are $E = \lambda e_A^{*} + [1-\lambda] e_{NA}^{\min *}$.

Comparing aggregate emissions under combinations (i)-(iv), it is straightforward to observe that alternatives (iii) and (iv) are dominated by alternatives (i) and (ii). Combinations (i) and (ii) are therefore feasible solutions to the minimization problem. In both combinations, since we are assuming that the budget is not binding, it should hold that $\varpi \pi_{\mathrm{A}} \lambda + \varpi \pi_{\mathrm{NA}} [1-\lambda] < B$.

Let us now analyze the case when the budget is binding:

CASE A2. Assuming $\gamma > 0$, i.e., the budget is binding, from (B9) implies:

(B9b) $$\lambda \frac{\partial e_A}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} - [1-\lambda] \frac{\partial e_{NA}}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} - \varpi \gamma \left[\lambda \frac{\partial \lambda}{\partial \pi_{NA}} - [1-\lambda] \frac{\partial \lambda}{\partial \pi_A} \right] = 0$$

When $\frac{\partial e_A}{\partial \pi_A} = \frac{\partial e_{NA}}{\partial \pi_{NA}} = 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} < 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} = 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} = 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} < 0$, for condition (B9b) to hold it is required that $\lambda > 1$, which contradicts one of the restrictions.

When $\frac{\partial e_A}{\partial \pi_A} < 0$ and $\frac{\partial e_{NA}}{\partial \pi_{NA}} < 0$, for condition (B9b) to hold it is required that one of the following conditions holds:

(i) $\lambda > 1$, which contradicts one of the restrictions.

(ii) $\pi_{NA} \geq \frac{t}{\phi'(0)}$ and $\pi_A > 0$ such that $\lambda = 1$. Under this combination, aggregate emissions are $E = e_A^*$.

(iii) $\pi_A \geq \frac{t}{\phi'(0)}$ and $\pi_{NA} > 0$ such that $\lambda = 0$. Under this combination aggregate emissions are $E = e_{NA}^*$.

Clearly, combinations (i) and (ii) are dominated by the feasible combinations when the budget is not binding.

CASE B. Let us assume $\pi_{\mathrm{A}} = 0$ ***and*** $\pi_{\mathrm{NA}} > 0$.

From (B1):

(B10) $$\lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi\lambda - \pi_{NA}\varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0$$

From (B2):

(B11) $$\left[1-\lambda\right]\frac{\partial e_A}{\partial \pi_{NA}}+e_A\frac{\partial \lambda}{\partial \pi_{NA}}-e_{NA}\frac{\partial \lambda}{\partial \pi_{NA}}+\gamma\left[-\varpi\left[1-\lambda\right]-\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_{NA}}\right]-\eta\frac{\partial \lambda}{\partial \pi_{NA}}=0$$

Multiplying (B10) by $\frac{\partial \lambda}{\partial \pi_{NA}}$ yields:

(B12) $$\left[\lambda\frac{\partial e_A}{\partial \pi_A}+\left[e_A-e_{NA}\right]\frac{\partial \lambda}{\partial \pi_A}\right]\frac{\partial \lambda}{\partial \pi_{NA}}+\gamma\frac{\partial \lambda}{\partial \pi_{NA}}\left[-\varpi\lambda+\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_A}\right]-\eta\frac{\partial \lambda}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}\leq 0$$

Multiplying (B11) by $\frac{\partial \lambda}{\partial \pi_A}$ yields:

(B13):
$$\left[\left[1-\lambda\right]\frac{\partial e_A}{\partial \pi_{NA}}+\left[e_A-e_{NA}\right]\frac{\partial \lambda}{\partial \pi_{NA}}\right]\frac{\partial \lambda}{\partial \pi_A}+\gamma\frac{\partial \lambda}{\partial \pi_A}\left[-\varpi\left[1-\lambda\right]+\pi_{NA}\varpi\frac{\partial \lambda}{\partial \pi_{NA}}\right]-\eta\frac{\partial \lambda}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}=0$$

Subtracting (B13) from (B12) yields:

(B14) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-\left[1-\lambda\right]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}-\gamma\varpi\left[\frac{\partial \lambda}{\partial \pi_{NA}}\lambda-\frac{\partial \lambda}{\partial \pi_A}\left[1-\lambda\right]\right]\leq 0$$

CASE B1. Assuming $\gamma=0$, i.e., the budget is not binding, from (B14) implies:

(B14a) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-\left[1-\lambda\right]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}\leq 0.$$

Condition (B14a) holds for all $\pi_{NA}>0$.

CASE B2. Assuming $\gamma>0$, i.e., the budget is binding, from (B14) implies:

(B14b) $$\lambda\frac{\partial e_A}{\partial \pi_A}\frac{\partial \lambda}{\partial \pi_{NA}}-\left[1-\lambda\right]\frac{\partial e_{NA}}{\partial \pi_{NA}}\frac{\partial \lambda}{\partial \pi_A}\leq\gamma\varpi\left[\frac{\partial \lambda}{\partial \pi_{NA}}\lambda-\frac{\partial \lambda}{\partial \pi_A}\left[1-\lambda\right]\right].$$

Condition (B14b) holds for all $\pi_{NA}>0$.

CASE C. Let us assume $\pi_{\mathrm{A}} > 0$ ***and*** $\pi_{\mathrm{NA}} = 0$.

From (B1):

$$\text{(B15)} \quad \lambda \frac{\partial e_A}{\partial \pi_A} + e_A \frac{\partial \lambda}{\partial \pi_A} - e_{NA} \frac{\partial \lambda}{\partial \pi_A} + \gamma \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} = 0$$

From (B2):

$$\text{(B16)} \left[1-\lambda\right] \frac{\partial e_A}{\partial \pi_{NA}} + e_A \frac{\partial \lambda}{\partial \pi_{NA}} - e_{NA} \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \left[-\varpi\left[1-\lambda\right] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \leq 0$$

Multiplying (B15) by $\frac{\partial \lambda}{\partial \pi_{NA}}$ yields:

$$\text{(B17)} \left[\lambda \frac{\partial e_A}{\partial \pi_A} + \left[e_A - e_{NA}\right] \frac{\partial \lambda}{\partial \pi_A} \right] \frac{\partial \lambda}{\partial \pi_{NA}} + \gamma \frac{\partial \lambda}{\partial \pi_{NA}} \left[-\varpi\lambda - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_A} \right] - \eta \frac{\partial \lambda}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} = 0$$

Multiplying (B16) by $\frac{\partial \lambda}{\partial \pi_A}$ yields:

(B18)

$$\left[\left[1-\lambda\right] \frac{\partial e_A}{\partial \pi_{NA}} + \left[e_A - e_{NA}\right] \frac{\partial \lambda}{\partial \pi_{NA}} \right] \frac{\partial \lambda}{\partial \pi_A} + \gamma \frac{\partial \lambda}{\partial \pi_A} \left[-\varpi\left[1-\lambda\right] - \pi_A \varpi \frac{\partial \lambda}{\partial \pi_{NA}} \right] - \eta \frac{\partial \lambda}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} \leq 0$$

Substracting (B17) from (B18) yields:

$$\text{(B19)} \quad -\lambda \frac{\partial e_A}{\partial \pi_A} \frac{\partial \lambda}{\partial \pi_{NA}} + \left[1-\lambda\right] \frac{\partial e_{NA}}{\partial \pi_{NA}} \frac{\partial \lambda}{\partial \pi_A} \leq \gamma\varpi \left[\frac{\partial \lambda}{\partial \pi_A} \left[1-\lambda\right] - \lambda \frac{\partial \lambda}{\partial \pi_{NA}} \right]$$

Condition (B19) never holds.

CASE D. Let us assume $\pi_{\mathrm{A}} = 0$ ***and*** $\pi_{\mathrm{NA}} = 0$.

Given that adopters and non-adopters emit at e^0 when $\pi_{\mathrm{A}} = 0$ and $\pi_{\mathrm{NA}} = 0$, this combination is not a good candidate to minimize aggregate emissions.

Chapter 3

Unraveling enforcement:
On the substitutability of detection and enforcement efforts

Peter Martinsson[a]
Clara Villegas-Palacio[b]

Abstract

In some contexts, weak law enforcement results in only a fraction of detected transgressors actually being sanctioned. The standard theoretical models of enforcement predict that, as long as the joint probability of detection and sanction is constant, the extent of violations does not vary with different combinations of the probability of monitoring and the probability of sanction given detection. In contrast, we propose an alternative theoretical model that predicts that the extent of violation is sensitive to such combinations, i.e., these two probabilities are not perfect substitutes. By using a laboratory experiment, we investigate the hypothesis of imperfect substitutability of monitoring and sanctioning probabilities. Our subjects include both environmental managers in Colombian firms and university students. Different combination of the probabilities resulting in the same joint probability of detection and sanctioning did not affect the violation behavior among managers, while students violate relatively less when facing a higher sanctioning probability for a given joint probability.

***JEL classification*:** C91; D60; H23; H40.

***Key words*:** compliance; deterrent effect; enforcement; experiment.

[a] Department of Economics, University of Gothenburg, Gothenburg, Sweden; e-mail: Peter.Martinsson@economics.gu.se; Ph +46 31 786 52 55
[b] Department of Economics, University of Gothenburg, Gothenburg, Sweden; e-mail: Clara.Villegas@economics.gu.se; Ph: +46 31 786 26 42. Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín.

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1. Introduction

Most standard models of enforcement and compliance with environmental regulations assume that once a violation is detected, a sanction is successfully imposed. However, in many countries, especially in developing and transitional countries, detected violators are not always sanctioned.[1] There are several reasons for this, ranging from weak institutions to enforce sanctions due to lack of resources or corruption to long, tedious, and costly legal procedures (Blackman, 2009a).[2] Thus, in these contexts, the probability of being sanctioned for a violation does not correspond to the probability of being detected; instead it is determined by the joint probability of being detected in violation and being sanctioned. Following the standard model of law enforcement with an assumed risk-neutral agent, the existence and extent of violation is determined by the gains from violation and expected losses caused by sanctioning, where the latter is the product of the size of the sanction and the joint probability of detection and sanctioning (e.g., Sandmo, 2002). Following Polinsky and Shavell (2007), for risk-neutral agents, when the joint probability of detection and sanctioning can be varied, a low joint probability of detection and sanctioning together with high sanctions are optimal from a societal point of view since such a combination saves enforcement costs without changing the behavior of the regulated agents. In reality, however, there are upper limits on sanctions, and the maximal sanction may not be the optimal one for

[1] An example of this situation is the following. Among Discharge Fee programs in developing countries, perhaps the best known is Colombia's wastewater discharge fee program (Blackman, 2009a), which requires the regulated polluters to self-report their discharges. Briceño and Chávez (2007) point out that some firms report false pollution levels with the intention of attaining a lower level of pollution fee. The verification of these self-reports is done through visits by the local environmental authorities to the regulated firms, yet there are no monetary sanctions that punish false reports of wastewater discharges. Moreover, the audits are very few and there are no reliable records for measuring the size of the transgressions.

[2] Citing Zinnes (1997), Blackman (2009b) presents Romania's experience with discharge fees as an example of enforcement problems in discharge fee programs in transitional countries. In 1993, about a quarter of the fines levied were collected in Romania. In Poland, in the early 1990s, only about 20% of fines charged were actually collected (Anderson and Zylicz, 1996). Another consequence of a weak institutional setting is the possible corruption of law enforcement agents, which erodes deterrence. For a review on corruption and enforcement, see Polisnky and Shavell (2007).

reasons such as limited wealth of individuals and considerations of fairness and risk preferences among people (Becker, 1968; Polinsky and Shavel, 2000).[3]

It might be claimed that the traditional models of law enforcement implicitly assume that the probability of detection and the probability of sanctioning given detection are perfect substitutes. The same joint probability of detection and sanctioning can be achieved by using different combinations of the probability of detection and the probability of sanctioning. Therefore, as long as the joint probability of detection and sanctioning is constant, the extent of violations will not change with different combinations of these two probabilities. However, agents' compliance behavior is not only determined by risk preferences, monetary benefits, and expected legal costs from violating. It may also be influenced by other motivations such as image concerns, intrinsic motivations, and legitimacy of the regulation (e.g., Andreoni et al., 1998; Torgler, 2002; Tyler, 2006). While intrinsic motivations to comply with regulations are associated with internal rules that are self-enforced, image motivation focuses on the fact that an agent derives utility from how her fellows perceive her, i.e., social approval. Legitimacy is a perceived obligation to authorities or existing social arrangements and, because of it, people feel that they ought to voluntarily obey rules (Tyler, 2006).[4] A regulated agent might use compliance behavior as an opportunity to express acceptance and legitimacy of the regulation to the authority or non-compliance as a way to express disapproval of the rule in place in an attempt to, somehow, influence future regulations. In this setting, the total expected cost of violating for a regulated agent consists of the expected legal cost, the intrinsic cost, the expected image cost, and the expected cost related to legitimacy

[3] Some studies have assessed the optimal trade-off between the probability of detection and sanctioning and the size of the fines (e.g., Shavell and Polinsky, 1979; Andreoni, 1991; Polinsky and Shavell, 1991; Bebchuk and Kaplow, 1992, 1993; Kaplow, 1992; Garoupa, 2001; Fees and Wohlschlegel, 2009) .

[4] According to Tyler (2006), although legitimacy and morality are similar in many ways, they are also differentiable. Legitimacy is a perceived obligation to societal authorities or to existing social arrangements. Moral values are personal standards to which people attempt to align their behavior. People obey most everyday laws because they feel that they have to obey legitimate authorities and because they believe that the prohibited conduct is morally wrong. Morality operates as a check against following immoral orders given by legitimate authorities.

consideration. Some of these expected costs, like image costs and costs related to legitimacy, are determined by the probability of being detected in violation but not necessarily by the joint probability of being detected and legally sanctioned. Therefore, for a given level of sanction, different combinations of the probability of detection and the probability of sanctioning given detection can result in different behavioral responses of the regulated agents. Thus, a new trade-off remains to be solved: the optimal trade-off between the probability of detection and the probability of sanctioning given detection.

The contribution of the present paper is twofold. First, we develop a theoretical model that, in addition to expected legal costs, takes into account intrinsic costs, expected image costs, and the expected costs related to legitimacy consideration faced by an agent when making compliance decisions. In contrast to the standard model of law enforcement, our theoretical model predicts that varying the combination between the probability of detection and the probability of sanction given detection affects the extent of violations, even if the joint probability of detection and sanctioning is kept constant. Second, by using a laboratory experiment, we empirically test our theoretical predictions that different combinations of the probability of detection and the probability of sanction result in different extents of violation even when the joint probability is kept constant. We run two treatments to test our hypothesis. In one treatment, the probability of being monitored is high and the probability of sanctioning low, while in the other treatment these probabilities are reversed. This allows us to test the effect of mixing the probabilities while keeping the joint probability fixed using a between-subject design.

Few papers have used laboratory experiments to examine compliance behavior of firms under environmental regulations.[5] In our experiment, each subject represents a firm

[5] Cason and Gangadharan (2006) use laboratory experiments to identify interactions between emission shocks, banking, compliance, and enforcement in an emissions trading market in the presence of emissions uncertainty. Murphy and Stranlund (2006) study the direct effects of enforcement on compliance and emission decisions as well as the indirect effects that occur due to changes in permit prices. In a later paper, Murphy and Stranlund

that produces a given quantity of emissions and is regulated by environmental taxes with a requirement to self-report emission levels.[6]

To our knowledge, all available evidence on behavior when monitoring and enforcing compliance of laws comes from laboratory experiments where students have been used as subjects. These results may be biased if those who make compliance decisions in the field behave differently from students. Some recent experiments have investigated subject pool effects. For example, Fehr and List (2004) compared Costa Rican CEOs and students, and Haigh and List (2005) looked at professional traders at the Chicago Board of Trade versus students, and found differences in both cases. In our experiment, we also test subject pool effects by using one sample of environmental managers of Colombian firms and another consisting of Colombian university students. This allows us to compare decisions made by university students to those made by experienced decision makers.

The structure of the paper is as follows. Section 2 presents a theoretical model of compliance with environmental tax schemes under imperfect enforcement. Section 3 provides details about the experimental design and procedures. Section 4 presents the results and, finally, Section 5 concludes the paper.

2. Firm behavior under imperfect monitoring and enforcement

Although with a different focus, our model builds on Sandmo (2002), who in his model explores the conditions under which the efficiency properties of taxes continue to hold

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(2007) test the hypotheses that the violations of risk neutral firms and the marginal effectiveness of increased enforcement across firms are independent of differences in their abatement costs and their initial permit allocations. Stranlund et al. (2008) investigate whether gross profit, aggregate expected penalties, and aggregate expected net profits deviate from theoretical predictions based on risk-neutral profit-maximizing firms with imperfect enforcement. Their findings suggest that observed violations in the experimental setting are lower than the predicted levels when subjects have strong incentives to violate their emission permits, and that individual emissions control responsibilities are distributed among firms as predicted.

[6] Our experiment resembles the research on income and tax evasion, where both laboratory experiments (e.g., Alm, 1992; Fortin et al., 2007; Friedland et al., 1978; Trivedi et al., 2003) and field experiments (e.g., Slemrod et al., 2001) have been used.

even when evasion is possible.[7] In our modeling approach, we focus on the behavior of a single competitive agent regulated by a system of uniform emission taxes. In the absence of environmental regulation, the agent emits e^0 units of pollution. To control her emissions, the agent must incur abatement costs $c(e)$, which are a function of the agent's selected emissions level e.[8] The abatement cost function represented as $c(e)$ is a strictly convex function with the following properties $c'(e) < 0, c''(e) > 0$. Let us assume that the agent must pay a uniform tax t per unit of pollutant emitted and that the tax is based on the self-reported emission level. If the firm makes a truthful report, the total amount of taxes to be paid is equal to te. However, the firm can evade tax by reporting a lower level of emissions. If the firm reports emissions equal to r, where $r < e$, then the total tax payment is given by tr. In this case, the agent's violation, v, is equal to the difference between the actual and self-reported emission levels, $v = e - r$, and the amount of tax evaded is equal to tv.[9]

In line with previous literature we assume that the regulator cannot monitor emissions perfectly without costs, and thus relies on a system of random inspections. Let π_d denote the probability that the regulator monitors the agent. We assume that π_d is exogenous and common knowledge among the agents. Moreover, we assume that the regulator can perfectly observe emission level and hence compliance status is perfectly determined.[10] This is to say that the probability of detection is equal to the probability of monitoring. If the monitoring reveals that the agent is non-compliant, i.e. if the agent is detected under-reporting

[7] Hardford (1978) was first to, in a rigorous model, study the consequences that follow from tax evasion by focusing on firm behavior under imperfectly enforceable pollution standards and taxes. Hardford (1987) extended his own work by considering self-reporting of emissions.

[8] Henceforth, for the sake of notation, we will use parentheses (.) to denote a function and brackets [.] to denote multiplication.

[9] The requirement to self-report emissions is common in the literature. Hardford (1987), Malik (1993), Kaplow and Shavell (1994), Livernois and McKenna (1999), Sandmo (2002), Macho-Stadler and Pérez Castrillo (2006), and Macho-Stadler (2008) included self-reporting in their analyses of enforcement policies and compliance.

[10] As Sandmo (2002) notes, the assumption of an exogenous probability of being monitored is a simplification. It is more realistic to assume that monitoring probability is a function of regulated firms' actions. We leave this point for future work.

emissions, the probability that a sanction is actually imposed is $\pi_{s|d}$. Thus, the joint probability of detection and sanction π is given by the product of π_d and $\pi_{s|d}$, i.e., $\pi = \pi_d \pi_{s|d}$. Traditionally, it has been assumed that the penalty is enforced with certainty, i.e., $\pi_{s|d} = 1$, and thus the joint probability of detection and sanction is $\pi = \pi_d$. The legal sanction $F(e-r)$ is determined through a strictly convex function in the level of violation $F'(e-r) > 0,\ F''(e-r) > 0$[11]. A convex penalty function is common in the literature, e.g., Harford (1978), Harford (1987), Sandmo (2002), and Macho-Stadler and Perez Castrillo (2006). If the probability of being detected is exogenous and the marginal penalty is constant, then the decision on reporting emissions will be binary by choosing between self-reporting everything and reporting nothing (e.g., Sandmo, 2002). For zero violation, the legal penalty is zero *F(0)=0*, but the marginal penalty is greater than zero: *F'(0)>0*. We assume that $\pi_{s|d}$ is exogenous and common knowledge among regulated agents. In addition to the legal sanction, we assume that the agent considers three additional factors when deciding the amount of emission to self-report: image motivations, intrinsic motivations, and legitimacy issues.

First, detection of violation can have an image effect in the eyes of peers regulated by the same law or society in general. In fact, policies such as public disclosure of environmental performance of firms are hypothesized to have an impact by improving the information communities, consumers, and other stakeholders have about individual firms (Blackman 2009b). This suggests the existence of image concerns among regulated agents, and these concerns are contingent on the probability that their actions will be observed by others. We assume that the probability of the regulator disclosing compliance behavior of each firm, denoted α, is exogenously given and common knowledge among agents.

[11] According to Farmer (2007), in practice sanctions are used worldwide yet their features vary. For example, under the EU trading scheme there is fixed financial penalty of EUR 40 per metric ton of carbon dioxide emitted above a company's allocation. Under the US trading schemes, there are automatic excess emission penalties. These are significantly higher than the market price for allowances and, therefore, vary.

Moreover, we assume that the probability of disclosure is the same for both violators of and compliers with the regulation. In our model, $0 \le \alpha \le 1$. In case $\alpha > 0$, image motivations may influence the decision of under-reporting. The image cost when not complying with the regulation is expressed by the function $I(e-r)$. In a pro-social environment where violation is socially punished by others, the agent will not face any image cost when reporting emissions truthfully, $I(0)=0$. In such an environment, if the agent under-reports emissions, i.e., $e-r>0$, the image cost increases in the level of violation, $I'(e-r)>0$. It seems natural to assume that, as the legal penalty, the image cost faced by an agent is progressive, i.e., significant under-reporting implies an image cost per under-reported unit that is higher than for small under-reported amounts, $I''(e-r)>0$. In a context where complying with the regulation is socially punished by others, an agent will face no image cost if she under-reports all her emissions, $I(e)=0$. In such a context, if the agent makes a positive report of emissions, her image cost decreases with the level of violation, $I'(e-r)<0, I''(e-r)>0$. If the extent of violation is not going to be disclosed to other regulated agents or to society in general, then the expected image cost equals zero.

Second, we assume that even if not detected, the agent may still bear a cost related to her intrinsic motivations from violating a regulation. In case of a firm, the intrinsic motivations can be interpreted as the existence of internal policies such as Corporate Social Responsibility policies. Portney (2005) argues that firms engage in Corporate Social Responsibility policies for two reasons: (i) *"firm managers have a moral obligation because of the charcter society gives them to operate*" and (ii) it is often in the economic interest of the firm not to violate. The intrinsic cost when not complying with the regulation is expressed by the function $M(e-r)$. The agent does not face any moral cost when reporting truthfully, $M(0)=0$. If the agent under-reports emissions, i.e., $e-r>0$, the moral cost increases in the level of violation $\mathrm{M}'(e-r)>0$. Analogous to the case of image costs and legal penalties, we assume that the moral cost faced by an agent is progressive in the level of violation $M''(e-r) > 0$. In our model, we assume that image motivations and intrinsic motivations are independently formed. This is to say that intrinsic motivations are not a function of prevailing compliance norms among regulated agents and in society in general. These two motivations, however, can go in the same direction, i.e., when the agent considers it morally wrong and it is socially punished to violate the regulation.

Third, we also consider that there is an effect related to the legitimacy of the policy. Legitimacy is defined by Tyler (2006) as the belief that authorities, institutions, and social arrangements are appropriate, proper, and just. Previous literature, e.g., in Tyran and Feld (2006) and Cárdenas et al. (2000), points out that exogenously imposed regulations do not always achieve compliance, but that compliance is improved if the law is endogenously chosen or self-imposed. This suggests that laws that are negotiated with the agents and therefore legitimated are more likely to be obeyed. In our model, we assume that regulated agents may use non-compliance as a way to express their assessment about the legitimacy of the policy to the regulator in an attempt to influence the type or design of the regulation in future periods[12]. A regulated agent that considers the regulation as legitimate faces a cost from violating since it gives the wrong message about legitimacy to the regulator. This effect is represented by the function $L(e-r)$. If the agent considers that the regulation is legitimate, she will not face any cost related to legitimacy when reporting emissions truthfully, $L(0) = 0$. In such a case, if the agent under-reports emissions, i.e., $e-r > 0$, the image cost increases in the level of violation $L'(e-r) > 0$ at an increasing rate $L''(e-r) > 0$. In a situation where the agent considers the regulation not to be legitimate, she will face no cost related to legitimacy if under-reporting all her emissions $L(e) = 0$. In such situation, if the agent makes

[12] In order to make this assumption, we will also assume that the firms consider that the regulator will make naïve inferences about the firm' compliance and will attribute compliance behavior only to legitimacy concerns among the firms.

a positive report of emissions, the cost related to legitimacy decreases with the level of violation at an increasing rate $L'(e-r)<0, I''(e-r)>0$. If the regulated agent is not monitored, there is no cost associated with legitimacy since the regulator will not observe the extent of compliance and therefore will not be able to infer anything about the agent's legitimacy assessment of the regulation.[13]

For the sake of clarification, consider the following. An agent prefers to always comply with the law. This agent feels it is wrong to break the law and violating a regulation is against her intrinsic motivations. Such an agent will face an intrinsic cost of under-reporting emissions in an effort to evade environmental taxes since it constitutes a violation of a law. If the agent perceives the regulation of paying for emissions as appropriate or legitimate, she will also face a cost of violating the regulation since it implies sending the wrong message to the regulator about the legitimacy of the policy. In this case, both intrinsic motivations and legitimacy motivations go in the same direction. However, it could be the case that the particular policy of self-reporting emissions, or even paying for the emissions is perceived by the agent as inappropriate or not legitimate. In such a case, intrinsic and the legitimacy motivations go in opposite directions. On one hand, when complying with the regulation, the agent faces a cost related to legitimacy. On the other hand, the agent faces an intrinsic cost when non-complying with the regulation since it constitutes breaking a law.

The total effect of intrinsic motivations, image motivations, legitimacy motivations, and legal penalties on the extent of under-reporting depends not only on the magnitude of the cost for each effect, but also on the relative importance assigned by the agent to each of them. The importance assigned by the agent to legal sanctions is denoted β;

[13] In our model, we assume that image cost, moral cost, and cost of signaling legitimacy never take a negative value; i.e., we assume that there are no image benefits, moral benefits, or benefits from legitimacy associated with compliance behavior.

to image motivations γ; to intrinsic motivations θ; and to legitimacy motivations η. The weights are such that $\gamma+\beta+\theta+\eta=1$, where $0\le\gamma\le1$; $0\le\beta\le1$; $0\le\eta\le1$; and $0\le\theta\le1$.

The regulated agent selects the actual and reported emission levels that minimize her expected costs of abatement and compliance as shown in equation (1):

(1) $$\underset{e,r}{Min}\ c(e)+tr+\beta\pi_d\pi_{s|d}\left[F(e-r)\right]+\gamma\pi_d I(e-r)\alpha+\eta\pi_d L(e-r)+\theta M(e-r)$$

$$s.t.\ e-r\ge 0.$$

The constraint in the optimization problem reflects the fact that there are no economic incentives to over-report emissions since it implies paying more taxes. The Lagrange equation for (1) is $\varphi=c(e)+tr+\beta\pi_d\pi_{s|d}\left[F(e-r)\right]+\gamma\pi_d I(e-r)\alpha+\eta\pi_d L(e-r)+\theta M(e-r)-\lambda\left[e-r\right]$.

If we assume a positive actual and reported emission level, the Kuhn-Tucker conditions, which are necessary and sufficient to determine the firm's optimal choices of levels of emissions and reports, are

(2) $$\frac{\partial\varphi}{\partial e}=c'(e)+\beta\pi_d\pi_{s|d}\left[F'(e-r)\right]+\gamma\pi_d I'(e-r)\alpha+\eta\pi_d L'(e-r)+\theta M'(e-r)-\lambda=0,$$

(3) $$\frac{\partial\varphi}{\partial r}=t-\beta\pi_d\pi_{s|d}\left[F'(e-r)\right]-\gamma\pi_d I'(e-r)\alpha-\eta\pi_d L'(e-r)-\theta M'(e-r)+\lambda=0,$$

(4) $$\frac{\partial\varphi}{\partial\lambda}=e-r\ge 0;\lambda\ge 0;\lambda\left[e-r\right]=0.$$

Based on the first order conditions, for a situation in which $0<r^*<e^*$, the agent chooses her optimal emission level e^* such that the marginal abatement cost equals the tax rate, $e^*=\left\{e\middle|c'(e)+t=0\right\}$. The optimal choice of self-reported level of emission r^* is determined such that the marginal cost of under-reporting equals the tax rate. The marginal cost of under-reporting is now given by four elements: (i) the weighted marginal expected legal fine in case there is a sanction $\beta\pi_d\pi_{s|d}\left[F'(e-r)\right]$, (ii) the weighted marginal expected cost derived from image concerns $\gamma\pi_d I'(e-r)\alpha$, (iii) the weighted marginal cost derived

from moral motivations $\theta M'(e-r)$, and the weighted marginal expected cost derived from legitimacy issues $\eta\pi_d L'(e-r)$. Therefore, the optimal self-reported emission is given by

(5) $$r^* = \left\{ r \middle| t - \beta\pi_d\pi_{s|d}\left[F'(e-r)\right] - \gamma\pi_d I'(e-r)\alpha - \eta\pi_d L'(e-r) - \theta M'(e-r) = 0 \right\}.$$

From equation (5), the extent of under-reporting is a function of the probability of detection, the joint probability of monitoring and sanction, the tax rate and the importance assigned to all motivations to comply with the regulation together with the parameters of the functions associated to them $v = v(\pi_d, \pi_d * \pi_{s|d}, t, \alpha, \beta, \gamma, \theta, \eta)$. If only the legal fine matters for the agent, which is the standard case in the literature, i.e., $\gamma\pi_d I'(e-r)\alpha = \theta M'(e-r) = \eta\pi_d L'(e-r) = 0$ and $\beta = 1$, then the optimal self-reported emission is given by equation (6).

(6) $$r^* = \left\{ r \middle| t - \pi_d\pi_{s|d}\left[F'(e-r)\right] = 0 \right\}.$$

In the standard case, only the tax rate, the joint probability, and the size of the marginal fine matter when deciding the extent of violation, $v = v(\pi_d * \pi_{s|d}, t)$.[14]

To investigate the predictions of our model, assume that the regulator decides to increase the probability of detection $d\pi_d > 0$, at the expense of reducing the probability of sanctioning, i.e., $d\pi_{s|d} < 0$, but keeps the joint probability constant such that $d\left[\pi_d\pi_{s|d}\right] = \pi_d d\pi_{s|d} + \pi_{s|d} d\pi_d = 0$. By definition, the change in the extent of violation is given by a simultaneous change in the probability of detection and probability of sanctioning:

(7) $$dv = \frac{\partial v}{\partial \pi_d} d\pi_d + \frac{\partial v}{\partial \pi_{s|d}} d\pi_{s|d}.$$

[14] When the agent-reported emission level is greater than zero, $r > 0$, the probability of detection and sanctioning influences the extent of under-reporting only through the self-report level, i.e. emissions are not a function of enforcement parameters which is the standard result in the literature (see Harford, 1978).

Taking the partial derivatives of equation (6) with respect to π_d and $\pi_{s|d}$ and replacing them in equation (7) yields the standard model prediction of the change in violation due to changes in π_d and $\pi_{s|d}$ (see Appendix A for derivation) as shown in equation (8).

$$(8) \qquad dv = \frac{-F'(v)}{\pi_d \pi_{s|d} F''(v)} \left[\pi_d d\pi_{s|d} + \pi_{s|d} d\pi_d \right] = 0$$

In case the joint probability is kept constant in the standard model, the extent of violation is not sensitive to changes in π_d and $\pi_{s|d}$. In our model, which also considers image, intrinsic, and legitimacy motivations, the optimal self-reported level of the firm is given by equation (5). Taking partial derivatives of (5) with respect to π_d and $\pi_{s|d}$ and replacing in (7) (see Appendix A for derivation) yields:

$$(9) \qquad dv = -\left[\frac{\gamma I'(v)\alpha + \eta L'(v)}{\psi} \right] d\pi_d \,,$$

where $\psi = \gamma\pi_d I''(v) + \theta M''(v) + \beta\pi_d \pi_{s|d} F''(v) + \eta\pi_d L''(v)$. From equation (9), the change in violation depends on the change in the weighted average of expected marginal image and expected marginal cost related to legitimacy, i.e., $[\gamma I'(v)\alpha + \eta L'(v)] d\pi_d$. This change is determined by the change in π_d. A larger change in the probability of detection results in a larger change in the extent of violation. If the result of the monitoring is not disclosed, i.e., $\alpha = 0$,it is implied that if the regulator increases the probability of detection $d\pi_d > 0$ but keeps the joint probability constant, then the extent of the violation decreases if and only if the regulation is perceived by the firm as legitimate, i.e., if $L'(e-r) > 0$. If, on the contrary the firm wants to send the message to the authority that the regulation lacks legitimacy, her extent of violation increases with the detection probability.

Hence, in contrast to the standard model of law enforcement, our theoretical model predicts that even when joint probability is kept constant, different combinations of detection and sanction probabilities will yield different extents of violations. Moreover, our model predicts that the difference in extent of violation between different combinations depends on the difference in detection probability between them. Larger differences in detection probabilities lead to larger differences in the extent of violations. The next section presents the experimental design and procedures of a laboratory experiment conducted to test the theoretical predictions of our model.

3. Experimental design and Procedures

To test the predictions of our theoretical model regarding the substitutability between the probability of detection and the probability of sanctioning, we conducted a series of laboratory experiments. We framed the experiment in the context of a firm that is regulated by environmental taxes and that is required to self-report its emissions.[15] The regulatory system has two key features: (i) an environmental tax is paid based on the self-reported amount of emission and (ii) the self-reported amount is monitored with a given known probability followed by a known probability of sanctioning given detected violation. In the experiment, each subject represents a firm that decides how much of the amount emitted to self-report for environmental taxation. Each firm is assumed to produce a given quantity of goods determined by the market conditions and a given amount of emission determined by the existing abatement technology. The amount of emissions from the production process was fixed to 15 units.[16]

[15] Murphy and Stranlund (2007) frame their experiment in terms of a production decision to avoid that attitudes with respect to the environment affect their result. We frame our experiment in the context of compliance with environmental taxes regulation given that one of our sample pools consists of environmental managers in firms regulated by the National Discharge Fee Program in Colombia and we wanted to see if their experience has influence on the results. Additionally, we also want to capture the effect of intrinsic motivations which could potentially be affected by attitudes with respect to the environment. However, we do not think of this as a problem given our between subjects design and that participants were randomly assigned to each treatment.

[16] Our participants did not decide on the real emissions. We tried this in a pilot study, but the subjects became confused. We detected this based on their choices and a follow-up questionnaire given after the experiment. Thus, we decided to keep the amount of emissions constant; hence they only had to decide on reported level of emission.

At the beginning of the experiment, each firm was given an endowment, *E*, of 50,000 tokens, which represents the profit from the production of goods before abatement and before the emission level was reported to the authority for environmental tax purpose. For each unit of pollutant emitted, the firm had to pay a fixed tax of 2,000 tokens. Thus, the total amount paid depends on how much emission the firm has self-reported. Each firm can self-report any emission level in the interval 0 to 15 units. Each firm faced a known and exogenous probability of being monitored by the regulator, π_d. Monitoring implies the authority comparing the firm's reported emissions to its true emission level. It was known by the subjects that once a firm is monitored, the regulator can perfectly determine the true emission level; hence detection and monitoring probabilities are equal. The probability of a firm being monitored was independent of the probabilities of other firms being monitored. If the firm was found under-reporting emissions, the regulator started a legal process to impose a sanction. However, not all of the initiated sanctioning processes were successful. Rather, each firm caught under-reporting emissions faced a known and exogenous probability of being sanctioned $\pi_{s|d}$. The probability of a firm being sanctioned given that it was caught under-reporting was independent of the probability of other detected firms being sanctioned. If sanction was imposed, the firm was penalized according to a sanction structure generated from a quadratic function $S = f(e-r) + \frac{g}{2}(e-r)^2$, where the parameters were set to *f=350* and *g=320* in the experiment. This quadratic specification for the penalty function was first used in experiments by Murphy and Stranlund (2006, 2007). The pay-off in tokens for individual *i*, P_i, was calculated as $P_i = E - tr$ if sanction was not imposed, while it is $P_i = E - tr - S$ if sanction was imposed. To facilitate calculations of actual pay-offs for different actions, each subject was given a pay-off matrix (shown in Appendix B), which shows the total earnings in tokens for all levels of self-reported emissions both with and without sanctioning.

Participants were recruited to the experiments from two sample pools: (i) students from Corporación Universitaria Lasallista, Medellín-Colombia and (ii) environmental managers of firms associated to the National Industrials' Association (ANDI) who participated in the 3rd academic meeting of ANDI-Medellín. Most of the firms participating in this academic meeting are regulated by the National Wastewater Discharge Fee Program in Colombia, in which firms are required to self-report their discharges.[17] Having two different sample pools allows us to compare the behavior of students with that of experienced decision makers. Earnings of the subjects in tokens were translated into Colombian pesos (COP). For the students pool, each token was converted to 0.5 COP, and for the environmental managers sample, one token was converted to one COP.[18] Subjects in both pools were paid 5,000 Colombian pesos (COP) for agreeing to participate and showing up on time. It should be noted that it was more convenient for the managers to participate since they were already at the venue of the experiment. This motivated why two groups with different opportunity cost have the same show-up fee.

In the experimental design, we have two treatments, each consisting of three combinations of the probability of detection and sanctioning. In the first treatment, which we label the High-Low treatment, subjects face three combinations of high probability of detection and low probability of sanctioning given detection. In the other treatment, labeled the Low-High treatment, subjects face three combinations of low probability of detection and high probability of sanctioning given detection. The experimental design is summarized in Table 1. As can be read from the table, combinations High-Low1 and Low-High1 have the

[17] For a complete description of the National Discharge Fee Program in Colombia, see, e.g., Blackman (2009a).

[18] In cases with samples with different opportunity costs, the absolute amount in either the experiment or the opportunity cost can be kept constant. We decided to keep the opportunity cost constant; it should be noted that Kocher et al. (2008) did not find a significant stake effect in a one-shot public goods game.

same joint probability, but different detection and sanctioning probabilities. In High-Low1, the probability of detection is 1 and the probability of sanctioning is 0.1, while the probabilities are reversed in Low-High1. The same design holds for the pairs High-Low 2 and Low-High2 with a joint probability of 0.16 as well as for High-Low 3 and Low-High3 with a joint probability of 0.28. Each subject was randomly assigned to either High-Low or Low-High and, thus, the effect of joint probabilities are tested in a between subjects design. To preserve confidentiality, earnings were privately paid in cash at the end of each experiment in a separate room. Each experimental session lasted about 1.5 hours.

Table 1. Experimental design.

Combination	***Probability of monitoring*** π_d	***Probability of sanctioning given detection*** $\pi_{s\|d}$	***Joint probability of monitoring and sanctioning*** $\pi_d * \pi_{s\|d}$
		High-Low Treatment	
High-Low1	1.0	0.1	0.10
High-Low2	0.8	0.2	0.16
High-Low3	0.7	0.4	0.28
		Low-High Treatment	
Low-High1	0.1	1.0	0.10
Low-High2	0.2	0.8	0.16
Low-High3	0.4	0.7	0.28

If firm act according to the standard model of economics of crime, we would observe the same extent of violation in the combinations with the same joint probabilities: High-Low1 and Low-High1; High-Low2 and Low-High2; High-Low3 and Low-High3. However, if firms consider aspects in addition to the pure expected monetary fines when making their decision on how much to self-report, we would expect different levels of violations in each pair of combinations. The difference in detection probability $d\pi_d$ between High-Low1 and Low-High1 is larger than the one between High-Low2 and Low-High2, which in turn is larger than the difference between High-Low3 and Low-High3. According to the predictions of our theoretical model, for a given joint probability of detection and sanction, the probability of detection itself is important, and therefore we would observe a difference in the extent of violations between our pairs of combinations as follows: $dv_{HL1-LH1} > dv_{HL2-LH2} > dv_{HL3-LH3}$ (see equation 9). Given that in our experiment the results of the monitoring are not disclosed, i.e., $\alpha = 0$, the image concerns effect in our extended model disappears. The direction of the change in violation, i.e., whether it is higher under High-Low or under Low-High, will therefore only depend on how our participants perceive the legitimacy of the regulation as shown in equation (9).

We conducted a pencil and paper experiments. For the student pool, we ran two sessions, i.e., one per treatment. In the first session, 30 students faced the High-Low combinations; in the second session, 30 students faced the Low-High combinations. For the environmental managers' pool, we ran one session with 39 participants, of which 20 faced Low-High combinations and 19 faced High-Low combinations. In the beginning of a session, the instructions were handed out. They included a description of the experiment, an example of how the experiment works, and some control questions to ensure that participants had understood the instructions before proceeding. The instructions were the same in the two treatments. Then the experimenter read aloud the instructions and answered questions. Once all subjects had completed the comprehensive questions, they had the possibility to ask any remaining question in privacy to the experiments. Then the experiment began. Once all subjects had handed in their self-report decisions on amount to self-report, the experimenter randomly selected which of the three combinations would be used for payment in cash; this procedure was described in detail in the instructions. Based on the probabilities in the selected combination, the instructor ran a lottery for each participant to decide whether he/she would be monitored and whether he/she would be sanctioned conditional on being caught under-reporting. The lottery was conducted by using the random number generator in EXCEL. A witness belonging to the same sample pool, who did not participate in the experiment, certified that the process was indeed random.

4. Results

This section presents the analyses of the experiment, but let us first present some socio-economic characteristics of our sample. Table 2 presents the descriptive statistics of our sample. In addition to gender and age, we collected information on morality and risk preferences as well as on some other background variables. We use the Moral Judgment Test (Lind et al., 1985), which is based on the theory of social development (Kohlberg, 1969), to measure the effect of so-called moral judgment competence on the compliance decision.[19] Moral judgment competence was defined by Kohlberg as “the capacity to make decisions and judgments which are moral and to act in accordance with such judgments” (Lind, 2000). This competence is indexed by the C-index, which ranges from zero to one hundred. According to Lind (2000), the C-index can be used to classify people into four categories of moral development: low (1-9), medium (10-29), high (30-49), and very high (above 50).

We measure risk preferences using Binswanger’s (1980) risk experiment, which asks the subject to choose one option out of two in ten choice sets presented to them. In each choice set, option A offers a fixed and for sure payment, while option B consists of a lottery with two possible outcomes, either winning twice the amount offered in A or zero. By varying the probability of winning in option B, the attitude toward risk can be determined. The probability of winning in option B is decreasing from one choice set to the next and, thus, the point at which subjects switch from option B to option A gives an indication of their risk aversion.

[19] Ibañez (2007) uses the Moral Judgment Test to explain the decision of cropping coca by farmers in Putumayo, Colombia.

Table 2. Descriptive statistics.

Variable	Description	Students		Managers		H_0: No difference between subject pools (P-value)
		Mean	Std dev.	Mean	Std dev.	
Female	1 if female, otherwise 0	0.47	0.50	0.51	0.50	0.44
Age	Age in years	21.2	2.57	28.54	6.22	0.00
Index of moral judgment competence	C-index (0-100)	14.37	8.94	13.93	10.46	0.32
Low index of moral judgment competence	*C-index (0-9) (20 students and 17 managers)*	*5.53*	*2.11*	*4.52*	*2.71*	*0.07*
Medium index of moral judgment competence	*C-index(10-29) (37 students and 19 managers)*	*17.43*	*6.25*	*19.37*	*7.18*	*0.03*
High index of moral judgment competence	*C-index (30-49) (3 students and 3 managers)*	*35.42*	*1.64*	*32.84*	*1.14*	*0.34*
Very high index of moral judgment competence	*C-index(50-100) (0 students and 0 managers)*	-	-	-	-	
Measure of risk aversion	Continuous variable within the interval (0,1]. The higher the number, the higher the risk aversion.	0.67	0.17	0.74	0.14	0.00
Guilt	Guilt from under-reporting 1. No guilty at all 5. Extreme guilt	3.45	1.03	3.47	1.21	0.62
Shame	Shame from being caught under-reporting 1. Not ashamed at all 5. Extremely ashamed	3.89	0.99	3.60	1.19	0.06

Note: P-values are based on a Mann-Whitney test for age, index of moral development, and risk aversion, while gender, guilt, and shame are based on a chi-squared test.

In our sample, we find that managers are significantly older and also significantly more risk averse than are students.[20] To elicit influence of emotions such as guilt and shame in decisions, we asked our participants after they had made their reporting decisions to indicate on a 1-5 scale (1=no guilt or shame; 5= extreme guilt or shame) the degree of guilt and shame they would feel if caught under-reporting emissions. The differences in guilt and shame between students and environmental managers are not significant at the 5% level.

Table 3 presents the description of the under-reporting in the experiment for students and managers separately and also for the different joint probabilities in the two treatments separately. In both treatments, the extent of under-reporting is lower than predicted by the standard model of economics of crime. This is an indication that our subjects had additional considerations when deciding about the extent of violations. Students under-report more than managers for all combinations in both treatments. Within High-Low and Low-High, we observe a reduction in violation as the joint probability increases from High-Low1 to High-Low3 and from Low-High1 to Low-High3 respectively, which is according to the standard model and also a possible outcome of our extension of the standard model.

Table 3. Descriptive statistics for violation.

Combination	***Violation by managers***		***Violation by students***	
	Mean	***Std. dev.***	***Mean***	***Std. dev.***
High-Low1	6.42	4.82	8.96	4.34
High-Low2	5.47	4.36	7.10	2.67
High-Low3	3.79	3.54	5.30	3.67
Low-High1	6.55	5.59	6.13	4.36
Low-High2	5.10	4.49	6.13	3.55
Low-High3	3.50	3.58	5.63	3.54

[20] Most environmental managers who participated in our experiments are environmental engineers in charge of the environmental management department of the firms. Environmental engineering as a profession is relatively new in Colombia (it has been offered at universities for around 12 years). This explains why the average age of environmental managers is 29.

Table 4 presents the test results of the null hypothesis of no differences in under-reporting for the same joint probabilities. In the case of our student sample, by using a Mann-Whitney test, we observe that there is a significant difference in the extent of violations only for High-Low1 and Low-High1. This can be explained from our extended model, in which the change in detection probability ($d\pi_d$) determines the size of the change in violations (see equation 9). Additionally, we observe that violations of students in High-Low are higher than violations in Low-High with the exception of High-Low3. This is consistent with our theory model which predicts an increase in the extent of violation when $d\pi_d > 0$ and $L'(v) < 0$.

By using a Mann-Whitney test, we find that the violations among managers are unaffected by changes in composition of monitoring and sanctioning probabilities when the joint probability is kept constant. In our theoretical model, this happens when the importance assigned to the legitimacy motivations is zero (see equation 9). This, together with the fact that, in our experiment, monitoring results are not disclosed, imply that managers only considered the expected legal fine and intrinsic motivations when making compliance decisions.

Table 4. Test of null hypothesis of no difference in violation for the same joint probabilities.

Null hypothesis	Students (p-value)	Managers (p-value)
No difference in violation between High-Low1 and Low-High1	0.02	0.87
No difference in violation between High-Low2 and Low-High2	0.34	0.74
No difference in violation between High-Low3 and Low-High3	0.81	0.68

Figures 1 and 2 show the histograms of violation for each sample pool. Visual comparison of the distributions of High-Low1 and Low-High1 for the student sample shows large differences compared to the managers, which was confirmed in the statistical tests. For the subject pool of managers, the distribution of under-reporting does not differ substantially between High-Low and Low-High. The average under-reporting is higher among students than among managers. We test the null hypothesis that mean violation is the same between the subject pools using a Mann-Whitney test for each combination separately. We reject the hypothesis of no difference for the case of Low-High3 at the 5% significance level (p-value= 0.05) and High-Low1 at the 10% significance (p-value=0.08) level.

Figure 1. Histograms of violation by combination of probabilities for managers.

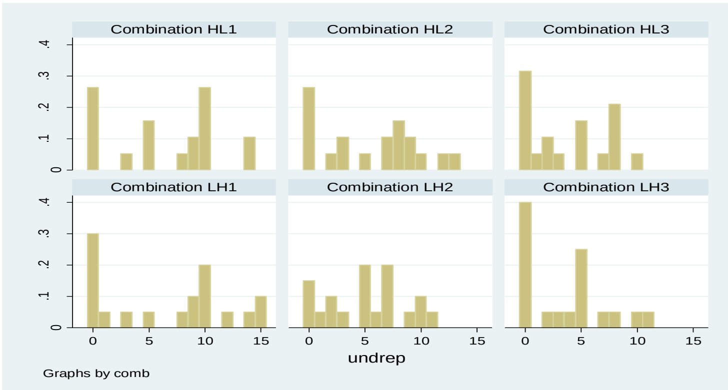
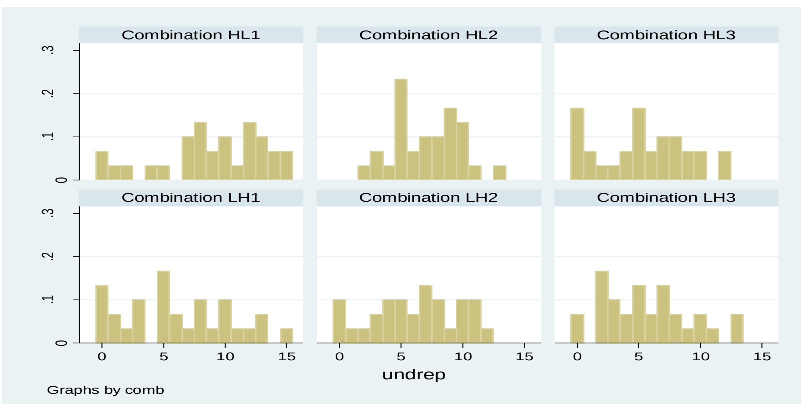


Figure 2. Histograms of violation by combination of probabilities for students.



We also investigate if the degree of under-reporting is statistically different within each treatment for different joint probabilities. We test the null hypothesis of no difference in under-reporting for all pair-wise combinations of different joint probabilities within a treatment, and Table 5 presents the results. In the student sample, we observe that there is a statistically significant difference in extent of violation between different joint probabilities when people face a low sanctioning probability, i.e., a High-Low combination.

Table 5. The Wilcoxon Matched-Pairs Ranks test of no sensitivity of under-reporting related to joint probabilities

	Students (p-value)	Managers (p-value)
High-low treatment		
Ho: No difference in extent of under-reporting between High-Low1 and High-Low2	0.00	0.00
Ho: No difference in extent of under-reporting between High-Low2 and High-Low3	0.00	0.00
Ho: No difference in extent of under-reporting between High-Low1 and High-Low3	0.00	0.00
Low-high treatment		
Ho: No difference in extent of under- reporting size between Low-High1 and Low-High2	0.74	0.00
Ho: No difference in extent of under- reporting size between Low-High2 and Low-High3	0.17	0.00
Ho: No difference in extent of under- reporting size between Low-High1 and Low-High3	0.39	0.00

The extent of violation under High-Low1 ($\pi_d * \pi_{s|d} = 0.1$) is significantly higher than that under High-Low2 ($\pi_d * \pi_{s|d} = 0.16$) and High-Low3 ($\pi_d * \pi_{s|d} = 0.28$). In contrast, when there is a high sanctioning probability, i.e., Low-High combinations, although extent of violation decreases as the sanction probability increases the differences are not statistically significant at conventional levels. In our proposed theoretical model, this is explained by the fact that detection probability influences the expected image and legitimacy motivations in addition to the expected legal fine, whereas sanctioning probability only influences the expected legal fine. If the difference in violation between different joints probabilities were only due to joint probability as such, then we would expect the same "significance result" under High-Low and Low-High. Conducting the same analysis for managers, we observe that a higher joint probability leads to a lower extent of violation irrespective of the treatment. This is also an indication that managers make their decisions only based on intrinsic and legal motivations.

Table 6 presents the marginal effects of a Tobit regression and explains the extent of under-reporting separately for each sample. We observe in the two samples that the coefficient of the joint probability of monitoring and sanctioning is significantly different from zero at the 5% significance level. The negative sign of this coefficient indicates that when joint probability increases, the extent of violation decreases. This is in line both with our findings in the non-parametric tests and with theoretical predictions. In our students' sample, we find a significant and positive effect of monitoring probability. When the probability increases, so does the extent of violation. According to our theory model, subjects who do not feel that the rule of paying for emissions is appropriate may use non-compliance to express their disapproval. For managers, monitoring probability per-se does not affect the extent of violation which is consistent with our non-parametric tests. We also find a gender effect in both samples: the extent of violation is significantly lower among females than among males. In contrast to the managers, for students the coefficient of the index of moral judgment competence is significantly different from zero at 5% although the effect is not large. The risk attitudes are also significantly different from zero at 5% for the students, but not for managers. Subjects with higher levels of moral judgment competence violate significantly less, and the higher the risk aversion the lower the extent of violation.[21]

[21] To test the robustness of the results to the choice of econometric model, we also estimated a count data model as well as a random effects model and Tobit models on the sub-sample with a positive extent of under-reporting. The statistical and economic significances of the results are robust to the different modeling approaches. Additionally, we conducted a likelihood ratio test to test the null hypothesis that coefficients of the explanatory

Table 6. Tobit regression for the extent of under-reporting.

Dependent variable: Extent of under-reporting	***Students***		***Managers***	
	Marginal effects	P-value	Marginal effects	P-value
Joint probability Detection and sanctioning $\pi_d * \pi_{s\|d}$	-12.29	0.002	-20.83	0.003
Detection probability π_d	3.10	0.001	0.68	0.692
Female	-2.38	0.037	-4.08	0.024
C-index	-0.12	0.020	-0.09	0.250
C-index * Female	0.17	0.007	0.08	0.424
Guilt	0.16	0.607	-0.12	0.815
Risk aversion measure	-5.57	0.002	2.63	0.474
Number of observations	180		114	

Based on our results of the non-parametric test and econometric analysis, for the manager sample, we cannot reject the hypothesis of substitutability between detection and sanctioning probabilities. This implies that a regulator may use different combinations of monitoring and sanctioning probabilities without affecting the behavior of regulated agents. However, the extent of violation chosen by environmental managers is lower than predicted by the standard model, indicating that there are determinants of the extent of violations additional to economic incentives. We use the Moral Judgment Test (Lind et al., 1985) to measure the effect of morality on violation decisions and measure risk preferences using Binswanger's (1980) risk experiment. For managers, pool variables such as gender, moral development, and risk aversion do not explain the extent of violation. This indicates that, although individual characteristics of the managers do not matter for firms' decisions, there are still considerations additional to monetary sanctions when deciding degree of compliance with regulations.

For the student sample, the chosen extent of violation is lower than predicted. The moral development index, the subject gender, and risk aversion have a significant effect

variables are the same between managers and students. We can reject the null hypothesis at the 5% level (p-value< 0.01).

on extent of violation. Moreover, for students, the fact that detection probability is important is made evident by the finding that, for this sample pool, different combinations of detection and sanctioning probabilities have different deterrence effects on extent of violation. The sign of detection probability in the student sample indicates that the extent of under-reporting increases with detection probability. A plausible explanation for this, from our theoretical model, is that students do not perceive the rule of self-reporting emissions and paying for them as legitimate.

5. Conclusion

The standard theory assumes that an agent chooses the extent of under-reporting by comparing the benefits and expected legal fines from violating. However, as shown in for example research on income and tax evasion as well as in more theoretical work on motivational factors behind pro-social behavior (e.g., Bénabou and Tirole, 2006), people do not violate the law as much as predicted and take factors other than legal fines into account when making compliance decisions. Additionally, standard theory predicts that as long as the joint probability of detection and sanctioning remains constant, the extent of violations of a regulated agent is insensitive to variations in detection and sanctioning probabilities. We propose an alternative theoretical model in which an agent not only considers the expected monetary fine in case she is caught under-reporting but also considers three other costs of violation. The agent considers a cost related to intrinsic motivations, a cost related to image motivation, and a cost related to the possibility of showing her opinion about the legitimacy of the regulation through compliance decisions. The two latter costs are directly related to the probability of being caught under-reporting. In contrast to the standard model of law enforcement, our theoretical model predicts that the extent of violation is different for different combinations of monitoring and sanction probabilities when the joint probability is kept constant.

By using a laboratory experiment, we investigate the effect of different combinations of detection and sanctioning probabilities on self-reported emissions to authorities, i.e., we analyze the substitutability of probability of detection and probability of sanctioning given detection when the goal is to deter violation. The results for the manager sample indicate that we cannot reject the hypothesis that detection and sanctioning probabilities are substitutes. This implies that the authority may use any mix of probabilities of detection and sanctioning without affecting the behavior of the regulated agents; i.e., only the joint probability of detection and sanctioning matters. A regulator who, subject to an enforcement budget constraint, decides on the probabilities of detection and sanctioning in order to minimize violations should allocate resources to detection and sanctioning such that each monetary unit spent on detection and on sanctioning given violation is detected leads to the same reduction in violations. A natural extension would be to investigate the effect of disclosure in this context.

From a methodological perspective, it is of interest to note that, in this study, students behaved differently than managers. In general, managers under-reported less and their behavior was more difficult to explain by differences in moral development, attitudes towards risk, and personal characteristics such as gender. Our results have clear implications for authorities in case of self-reported emission levels, but it is suggested that future research also investigate whether the effect is the same for choice of emission levels. Needless to say, replications in a laboratory as well as implementation in field experiments are of course warranted for such an important issue.

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Appendix A

Equation (5) in the text, called (A1) in this appendix, is as follows:

(A1) $$t-\beta\pi_d\pi_{s|d}\left[F'(e-r)\right]-\gamma\pi_d G'(e-r)\alpha-\eta\pi_d L'(e-r)-\theta I'(e-r)=0$$

Taking the partial derivative with respect to π_d yields:

(A2)

$$\gamma G'(v)\alpha+\gamma\pi_d G''(v)\alpha\frac{\partial v}{\partial\pi_d}+\beta\pi_{s|d}F'(v)+\beta\pi_d\pi_{s|d}F''(v)\frac{\partial v}{\partial\pi_d}+\theta I''(v)\frac{\partial v}{\partial\pi_d}+\eta L''(v)\frac{\partial v}{\partial\pi_d}+\eta L'(v)=0$$

Solving for $\frac{\partial v}{\partial\pi_d}$:

(A3) $$\frac{\partial v}{\partial\pi_d}=\frac{-\gamma G'(v)\alpha-\beta\pi_{s|d}F'(v)-\eta L'(v)}{\gamma\pi_d G''(v)\alpha\pi_d+\beta\pi_d\pi_{s|d}F'''(v)+\theta I''(v)+\eta L''(v)}$$

Taking the partial derivative with respect to $\pi_{s|d}$ yields:

$$\gamma\pi_d G''(v)\alpha\frac{\partial v}{\partial\pi_{s|d}}+\beta\pi_d F'(v)+\beta\pi_d\pi_{s|d}F''(v)\frac{\partial v}{\partial\pi_{s|d}}+\theta I''(v)\frac{\partial v}{\partial\pi_{s|d}}+\eta L''(v)\frac{\partial v}{\partial\pi_{s|d}}=0$$

Solving for $\frac{\partial v}{\partial\pi_{s|d}}$:

(A4) $$\frac{\partial v}{\partial\pi_{s|d}}=\frac{-\beta\pi_d F'(v)}{\gamma\pi_d G''(v)\alpha\pi_d+\beta\pi_d\pi_{s|d}F'''(v)+\theta I''(v)+\eta L''(v)}$$

Replacing (A3) and (A4) in $dv=\frac{\partial v}{\partial\pi_d}d\pi_d+\frac{\partial v}{\partial\pi_{s|d}}d\pi_{s|d}$ and rearranging yields:

(A5) $$dv=\frac{-\beta F'(v)\left[\pi_d d\pi_{s|d}+\pi_{s|d}d\pi_d\right]-\left[\gamma G'(v)\alpha+\eta L'(v)\right]d\pi_d}{\gamma\pi_d G''(v)\alpha\pi_d+\beta\pi_d\pi_{s|d}F'''(v)+\theta I''(v)+\eta L''(v)}$$

Given $\left[\pi_d d\pi_{s|d}+\pi_{s|d}d\pi_d\right]=0$, it follows that:

(A6) $$dv=\frac{-\left[\gamma G'(v)\alpha+\eta L'(v)\right]d\pi_d}{\gamma\pi_d G''(v)\alpha\pi_d+\beta\pi_d\pi_{s|d}F'''(v)+\theta I''(v)+\eta L''(v)}$$

In the standard models of enforcement of law, $\left[\gamma G'(v)\alpha+\eta L'(v)\right]=0$ and therefore $dv=0$

Chapter 4

Does disclosure crowd out cooperation?*

Peter Martinsson[a]
Clara Villegas-Palacio[b]

Abstract

This paper investigates whether disclosure crowds out pro-social behavior using a public goods experiment. In a between-subject design, we investigate different degrees of disclosure. We find a small positive but insignificant effect of disclosure treatments on contributions to the public good. Thus, our empirical findings are consistent crowding-out theory.

***Key words*:** disclosure, image motivation, public goods experiment.

***JEL classification*:** C91, H41.

[a] Department of Economics, University of Gothenburg, Gothenburg, Sweden; e-mail: Peter.Martinsson@economics.gu.se; Ph +46 31 786 52 55 (Corresponding author).
[b] Department of Economics, University of Gothenburg, Gothenburg, Sweden; e-mail: Clara.Villegas@economics.gu.se; Ph: +46 31 786 26 42. Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín.

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1. Introduction

Over the last few decades, many different types of external interventions have been implemented in various areas ranging from environmental protection to charitable giving with the aim of increasing people's pro-social behavior. However, as pointed out by Frey and Jegen (2001) and Nyborg and Rege (2003), it has been documented in the literature that external interventions may enhance intrinsic motivations (crowding in) when the external intervention is perceived by subjects as supportive, or reduce intrinsic motivations (crowding out) when the intervention is perceived by subjects as controlling. In cases where the decrease in intrinsic motivation is larger than or equal to the increase in other types of motivations from the intervention, crowding out has occurred. For example, Titmuss (1970) argued that if people were paid for blood donations, the supply of blood would decrease. In a recent field experiment by Mellström and Johannesson (2008), Titmuss's argument is partly supported by the empirical findings. In a similar vein, Frey and Oberholzer-Gee (1997) find that the acceptance of "not-in-my-backyard-projects" is reduced if monetary compensation is offered, while a study by Gneezy and Rustichini (2000) shows that an imposed fine for late pick up of children from daycare increases the number of late pick-ups. To affect pro-social behavior in the desired direction, it is important to understand the underlying motivational factors. Benabou and Tirole (2006) discuss three broad motivations to why individuals behave pro-socially: (i) intrinsic, (ii) extrinsic, and (iii) image motivation.[1] While intrinsic and extrinsic motivations focus on factors such as altruism and monetary rewards, image motivation focuses on the fact that an individual derives utility from how other people perceive her, i.e., social approval, and from the way she perceives

[1] There is a similar classification in, e.g., Ariely *et al*. (2009). For early work on intrinsic motivation, see, e.g., Deci (1975).

herself (e.g., self-image). Most of the research on testing the hypothesis of crowding out has focused on monetary compensation, which directly affects extrinsic motivation.

The objective of the present paper is to investigate whether disclosure, as an external intervention, crowds out contributions to a public good by using an experimental approach, and more specifically, we test the effect of different degrees of disclosure on contribution levels in our public goods experiments. In contrast to the anonymous setting in public goods experiments, many situations in our daily lives contain an element of disclosure of both identities and contributions. Not surprisingly, disclosure has been used in many situations ranging from public announcements at fundraising events to official reporting of pollution levels of companies, with the common purpose of using image motivations to induce pro-social behavior. By using a one-shot public goods experiment based on the design in Fischbacher *et al.* (2001), we focus on the effect of three different types of disclosure on contributions to a public good, namely (i) out-group disclosure, where a subject's identity and contribution are disclosed to all subjects in the experimental session but group belonging is not disclosed, (ii) in-group disclosure, where each subject's identity and contribution are revealed to the group members only, and (iii) joint in-group and out-group disclosure, i.e., a subject's contribution is disclosed to all subjects of the session, together with a baseline treatment comprising of the standard setting of not disclosing group belonging.[2] To avoid confounded effects between disclosure and stereotyping based on gender and beauty (e.g., Andreoni and Petrie, 2008), group belonging and contribution were disclosed after all participants had made their contributions. These three types of disclosure schemes can be implemented in many local public good situations, e.g., in the context of water

[2] It should be noted that a one-shot experiment rules out that strategic motives can play a role, although strategic motives related to meeting the same persons after the experiment cannot be ruled out.

quality of rivers in different watersheds. In this situation, the local environmental authority has the possibility to choose a disclosure scheme, where subjects' behavior can be disclosed either in-group to others situated along the same river, out-group to other firms/people in the region but not necessarily situated along the same river, or a combined approach. In our analysis, we go beyond the existing studies by disentangling the effect of in-group disclosure, i.e., decisions that are revealed only to the group members, and out-group disclosure, i.e., decisions that are revealed to everyone without stating group belongings, on pro-social behavior in a public good setting.

The little existing experimental evidence regarding using disclosure as an external intervention to increase pro-social behavior is mixed. A few laboratory experiments have investigated the effect of disclosure on cooperation using public goods experiments.[3] Rege and Telle (2004) tested whether social approval affects cooperation in a one-shot public good experiment using an in-group disclosure strategy. In the disclosure treatment, where the subjects themselves revealed their contributions to the other members of their own group, contributions to the public good were significantly higher compared to a standard setting with no disclosure. In contrast, Noussair and Tucker (2007) did not find a significant difference in a one-shot experiment with disclosure using a design similar to Rege and Telle (2004), while they did find significantly lower contributions in a multi-period public goods experiment with disclosure.[4] List

[3] Despite the fact that the standard public goods experiment is conducted anonymously, and in contrast to predictions of standard economic theory, subjects on average contribute a positive amount to public goods (e.g., Leyard, 1995; Zelmer, 2003).

[4] A related study by Burnham and Hare (2007) included a treatment where subjects were watched by a robot with eyes, and this significantly increased the contributions. There are some papers on the effect of disclosure in a multi-period public goods game. Gächter and Fehr (1999) studied the effect of social approval incentives introduced at the end of a 10 period public good game on contributions. A number of papers have investigated the effect of public disclosure of behavior but not identity. Croson (2001) found in multi-period public goods experiments that disclosing information to other group members about contributions without revealing any identities has no significant effect on contribution, while Sell and Wilson (1991) found, using a similar design, that disclosure of contribution, but not identity, does have a significant impact on contributions. Laury *et al*. (1995) test the differences in contributions in a

et al. (2004) studied the effect of different degrees of anonymity when voting on whether or not all of the experiment participants have to contribute the whole participation fee to a public good. They found that that random disclosure of donation to a public good resulted in a significantly higher share of yes responses compared to a treatment where the answer to the referendum was completely anonymous.[5] In a field experiment, Soetevent (2005) investigated church offerings among 30 churches in the Netherlands. He found that significantly higher donations to causes outside the church were made when open collection baskets were used instead of ”closed” collection bags. Yet, the effect vanished over time, and he did not find this effect for offerings with an internal cause.[6] His design could be seen as a large in-group treatment with partial disclosure since only neighbors could potentially see the amount donated by someone else. By using a lab experiment and a field experiment to test for social approval, Ariely *et al*. (2009) found that donations increase in size if they are seen by others in a treatment. As discussed in Blackman (2008), disclosure has been frequently used in a number of countries to reveal the pollution levels among firms. Although the results of using disclosure as an external intervention to regulate pollution are mixed, the main effect seems to be reduced pollution among the heaviest polluting firms.[7] The main finding of our public goods experiments is that disclosure increases contributions to the public good, yet the effect is statistically insignificant at conventional levels. This indicates crowding-out in a similar manner as monetary rewards. The rest of the paper is organized as follows: Section 2 presents the experimental design and procedures. Section 3

double-blind versus a single-blind treatment, but did not find a significant difference in contribution levels related to disclosure.

[5] Andreoni and Bernheim (2009) found that the proportion of equal split in a dictator game increases as the probability of disclosure decreases.

[6] Alpizar *et al.* (2008) found in a field experiment on donations to a national park that donations made in front of a solicitor are significantly higher than those made anonymously.

[7] A related literature explores the effects of leading by example on contributions to public goods. In this type of experiment, the leader decides and announces her contribution before the other group members make their contributions. Such leadership has been found to increase contributions in comparison with the standard anonymous and simultaneous contribution to the public good (e.g., Güth *et al*., 2006; Rivas and Sutter, 2009).

contains the results from our analysis. Finally, Section 4 offers a discussion and concluding remarks.

2. Experimental design

Our experiment builds on the experimental design by Fischbacher *et al.* (2001).[8] The key features of their design are elicitation of both unconditional and conditional contributions to a public good. In the unconditional setting, subjects are asked how much they would like to contribute to a public good, which replicates a standard one-shot public good experiment. In the conditional contribution setting, the strategy method is used, i.e., subjects are requested to fill in a conditional contribution table that specifies how much they would like to contribute to a public good conditional on each of the possible average contribution levels of the other members of their group (rounded to the nearest integer). In the standard experimental set-up, neither group belonging nor contributions at the individual level are revealed to subjects before, during, or after the experiment. In the disclosure treatments, contributions and identity are revealed following completion of all contributions, and the exact information on the disclosure procedure is thoroughly described in the instructions read prior to the contribution decisions.[9]

We use a standard linear public goods experiment. Each subject is endowed with 20 tokens and the marginal per capita return from the public good is set to 0.4. Each group consists of four members. Thus, subject *i*'s payoff in tokens is given by

[8] For other studies using this design, see, e.g., Fischbacher and Gächter (2009), Herrmann and Thöni (2009), and Kocher *et al*. (2008).

[9] It should be noted that this is different from previous experiments. In Andreoni and Petrie (2004), subjects could see photos of their group members, but their decisions were not revealed to others in a face-to-face situation. In Rege and Telle (2004), the subjects made their decisions in front of the other members of their respective groups. Given gender and beauty stereotypes (see, e.g., Andreoni and Petrie, 2008), it is difficult to know whether and in what direction such disclosure can be expected to affect contributions.

$$\pi_i = 20 - c_i + 0.4\sum_{i=1}^{4} c_i \ , \qquad (1)$$

where c_i is the amount invested in the public good by individual *i*. In order to make each of the choices incentive compatible, for three of the subjects in each group, the unconditional contribution counts as their contribution to the public good. The contribution from the fourth subject, who is randomly selected from the group, is based on her conditional contribution table. More exactly, the conditional contribution she reported for the average unconditional contributions of the other three members is taken as her contribution to the public good. Thus, by adding the three unconditional contributions and the conditional contribution by the fourth member, the total contribution by the group to the public good can be calculated using equation (1).

Our 2x2 experimental design is summarized in Table 1. The two dimensions in our experiment are disclosure to members of own group, i.e., in-group disclosure, and disclosure to all subjects in a session, i.e., out-group disclosure. The no-disclosure treatment is a standard public goods game setting with complete anonymity regarding both the identities of and the contributions made by the subjects. In the out-group disclosure treatment, each subject is asked one at a time, by using the experimental identification numbers, to stand up in front of the group after the completion of the experiment, whereby her income-relevant decision is publicly announced by the experimenter to all subjects in that session, without any reference to group belonging. In the in-group disclosure treatment, the contributions of the subjects are disclosed to group members only. In this treatment, the four group members come together, one group at a time, in a room next door. Once the four group members are seated, each subject is asked one at a time by using experimental identification numbers to stand up in front of the others, whereby her income-relevant decision is publicly announced by the experimenter. In the joint disclosure treatment, the four group members are asked, one group at a time, to sit on four chairs in front of all participants in the session. Then, the income-relevant decision is revealed by the experimenter, using the same procedure as in the other two disclosure treatments.

Table 1. The experimental design of the public goods experiments.

		Out-group disclosure *(Contributions and identity announced to all participants in the session)*	
		No	Yes
In-group disclosure *(Contributions and identity announced only to group members)*	No	***No disclosure*** Standard public good game without disclosure	***Out-group disclosure*** Public good game with only out-group disclosure
	Yes	***In-group disclosure*** Public good game with only in-group disclosure	***Joint disclosure*** Public good game with both in-group and out-group disclosure

An experimental session consisted of the following stages: At the beginning of a session, participants completed the Mach-IV test (Christie and Geis, 1970).[10] According to Vecchio and Sussmann (1991), the resulting test score can be used as a proxy of the degree of an individual's selfishness. The purpose was to be able to test whether the fraction of selfish subjects was the same across treatments. Once all participants had completed the Mach-IV test, the experimental instructions were handed out and read aloud to the subjects.[11] Several examples and individual exercises were provided as well. To check for the subjects' understanding of the experiment, the experimenter publicly solved the exercises once all participants had finished answering them. Any additional questions the subjects had were then answered in private. The subjects

[10] The Mach-IV test has been applied in previous experiments, e.g., Gunnthorsdottir *et al*. (2002).
[11] The instructions are available from the authors upon request.

simultaneously decided how much to contribute unconditionally to the public good, and filled in the conditional contribution table, where they indicated their contribution to the group account given the average contribution (rounded to the nearest integer) of the other three group members. After the decision sheets had been collected, the participants were asked in writing about their beliefs regarding the total unconditional contribution levels of the other three participants to the public good account. As in Gächter and Renner (2006), we monetarily rewarded subjects by using tokens for accurate guesses. Then the subjects completed a socio-economic questionnaire. By using the random number generator in EXCEL, the experimenter randomly selected one member in each group for whom the conditional contribution was the income relevant decision and then calculated the amount to be paid to each subject. In the disclosure treatments, the contribution-revealing stage was conducted and finally all subjects were paid privately in cash.

3. Experimental results

Our subjects were students at Universidad Nacional de Colombia-Sede Medellín, Colombia. Participants were randomly selected from a list of people who registered in response to an e-mail invitation to participate in the experiment. We ran four treatments (with two sessions per treatment) corresponding to the 2x2 design described in Table 1. In each session, there were 24 participants randomly allocated to groups of four. Each token earned in the experiment equaled 750 Colombian pesos.[12] We began by investigating the homogeneity between subjects in different treatments. Using the Kruskal-Wallis test we can neither reject the null hypothesis of no differences between treatments in degree of selfishness (based on the Mach IV index) nor the null hypothesis of the same gender composition using a chi-square test. On average, subjects earned

[12] At the time of the experiment, 2,275 Colombian pesos = 1 USD.

24,000 Colombian pesos (approximately 10.5 USD) in the 90 minutes that the sessions lasted, including an additional show-up fee of 5,000 Colombian pesos (approximately 2.3 USD).

3.1 Unconditional Contributions to the Public Good

The mean unconditional contribution for the four treatments is shown in Table 2, where a subject's contribution is denoted in percent of her maximum possible contribution of 20 tokens. In the standard public goods game (without disclosure), subjects on average contributed 7.98 tokens (39.9% of the endowment). Introducing only out-group disclosure increases the average contribution to 8.77 tokens (43.8%). Introducing out-group disclosure when in-group disclosure was already implemented resulted in an increase from 8.64 tokens (43.2%) in the in-group disclosure treatment to 9.62 tokens (48.1%) in the joint disclosure treatment. In a similar way, the effect of in-group disclosure can be made conditional on out-group disclosure. Introducing only in-group disclosure increases the average contribution to 8.64 tokens (43.2%). Introducing in-group disclosure when out-group was already implemented resulted in an increase from 8.77 tokens (43.8%) to 9.62 tokens (48.1%). Finally, the overall effect by combining out-group and in-group disclosure compared to no disclosure consisted of an increase from 7.98 tokens (39.9%) to 9.62 tokens (48.1%). We conducted a Wilcoxon-Mann-Whitney test to test the null hypothesis of equal distributions of unconditional contributions in all treatment pairs, and we cannot reject the null hypothesis for any of the pairs of treatments at the 5% significance level.[13] Similarly, the null hypothesis of equal distribution of unconditional contributions across the four treatments is not rejected at the 10% level based on a Kruskal-Wallis test (p-value=0.68).

[13] We performed a Kolmogorov-Smirnov test of the null hypothesis of equal distributions in treatment pairs, and we cannot reject the null hypothesis at the 5% significance level in any of the pair-wise tests.

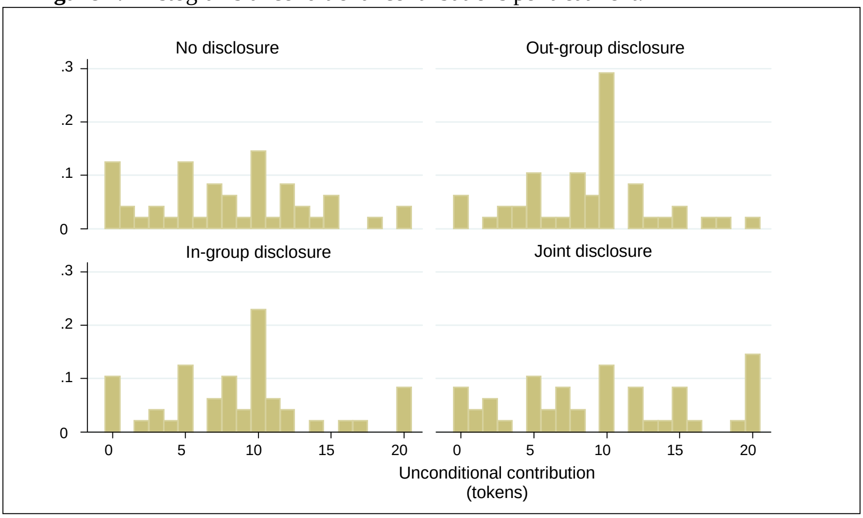
Table 2. Average unconditional contributions in the different treatments (contributions in percentage of endowment in parentheses).

		Out-group disclosure			
		No	***Yes***	***Change***	***H_0: No difference (p-value)***
In-group disclosure	***No***	***No disclosure*** 7.98 tokens (39.9%)	***Out-group design*** 8.77 tokens (43.8%)	0.79 tokens (3.9%)	0.43
	Yes	***In-group disclosure*** 8.64 tokens (43.2%)	***Joint disclosure*** 9.62 tokens (48.1%)	0.98 tokens (4.9%)	0.50
Change		0.66 tokens (3.3%)	0.85 tokens 4.3%		(No-disclosure vs. Joint disclosure) 1.62 tokens 8.2%
H_0: No difference (p-value)		0.64	0.61		0.24

Note: The pair-wise tests are based on a Wilcoxon-Mann-Whitney test while the overall test is based on the Kruskal-Wallis test.

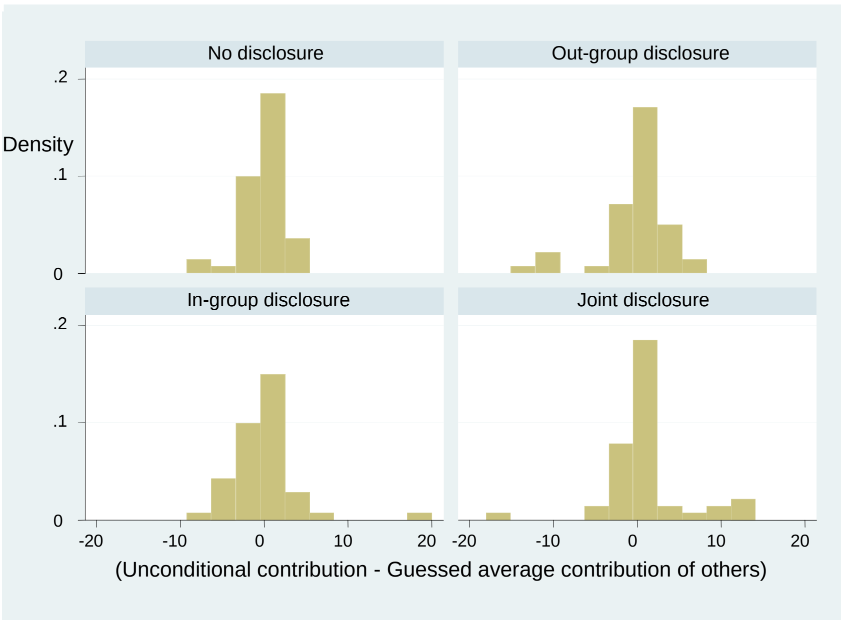
Figure 1 shows the distribution of unconditional contributions per treatment using histograms. In the analysis below, we focus on comparing the different disclosure treatments to the base case of no disclosure. Compared to the no-disclosure treatment, the main effect of out-group disclosure is an increase in the proportion of subjects contributing 50% of the endowment. A similar effect is found for in-group disclosure, but additionally, there is an increase in the proportion of unconditional contributions of full endowment. Interestingly, the joint disclosure treatment results in a more uniformly distributed contribution pattern than in out-group or in-group disclosure, i.e., heterogeneity in contribution increases. Following Rege and Telle (2004), we examined the behavior in more detail by first studying the number of subjects who gave everything or nothing in the unconditional contribution treatment. The null hypothesis of equal proportions of full contributors in all four treatments is not rejected at the 5% significance level (p-value=0.09) using a chi-square test. Moreover, the proportion of zero contributors is not statistically different across the four treatments (p-value=0.75) using the same test. We then conducted pair-wise tests between treatments of the null hypothesis of equal proportions of full contributors and zero contributors respectively, and we only reject the null hypothesis of equal proportions of full contributors between out-group disclosure and joint treatment at the 5% significance level (p-value=0.03). Using a chi-square test, we cannot reject the null hypothesis of equal proportions of subjects contributing 50% of the endowment at the 5% significance level between the out-group disclosure and the joint disclosure treatments (p-value=0.04).

Figure 1. Histograms unconditional contributions per treatment.



As expected, the distribution of the guessed contributions of the other group members follows a similar pattern as the distributions of own unconditional contributions. In Figure 2 below, we show the histograms of the difference between own unconditional contribution and the guessed average contributions of the other group members. In all four treatments, Figure 2 shows a spike at 0, meaning that most subjects guessed that others unconditionally contribute the same as themselves. In a pair-wise chi-square test, where we categorized behavior into three groups (i.e., own contribution is less than, the same as, or higher than the guessed average contribution by others), we cannot reject the null hypothesis of no difference between any of the pairs at the 5% significance level.

Figure 2. Histograms of differences between unconditional contribution and guessed contribution per treatment.



In Table 3, Model 1 presents the results of the Tobit regression of the unconditional contribution on the disclosure treatments. We observe that none of the treatment variables are significant. This means that the unconditional contribution to a public good is not significantly different under any of the disclosure treatments compared to the unconditional contribution in the anonymity treatment. In Model 2, when the subjects' guessed average contributions of others is included as an additional explanatory variable, we observe that guessed contribution has a positive and significant effect on unconditional contributions. When the belief about others' contributions increases by 1 token the unconditional contribution increases by 0.30 tokens. This indicates that, on average, subjects are imperfect conditional cooperators. The effects of the dummy variables for in-group and out-group disclosure on unconditional contributions have the expected positive sign, yet they are not significant at conventional levels.

Table 3. Results from Tobit regression model. Dependent variable: unconditional contribution.

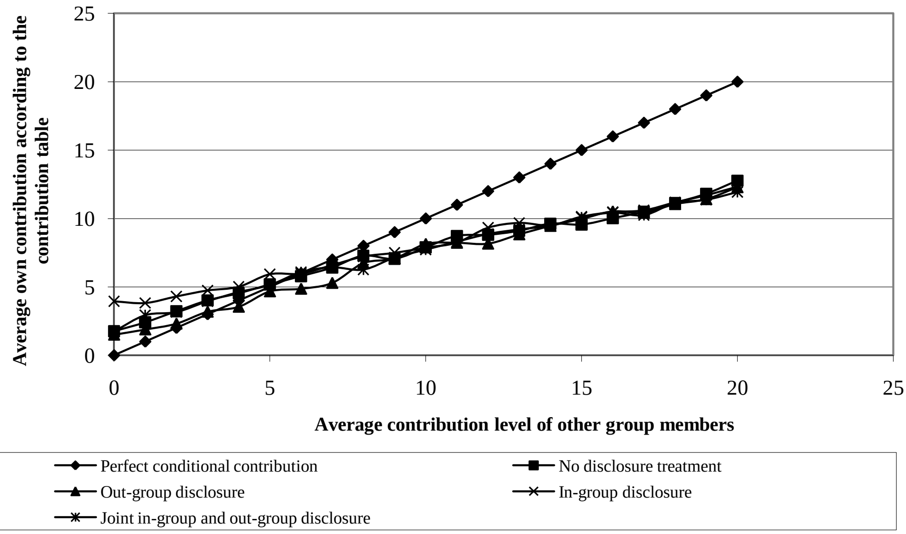
	Model 1	***Model 2***
Independent variables	Marginal effects	Marginal effects
In-group disclosure	0.85	0.36
	(1.31)	(0.90)
Out-group disclosure	0.96	0.38
	(1.30)	(0.89)
Joint disclosure	2.09	1.63*
	(1.31)	(0.90)
Guessed average contribution of others		0.31***
		(0.02)

Note: *, **, and *** denote significance at the 10%, 5%, and 1% level respectively. Standard errors reported in parenthesis.

3.2 Types of contributors

We use the conditional contribution tables to analyze the relationship between a subject's own conditional contribution and the average contribution of the other members in her group. Following Fischbacher *et al.* (2001), we plot the relation between the average own conditional contribution (on the vertical axis) and the other members' average contribution (on the horizontal axis). Figure 3 shows the results. The figure shows that, on average, a subject's own conditional contribution increases when the average contribution of the other members increases, which indicates that subjects on average behave as conditional contributors. The fact that the slope is less than one, this indicates imperfect conditional cooperation, which is similar to the regression results reported in Table 3 based on unconditional contributions. As can also be seen, when the average contribution of others is zero, subjects on average contribute more than zero in all treatments, indicating some degree of altruism. These patterns are consistent with, e.g., Fischbacher and Gächter (2009a), Fischbacher *et al.* (2001), and Kocher *et al.* (2008).

Figure 3. Average own contribution level for each average contribution level of other group members, by treatment.



We classify subjects into the five categories of contribution behavior types as defined by Fischbacher *et al*. (2001): free-riders, conditional cooperators[14], unconditional cooperators (excluding free-riders), hump-shaped contributors, and others. The proportions of subjects in the

[14] We classify subjects as conditional cooperators if their contribution is monotonically increasing with the average contribution of other group members. We count subjects with non-monotonically increasing contributions as conditional cooperators if the Spearman rank correlation coefficient between own and others' contributions is significant at the 1% level (as in, e.g., Fischbacher *et al.*, 2001, and Fischbacher and Gächter, 2009b).

different categories are shown in Table 4 together with the average unconditional contribution and the guessed average unconditional contribution of each type. In the no-disclosure treatment, 62.5% are classified as conditional cooperators, while in the joint treatment, 75% are classified as conditional cooperators. Comparing our results in the standard public good game setting with no disclosure with results in for example Fischbacher *et al.* (2001) and Kocher *et al.* (2008), we find that the proportion of conditional cooperators in our case is higher than the 50% obtained by Fischbacher *et al*. (2001), but lower than the 80.6% obtained by Kocher *et al.* (2008) in their US sample.[15] The proportion of free-riders in our standard pubic goods experiment is much lower than in the other studies, i.e., around 5% in all treatments except in joint disclosure where it is 12.5%. The latter is in line with the increased heterogeneity found in that treatment. The proportion of subjects in the "others" category is roughly the same as in previous studies, but in our joint disclosure treatment the fraction is substantially lower.

The proportions of types of contributors are not significantly different at the 5% level across treatments based on a chi-square test (p-value=0.40). In a more detailed analysis, we test the null hypothesis of equal proportions of types in treatment pairs using a chi-square test. We cannot reject the null hypothesis of equal proportion in any of the pairs at the 5% significance level. We conducted a Wilcoxon-Mann-Whitney test of the null hypothesis of equal distributions of unconditional contributions for each type of subject in treatment pairs. The distribution of unconditional contribution by subjects classified as cooperators under joint disclosure is significantly different than the distribution of unconditional contribution of conditional

[15] The fraction of conditional contributors in our study falls between the numbers obtained by Kocher *et al* (2008) in the US (80.6%) and those obtained in Austria (44.4%) and in Japan (41.7%). The proportion of conditional contributors in our study is larger than the figures obtained by Herrmann and Thöni (2009), where 48-60% are conditional contributors depending on location in Russia.

cooperator types under out-group disclosure (p-value=0.03).[16] Based on a Wilcoxon-Mann-Whitney test, we cannot reject the null hypothesis of equal distribution of guessed average unconditional contributions in treatment pairs. This indicates that disclosure schemes do not impact beliefs about others' contributions.

[16] We also found significant differences in the distribution of unconditional contributions of hump-shaped contributors between Treatments 3 (in-group disclosure) and 4 (joint disclosure) at 10% and in the distribution of unconditional contributions of other patterns between Treatments 1 (no disclosure) and 2 (out-group disclosure) at 10%.

Table 4. Distribution of contributor types per treatment.

Type of contributor	***Standard (anonymity)***		***Out-group disclosure***		***In-group disclosure***		***Joint disclosure***	
	Distri-bution	*Average unconditional contribution (tokens)*	*Distri-bution*	*Average unconditional contribution (tokens)*	*Distri-bution*	*Average. unconditional contribution (tokens)*	*Distri-bution.*	*Average unconditional contribution (tokens)*
Free-rider	4.17%	0.50 (0.71)	4.17%	9.00 (12.73)	6.25%	0.0 (0.00)	12.50%	0.67 (1.03)
Conditional cooperator	62.50%	9.33 (5.12)	70.83%	8.62 (3.81)	64.58%	9.06 (4.84)	75.00%	11.58 (5.48)
Unconditional cooperator	4.17%	0.50 (0.71)	0.00%	-	4.17%	20.00 (0.00)	0.00%	-
Hump-shaped	8.33%	8.75 (7.45)	8.33%	5.00 (3.56)	4.17%	3.00 (0.00)	6.25%	6.67 (2.89)
Others	20.83%	6.60 (3.95)	16.67%	11.25 (4.65)	20.83%	8.80 (2.79)	6.25%	7.00 (10.30)
Number of observations		48		48		48		48

4. Discussion and conclusions

In this paper, we have experimentally analyzed whether disclosure as an external intervention crowds out intrinsic motivation. By using a public goods experiment based on the design developed by Fischbacher *et al*. (2001), we implemented three different disclosure treatments, namely in-group disclosure, out-group disclosure, and joint disclosure, in addition to a treatment with no disclosure (i.e. a standard public goods experiment), using a between-subject design. Our design explores beyond previous experiments by testing the effect of different degrees of disclosure.

We present evidence indicating that the incentives provided by the three disclosure treatments increase unconditional contributions to the public good compared to the no-disclosure treatment, although the effect is not statistically significant at conventional levels. This shows that the expected positive effect (crowding-in) of image motivation on may be offset by two other effects : (i) a crowding-out effect of image motivations given by the desire to appear intrinsically motivated rather than motivated by appearances; (ii) a crowding-out effect of intrinsic motivations consistent with the crowding theory of Frey and Jegen (2001). Our results are therefore consistent with the crowding theory. Future research on disentangling the effects of disclosure schemes on image motivations from the effects on intrinsic motivations is needed.

We find that, when implementing joint in-group and out-group disclosure, the proportion of subjects contributing the whole endowment significantly increases, compared to the no disclosure treatment, while the proportion of non-contributors does not change significantly. The fact that the distribution of contributions varies across treatments is an indication of heterogeneous image concerns among our participants. Our results constitute empirical support for the theoretical prediction of Benabou and Tirole (2006) model which sustains that when individuals are heterogeneous in image concerns, pro-social behavior under disclosure might be suspected of being triggered by appearances rather than by intrinsic motivations, limiting the effectiveness of the policy.

Our paper contributes to the ongoing discussion on whether external interventions crowd out pro-social behavior. Many of the external interventions investigated previously are of a one-shot nature. Thus, a natural extension is to investigate the effect of disclosure over time. From the findings in Gächter and Fischbacher (2009a), where contribution type was found to be stable over time, we would predict that higher unconditional contribution levels combined with a larger share of conditional cooperator types would result in a relatively slower decay in contributions over time. However, in the joint treatment, the fractions of free-riders as well as of conditional cooperators were larger, which most likely would increase the speed of decay over time. From a policy perspective, future research should focus on investigating the effect of different degrees of disclosure in real life. One approach would be to conduct a field experiment using a design similar to the one used here. Such an experiment could establish whether there exists an optimal degree of disclosure or whether crowding-out theory is generally supported.

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Chapter 5

Conditional Cooperation and Social Group

- *Experimental Results from Colombia-* [1]

Peter Martinsson[a]
Clara Villegas-Palacio[b,c]
Conny Wollbrant[d]

Abstract

In contrast to previous studies on cross-group comparisons of conditional cooperation, this study keeps cross- and within-country dimensions constant. The results reveal significantly different cooperation behavior between social groups in the same location.

Keywords: Conditional cooperation, experiment, public goods, social group

***JEL Classification*:** C91, H41.

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[a] Department of Economics, School of Business, Economics and Law, University of Gothenburg, P.O. Box 640, 405 30 Gothenburg, Sweden, (email) Peter.Martinsson@economics.gu.se, (ph) + 46 (0) 31 786 5255, (fax) + 46 (0) 31 786 1043.
[b]Department of Economics, School of Business, Economics and Law, University of Gothenburg, (email) Clara.Villegas@economics.gu.se.
[c]Facultad de Minas, Universidad Nacional de Colombia, Sede Medellín, Colombia, (email) civillegas@unal.edu.co.
[d] Department of Economics, School of Business, Economics and Law, University of Gothenburg, P.O. Box 640, 405 30 Gothenburg, Sweden, (email) Conny.Wollbrant@economics.gu.se.

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1. Introduction

Voluntary contribution to public goods is frequently found both in the field and in the laboratory (e.g., see Gächter, 2007). Fischbacher et al. (2001) developed a one-shot public goods experiment in which subjects are asked for 1) an unconditional contribution to a public good, as in standard public goods experiments; and 2) a conditional contribution to the public good, given all possible average contributions (rounded to the nearest integer) of other group members. By investigating the profile of conditional contributions, subjects can be grouped into contributor types, such as free riders and conditional cooperators. (In other words, their degree of cooperation is conditional on their beliefs about others' cooperation.) Early evidence from experiments using the type classification following Fischbacher et al.'s approach used university students in Western countries as subjects (see, e.g., Gächter, 2006, for an overview). Generally, conditional cooperators are the dominating type (Fischbacher et al., 2001); however, most conditional cooperators are not perfect conditional contributors, but contribute slightly less than others. Kocher et al. (2008) replicated the experiment by Fischbacher et al. (2001) in three different countries and found differences in both the distribution of types and the share of conditional cooperation. Herrmann and Thöni (2009) conducted the same experiment in two rural and two urban locations in Russia and found that their fractions of conditional cooperators varied 48–60 percent within location, but that the differences between the locations were insignificant. The evidence from studies testing the effect of cultural background on behavior, using a standard multi-period public goods game, has been mixed as well (e.g., Brandts et al., 2004; Burlando and Hey, 1997; Herrmann et al., 2008).

When comparing experimental findings between locations, we identified three dimensions along which different locations may differ: 1) cross-country differences (e.g., religion and social norms), 2) within-country differences (e.g., rural versus urban areas), and 3) social group differences (e.g., age, trust, and income). Given these differences, it is not surprising that different locations yield different behavior. In this vein, Heinrich et al. (2005) found that those who see greater payoffs for cooperation in everyday life exhibit greater levels of prosociality in experimental games. La Ferrara (2002) found that relatively wealthy individuals are less likely to be a part of any group because benefits from cooperation do not outweigh the cost of membership for them. This opens up the question of whether preferences for cooperation vary across social groups.

The objective of the present paper is to investigate cooperative behavior in different social groups by keeping cross- and within-country differences constant. We used university students recruited from two universities in Medellin, Colombia, who differed in social-class: 1) socio-economic strata 2 and 3 (i.e., the "medium-low" group), and 2) socio-economic strata 4, 5, and 6 (i.e., the "high" group).[2] We used the design of Fischbacher et al. (2001) to measure cooperative behavior in a public goods context.

2. Experimental Design and Procedure

We conducted a standard linear public goods experiment, following the same format as Fischbacher et al. (2001), where subject i's payoff in tokens is given by:

$$\pi_i = 20 - c_i + 0.4\sum_{i=1}^{4} c_i \ , \qquad (1)$$

where 20 is the endowment and c the amount invested in the public good. Each group consisted of four randomly matched members. The marginal return from the public good was set to 0.4, ensuring a conflict between the dominant strategy to contribute zero, i.e., to free ride, and the full contribution Pareto optimum solution.

We asked our subjects to indicate how much they would like to contribute, both unconditionally and conditionally, to the public good. In the case of conditional contributions, subjects were asked how much they would like to contribute, conditional on the average contribution of the other members of the group, which included all integers numbers from 0 to 20 (i.e., the strategy method). To ensure incentive

[2]There are six social strata in Colombia: 1 (low-low), 2 (low), 3 (medium-low), 4 (medium), 5 (medium-high), and 6 (high). Strata 1–3 receive domestic public service subsidies, such as provision of water, electricity, and gas; 5–6 pay additional contributions toward the cost of public services. Stratum 4 receives no subsidies, but this group does not contribute either. The strata are indicators of people's socio-economic conditions.

compatibility for all decisions, the payoff relevant decision for three randomly selected members was the unconditional contribution. By using their average unconditional contribution, the contribution of the fourth member was given by his/her conditional contribution for that specific average contribution. Then, each member's monetary payoff could be calculated using equation (1). After the experiment, subjects were asked to guess the total contribution of the other three group members, and accuracy of guesses was monetarily rewarded.

The experiments were conducted at one socio-economic "medium-low" university (Universidad Nacional de Colombia) and one "high" university (Escuela de Ingeniería de Antioquia), both in Medellín, Colombia.[3] At both places, we ran two sessions with 24 subjects each; students of mathematics, psychology, and economics were excluded. The procedure of the experiment was the same at both places. Examples and individual exercises were used to ensure that subjects understood the experiment. Each session lasted approximately 90 minutes and the payoffs were calibrated to reflect opportunity costs. For the medium-low group, each token equaled COP 750, while the corresponding figure was COP 1,000 for the high group.[4] Average earnings were COP 25,000 for the high group and COP 23,000 for the medium-low group. (Both figures include a show-up fee of COP 5,000.)

3. Results

We followed the standard approach when defining the four contributor types (see Fischbacher et al., 2001). Conditional contributors submitted a contribution table showing

[3] At Universidad Nacional de Colombia (the medium-low group), approximately 80% of the student population belongs to strata 2 and 3, 11% to stratum 4, and only 5% to strata 5 and 6 (see Rico 2005). This is a public university where the cost of a six-month term is about the minimum monthly salary for students of stratum 3. At Escuela de Ingeniería de Antioquia, a private university, students mainly belong to strata 4, 5, or 6, and the cost is 10 times higher.

[4] In cases with samples with different opportunity costs, either the absolute amount in the experiment or the opportunity cost can be kept constant. We decided to keep the opportunity cost constant; it should be noted that Kocher et al. (2008) did not find a significant stake effect in one-shot public goods game. COP = Columbian Pesos; the exchange rate at the time of the experiment was US$ 1 = approximately COP 2,000. A lunch in the medium low–social class university costs approximately 75% of a lunch at the high social-class university.

a monotonically increasing own contribution for an increasing average contribution of the other members.[5] Free riders were characterized by a zero contribution for every possible average of the other members. Unconditional contributors submitted the same positive contribution independent of others' average contribution. Hump-shape contributors (also known as triangle contributors*)* showed monotonically increasing contributions up to a given average level of others' contributions, after which their contributions decreased. The category referred to as "Others" constituted the remaining participants.

Table 1 displays the distributions of types by social group. The dominating type is conditional cooperators, comprising 51 percent and 62 percent of the high group and the medium-low group, respectively. This is very close to the figures reported by, e.g., Fischbacher et al. (2001) and Fischbacher and Gächter (2006). Interestingly, 25 percent of the subjects in the high group were classified as free riders, compared to 4 percent in the medium-low group.

We rejected the null hypothesis of no differences in distribution of types between groups at the 5-percent significance level (p = 0.03; Chi2-test).[6] This is explained by a rejection of the hypothesis of no differences in share of free riders between the two groups at the 1 percent significance level (p = 0.004; Chi2-test). Table 1 also presents the average unconditional contribution for each type; the difference between the groups is statistically insignificant at conventional levels.

The relationship between the subjects' own conditional contribution and the average contribution of other group members is shown in figure 1. When the average contribution of others was zero, subjects in the medium-low group contributed more than those in the high group. Also, the difference in slope between the perfect conditional cooperation line and the plotted line, which represents degree of self-serving bias, was significantly larger in the high group. The regression results confirm the results shown in figure 1.

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[5] We also included those without a monotonically increasing contribution, but with a highly significant (at 1%) positive Spearman rank correlation coefficient between own and others' contributions (see Fischbacher et al., 2001; Fischbacher and Gächter, 2006).

[6] This result is robust to systematic exclusion of types, e.g., excluding "others" (p = 0.026, Chi2-test).

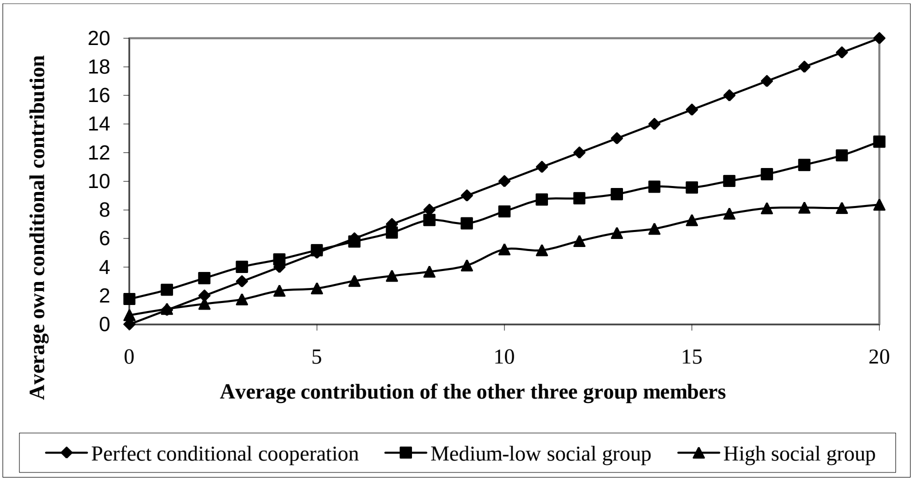
Table 1. Distribution of player types, average unconditional contribution, and guessed contribution.

	High socio-economic group			Medium-low socio-economic group		
	Distribution	Avg.uncond. contrib.	Avg. guessed contribution	Distri-bution	Avg. uncond. contrib.	Avg. guessed contribution
Unconditional cooperators	0.00%	0.00 (0.00)	0.00 (0.00)	4.17%	0.50 (0.71)	0.00 (0.00)
Conditional cooperators	54.17%	9.64 (4.68)	9.88 (4.78)	62.50%	9.33 (5.12)	9.50 (4.93)
Hump-shape contributors	8.33%	6.50 (7.85)	11.00 (7.53)	8.33%	8.75 (7.46)	8.25 (6.40)
Free-riders	25.00%	3.83 (7.02)	6.50 (7.43)	4.17%	0.50 (0.71)	2.00 (0.00)
Others	12.50%	8.00 (4.47)	7.67 (4.23)	20.83%	6.60 (3.95)	7.30 (4.16)

Note: Avg. uncond. contrib = average unconditional contributions; standard errors in parentheses.

Note: Avg. guessed. contrib = average guessed contributions; standard errors in parentheses.

Figure 1. Average own conditional contribution vs. average contribution of the other three group members.



Using two-sided Mann-Whitney U-tests, we found no significant difference in mean unconditional contribution between groups; it was 7.98 tokens in the medium-low group and 7.68 in the high group ($p = 0.75$). These levels of unconditional contributions, around 40 percent of the endowment, are in line with earlier findings (e.g., Kocher el at., 2008).

We elicited beliefs about others' contribution in the unconditional case, and found no significant differences in beliefs between the high group (8.83) and the medium-low group (8.23, where $p = 0.71$). Furthermore, regression results revealed that both groups can be classified as imperfect conditional cooperators (table 2). In addition, the high group displayed a significantly higher level of self-serving bias, which is similar to findings from the analysis of the conditional contribution tables.

Table 2. Regression results.

Dep. var: unconditional contribution in tokens	Tobit
	Coef.
Guessed contribution	0.948**
	(0.102)
Guessed contribution x High socio-economic group	-0.312*
	(0.140)
High socio-economic group	1.778
	(1.387)
Constant	0.181
	(0.984)
Sigma	4.079
	(0.341)
Number of observations	94
R-squared	0.58

Note: *** denotes significance at the 1% level, ** at the 5% significance level, * at 10% significance level. and t-statistics in parenthesis.

4. Conclusion

There is a growing interest in understanding whether behavior is the same across locations. By holding cross- and within-country dimensions constant, we investigated cooperative behavior between social groups in the same location. Our results suggest that different social groups exhibit differences both in terms of composition of types and extent of conditional cooperation.

As shown by Fischbacher and Gächter (2009), the decline in cooperation over time is caused by imperfect conditional cooperation. Thus, even if the unconditional contributions are similar across locations, the degree of imperfect conditional cooperation and the fraction of free riders are important factors determining the long-term differences in contributions to public goods. As a consequence, policymakers may need to consider different policy schemes. Following Gächter (2006), a social group where most individuals are conditional cooperators needs policies that sustain beliefs for cooperation of its integrants. In contrast, in situations where free riding dominates, policies involving monitoring and penalties may be required to enhance cooperation. Because a substantial part of public goods is local (e.g., teamwork and local environmental public goods governed by common property regimes such as lakes, pastures and irrigation systems), it is important to understand local preference heterogeneity.

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